Net Zero Aerial Capability (NZArC) Scoping Report

A Review of the Role of Uncrewed Aerial Systems in the Decarbonisation Strategy of NERC Aerial Activities

UKRI
Natural Environment Research Council

Contents

Authors 4
Acknowledgements 4
Glossary 5
1. Executive Summary 9
2. Context 12
2.1 Purpose 12
2.2 Scope 12
2.3 Drivers 12
2.3.1 UKRI and NERC Decarbonisation Targets 12
2.3.2 Science and Technology Innovation 12
2.3.3 UK Government Context 13
2.4 Use of UASs in UK Environmental Science Research Centres 13
2.4.1 British Antarctic Survey (BAS) 13
2.4.2 British Geological Survey (BGS) 19
2.4.3 National Centre for Atmospheric Science (NCAS) 23
2.4.4 National Centre for Earth Observation (NCEO) 29
2.4.5 National Oceanographic Centre (NOC) 33
2.4.6 Plymouth Marine Laboratory (PML) 36
2.4.7 Scottish Association for Marine Science (SAMS) 39
2.4.8 UK Centre for Ecology and Hydrology (UKCEH) 41
3. Methodology 45
3.1 NZArC Steering Group and Report Writing 45
3.2 Community Engagement 45
3.2.1 First Workshop 46
3.2.2 Second Workshop 48
3.3 Authorship of Report 50
3.4 Referencing Existing Resources 50
3.5 Intentional Repetition 50
4. Findings 51
4.1. Regulatory Factors 51
4.1.1. Current State of Affairs 51
4.1.2. Where We Want to Be 52
4.1.3. Gap Analysis (Barriers/Challenges and Solutions/Opportunities) 53

4.1.4. Recommendations for Advancement ... 54
4.2. Technology - Platforms ... 54
4.2.1. Current State of Affairs ... 56
4.2.2. Where We Want to Be ... 57
4.2.3. Gap Analysis (Barriers/Challenges and Solutions/Opportunities) ... 58
4.2.4. Recommendations for Advancement ... 63
4.3. Technology - Sensor Integration ... 64
4.3.1. Mechanical Fit and Power ... 64
4.3.2. Integrating Position ... 64
4.3.3. Triggering the Sensors ... 65
4.3.4. Where We Want to Be ... 65
4.3.5. Gap Analysis (Barriers/Challenges and Solutions/Opportunities) ... 66
4.3.6. Recommendations for Advancement ... 66
4.4. Technology - Discipline-specific Sensors ... 67
4.4.1. Atmospheric Science ... 67
4.4.2. Ecology and Biodiversity ... 71
4.4.3. Geosciences ... 74
4.4.4. Glaciology ... 79
4.4.5. Hydrology ... 82
4.4.6. Oceanography ... 86
4.4.7. Earth Observation ... 89
4.5. Data ... 94
4.5.1. Current State of Affairs ... 96
4.5.2. Where We Want to Be ... 97
4.5.3. Gap Analysis (Barriers/Challenges and Solutions/Opportunities) ... 98
4.5.4. Recommendations for Advancement ... 99
5. Conclusions and Recommendations ... 100
5.1 Overarching Conclusions & Recommendations ... 100
5.2 Sector Specific Conclusions & Recommendations ... 104
5.2.1 Technology ... 104
5.2.2 Data ... 106
6. Appendix - Existing Use Cases ... 115
Large-Scale Wildlife Surveys Using Fixed-Wing Remotely Piloted Aerial Systems ... 115
Sea Ice Observations for Ship Navigation ... 117
Walrus from Space – UAS Images to Validate Walrus Satellite Count ... 119
Snow Hill Emperor Penguins: Using UASs and Citizen Science to Monitor Emperor Penguin Numbers ... 121

SWARM – Windracers Ultra for Environmental Science Data Collection 124
UASs for Abandoned Mine Activity: Monitoring Contaminated Land 126
Kilbourne Hole Volcano 127
Geoenergy Monitoring for Energy Security... 129
Geological Conservation at Croft Quarry 131
Geological Fault Mapping... 133
Geothermal Energy Research in Mexico 135
Infrastructure Assessment at Slaithwaite Reservoir 137
Landslide Monitoring at Hollin Hill, Yorkshire... 139
Methane Plume Detection Using CH_4 Sensor.. 141
Mineral Exploration and Field Skills Training 143
Monitoring Coastal Landslides at Aldbrough Coastal Landslide Observatory 145
Pond Identification Through Vegetation at Gresham Marshes, Notts.. 147
UAS Quantification of Greenhouse Gas Emission Fluxes 149
Upscaling Vegetation Structure and Function... 151
UAS for Wildfire Observations... 153
UAS for Evapotranspiration 155
HyperDrone: SWIR Multispectral Proxies for Plastic Debris on Shorelines 7B 157
Hydrogen-Fuelled Survey Platform 159
NERC UAV School (PhD-Level Course).. 161
NERC NEXUSS Grand Challenge.. 163
WesCon–WOEST Field Campaign Summer 2023.. 165

Authors

Philip Anderson (SAMS), Luke Bateson (BGS), Barbara Brooks (NCAS), Richard Dale (SAMS), Nick Everard (UKCEH), Charlotte Francoz (NOC), Charles George (UKCEH), France Gerard (UKCEH), Tom Jordan (BAS), Zixia Liu (NCEO), Aser Mata (PML), Hugo Ricketts (NCAS), Carl Robinson (BAS), Pilvi Saarikoski (BAS), Beatrix Schlarb-Ridley (BAS), Kay Smith (BGS), James Strong (NOC), Martin Wooster (NCEO)

Acknowledgements

This report was supported by the following institutions: British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML), Scottish Association for Marine Science (SAMS) and UK Centre for Ecology and Hydrology (UKCEH); these are jointly referred to as the 'NERC Centres and Collaborating Institutes' for the remainder of the report.

The Net Zero Aerial Capability (NZArC) Steering Group (SG; comprised of, in alphabetical order by first name: Aser Mata (PML), Barbara Brooks (NCAS), Beatrix Schlarb-Ridley (BAS), Charles George (UKCEH), Charlotte Francoz (NOC), James Strong (NOC), Kay Smith (BGS), Luke Bateson (BGS), Martin Wooster (NCEO), Philip Anderson (SAMS), Pilvi Saarikoski (BAS), Richard Dale (SAMS) and Zixia Liu (NCEO)) would like to thank NERC for the financial support for this work (grant title: Net Zero Aerial Capability, Uncrewed Aerial System NZArC: UAS – Scoping Project) and the NERC Capital and Place Team (Nichola Badcock, Rachel Lamb, Kola Akinola, Magdalena Basiewicz) for the practical support and guidance provided.

The SG would like to thank all those in the NERC Centres and Collaborating Institutes who aided in the community engagement activities and the development of this report. The SG would also like to thank all those who have reviewed and commented on the document.

Finally, the SG would like to thank the wider community and key regulatory stakeholders for their engagement without which this report could not have been developed.

Glossary

ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
ADCP	Acoustic Doppler Current Profiler
ADR	Atomic Dielectric Resonance
ADSB	Automatic Dependent Surveillance Broadcast
AGL	above ground level
AI	Artificial Intelligence
AMOF	Atmospheric Measurement and Observation Facility
AMS	Airspace Modernisation Strategy
AONB	Area of Outstanding Natural Beauty
APL	Airborne Processing Library
AQ	Air Quality
ARF	Airborne Research Facility
ARA	Advanced Research Aircraft
ARSF	Airborne Research & Survey Facility
ASCII	American Standard Code for Information Interchange
ASPA	Antarctic Specially Protected Area
ASSI	Air Safety Support International
ASV	Autonomous Surface Vehicle
ATSC	Advanced Training Short Course
AUV	Autonomous Underwater Vehicle
BAS	British Antarctic Survey
BGS	British Geological Survey
BVLOS	Beyond Visual Line of Sight
CAA	Civil Aviation Authority
CAL/VAL	Calibration/Validation
CAPS	Cloud Aerosol and Precipitation Spectrometer
CAST	Co-ordinated Airborne Studies in the Tropics
CEDA	Centre for Environmental Data Analysis
CMS	Computer Modelling Support
COINS	Copernicus *In Situ*
COMNAP	Council of Managers of National Antarctic Programs
CONOPS	Concept of Operations
COST	Cooperation in Science and Technology
COTS	Commercial Off-The-Shelf
CT^2	Temperature Structure Function Coefficient
DEM	Digital Elevation Model
dGPS	Differential Global Positioning System
DOAS	Differential Optical Absorption Spectroscopy
DOI	Digital Object Identifier
DP	Dynamic Positioning
DSM	Digital Surface Model
DTM	Digital Terrain Model
EA	Environment Agency
EC	Eddy Covariance
EDS	Environmental Data Service
EGU	European Geosciences Union

EKF	Ekman Kalman Filter
EMR	Electromagnetic Radiation
EO	Earth Observation
ESA	European Space Agency
ET	Evapo-Transpiration
EUMETNET	European National Meteorological Services
eVTOL	Electric Vertical Take Off and Landing
FAAM	Facility of Airborne Atmospheric Measurement
FAIR	Findable Accessible Interoperable and Reusable
FLIR	Forward Looking Infrared
FMRI	Future Marine Research Infrastructure
FSF	Field Spectroscopy Facility
GCP	Ground Control Points
GEP	Geophysical Equipment Pool
GHG	Greenhouse Gas
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GOOS	Global Ocean Observing System
GPR	Ground Penetrating Radar
GSD	Ground Sampling Distance
GVC	General Visual Line of Sight Certificate
HAPS	High Altitude Platforms
HTOL	Hybrid Take Off and Landing
HyTES	Hyperspectral Thermal Emissions Spectrometer
ICOS	Integrated Carbon Observation System
INS	Inertial Navigation System
IP	Ingress Protection
IPCC	Intergovernmental Panel on Climate Change
IR	Infrared
ISARRA	International Society for Atmospheric Research using Remotely piloted Aircraft
ITAR	International Traffic in Arms Regulations
JPL	Jet Propulsion Laboratory
KBH	Kilbourne Hole
KCL	Kings College London
KEP	King Edward Point
LDS	Laser Displacement Sensor
LEL	Lower Explosive Limit
LiDAR	Light Detection and Ranging
LST	Land Surface Temperature
LSTM	Land Surface Temperature Measurement
LWIR	Longwave Infrared
MARS	Marine Autonomous and Robotic Systems
MCA	Maritime and Coastguard Agency
MCM	Master Chemical Mechanism
MIR	Midwave Infrared
ML	Machine Learning
MLU	Mid Life Upgrade
MoD	Ministry of Defence
MPAS	Model for Prediction Across Scales

MSP	Marine Spatial Planning
NAEO	NCEO Airborne Earth Observatory
NASA	North American Space Agency
NERC Centres and Collaborating Institutes	*throughout the report, this refers to: BAS, BGS, NCAS, NCEO, NOC, PML, SAMS, UKCEH*
NCAS	National Centre for Atmospheric Science
NCCA	National Centre for Coastal Autonomy
NCEO	National Centre for Earth Observation
NEODAAS	NERC Earth Observation Data Acquisition and Analysis Service
NERC	Natural Environment Research Centre
netCDF	Network Common Data Form
NIR	Near Infrared
NMEA	National Marine Electronics Association
NMEP	National Marine Equipment Pool
NMF	National Marine Facilities
NOC	National Oceanography Centre
NRW	Natural Resources Wales
NSF	National Science Foundation
NZArC	Net Zero Aerial Capability
NZOC	Net Zero Oceanographic Capability
OD	Ordnance Datum
PASIN	Polarimetric radar Airborne Science INstrument
PDC	Polar Data Centre
PfCO	Permission for Commercial Operations
PIDINST	Persistent Identifier for Instruments
PIDS	Persistent Identifiers
PDRA	Post-doctoral Research Assistant
PGS	Post Graduate Student
PM	Particulate Matter
PML	Plymouth Marine Laboratory
PPK	Post-Processed Kinematic
PTU	Pressure, Temperature, Humidity
QA	Quality Assurance
QC	Quality Control
QGIS	Quantum Geographic Information System
RAE	Recognised Assessment Entity
RE	Red Edge
RGB	Red Green Blue
ROV	Remote Operated Vehicle
RRS	Royal Research Ship
RS	Remote Sensing
RTK	Real-Time Kinematic positioning
SAF	Sustainable Aircraft Fuel
SAMS	Scottish Association for Marine Science
SEPA	Scottish Environment Protection Agency
SfM	Structure-from-Motion
SG	South Georgia
SIAC	Sensor Invariant Atmospheric Correction
SLR	Sea Level Rise

SME	Small and Medium-sized Enterprises
SOP	Standard Operating Procedure
SPTA	Salisbury Plain Training Area
SRA	Scientific Robotics Academy
SSP	Smart Sound Plymouth
SSSI	Site of Special Scientific Interest
SWIR	Shortwave Infrared
tCO_2e	Tonnes of CO_2 equivalent
TDEM	Time-Domain Electromagnetic
TKE	Turbulent Kinetic Energy
TIR	Thermal Infrared
TLS	Terrestrial Laser Scanning
TO	Twin Otter
TRL	Technology Readiness Level
TSEB	Two Source Energy Balance
UAS	Uncrewed Aerial System
UCL	University College London
UKCEH	UK Centre for Ecology and Hydrology
UKESM	UK Earth System Model
UKHO	UK Hydrographic Office
UKMO	UK Met Office
UKRI	UK Research and Innovation
UNAVCO	University NAVSTAR Consortium
USV	Uncrewed Surface Vehicle
VLOS	Visual Line of Sight
VNIR	Visible and Near-Infrared
VOC	Volatile Organic Compounds
VR	Virtual Reality
VTOL	Vertical Take-Off and Landing
WAS	Whole Air Sampling
WMO-GAW	World Meteorological Organization Global Atmosphere Watch
WRF	Weather Research and Forecasting
wxUAS	Weather Uncrewed Aerial System
XRF	X-ray Fluorescence
XRD	X-ray Diffraction

1. Executive Summary

This scoping report is part of NERC's response to the challenge of achieving Net Zero by 2040 while maintaining and developing its airborne science capabilities. These capabilities are essential to inform decision-makers with relevant and reliable environmental evidence and to drive forward the frontiers of science. The response includes, but is not limited to expanding, strengthening and developing capability and capacity in Uncrewed Aerial Systems (UASs).

This report, based on engagement with key stakeholders including the NERC UAS user community, and co-authored by representatives from eight NERC Centres and Collaborating Institutes, articulates the current state-of-play for UASs within environmental research as it is adopted by NERC Centres and Collaborating Institutes and in different environmental disciplines. It outlines the vision for expanding UAS usage within environmental scientific research, highlights barriers and opportunities regarding regulation, technology (including, platforms, sensors and integration) and data flows and provides recommendations to inform future NERC perspectives on the use of UASs for environmental research. These aim to help prioritise opportunities to deliver a programme of low-carbon UASs and sensor capability that can be linked to the NERC carbon pathway to Net Zero by 2040.

To overcome key barriers, the report makes the following recommendations:

1. *To overcome regulatory barriers: (1):* Nominate a single NERC-funded point of contact with the Civil Aviation Authority (CAA): an expert from one of the NERC Centres and Collaborating Institutes acting as a coordinating officer, proactively building a relationship and managing requests to minimise duplication of effort. (*2):* Establish and maintain a central documentation repository and FAQ database. It is envisaged that the repository would include, but not be restricted to, regulatory paperwork, central operations manuals and standard operating procedures (SOP), predefined risk assessment and templates, links to information sources, a central log of incidents and outcomes lessons learned (evidence of building a culture of safety and trust with CAA) and a central list of existing equipment and pilots.

2. *To build capacity and capability:* Develop one or more geographically accessible or discipline-focused CAA-approved training centre(s) and programme(s).

3. *To encourage the most fruitful technology development and integration:* Work towards cross-council leveraging of expertise to facilitate the rapid development of compatible sensors and platforms.

4. *To strengthen trust in the veracity of measurements:* Develop and adopt proven, transparent and, if applicable, internationally recognised best practices for calibration, operations and data processing.

5. *To facilitate data uptake by third-party-users: (1):* Develop and adopt standard file formats, aligned with internationally recognised best practices and resource data centres appropriately to facilitate the development of user and provider tools for enhanced useability and inclusion. (*2):* Integrate UAS data sources into planning for Digital Research Infrastructure.

In addition to providing further detailed conclusions and recommendations specific to regulation, technology (including platforms, sensors and integration) and data flows, the report also makes the following overarching recommendations for the UAS community and for NERC:

A. Key Overarching Recommendations for the Community

Best practice:

A1. Quantify and reduce bias and variance in UAS-based measurements.
A2. Co-develop, share and adopt open and transparent data processing protocols and open licence UAS data processing pipelines.
A3. Develop and adopt recognised best practice operational protocols.

Coordination:

A4. Create a network to work together more extensively and share experience, knowledge and capabilities.
A5. Convene expert working groups to establish feasible development pathways and to build mutual understanding.
A6. Improve access to both UAS capability and UAS-derived data.

Wider engagement:

A6. Make the best use of Citizen Science, with the caveat of quality control.
A7. Encourage UAS and sensor suppliers to maintain backwards compatibility.
A8. Be proactive in engaging with international bodies working on data standards, guidance, formats and approaches.

B. Key Overarching Recommendations for NERC

Strategic steer:

B1. NERC to develop a strategy on science and innovation in remote data collection, autonomous and robotic capability, leveraging synergies across aerial, marine and terrestrial sectors.

Funding:

B2. Focused calls for development of UAS sensors and application of innovative UAS technologies relevant to the natural environment, including the understanding and quantification of measurement biases.
B3. Drive innovation across NERC by developing joint programmes and initiatives across UKRI (challenge areas) and across institutions.

Resources:

B4. Develop a "pilot pool" both for regular surveying of proven systems and test pilots for first flights of novel configurations, linked to a NERC UAS training centre/programme approved by CAA.
B5. Provide dedicated field test/flying areas for sensor and airframe synergy development and training of pilots.

Data recommendations:

B6. Develop and maintain a central resource to gather, store, disseminate and communicate information across the sector.
B7. Have a joined-up approach across the NERC Environmental Data Service to negate the need for a new dedicated data centre for UAS data.

Skills and knowledge recommendations:

B8. Establish UK forums to encourage collaboration and sharing of skills, fabrication capability and experience within and between UAS specialist groups.
B9. Provide funding support for the development of a NERC Doctoral Focal Award specific to encouraging UAS usage in environmental science, training the next generation and breaking down barriers to access.
B10. Facilitate UK-wide travel support and community building/knowledge transfer to engage with the global community.

In conclusion: UASs are part of a portfolio of actions that, when implemented well, offer a tremendous opportunity both to reduce the carbon footprint of environmental research and thereby contribute to UKRI's Net Zero goal for 2040 and to provide substantial scientific benefit. The community of NERC Centres and Collaborating Institutes is enthusiastic to explore these opportunities to ensure validated UASs can address appropriate science questions with lowest possible environmental impact, following best regulatory practice and leading to trusted, FAIR and well-managed data. The authors of this report are keen to continue working with NERC Head Office to build on the recommendations of this scoping study and to turn this potential into realised benefit.

2. Context

2.1 Purpose

In line with UKRI's objective of becoming a carbon-neutral organisation by 2040, NERC is seeking to identify options for developing a world-class and world-leading aerial capability with a reduced carbon footprint; a capability that spans the broad spectra of platform size, range, payload and operational ceiling and that is grounded in delivering quality assured data and ease of access. This requires expanding, strengthening and developing capability and capacity in Uncrewed Aerial Systems (UASs).

The Net Zero Aerial Capability (NZArC) programme will focus on exploring the route to increased usage of UASs for aerial-based research, to enhance NERC's low-carbon research capability. This report, part of the first work package of NZArC, is primarily internal-facing (for NERC), but also has public-facing value (for the wider environmental science community). It aims to enable NERC to plan effectively for future opportunities in this space.

2.2 Scope

The report articulates the current state-of-play for UASs within environmental research as it is adopted by NERC Centres and Collaborating Institutes and in different environmental disciplines. It outlines the vision for expanding UAS usage within environmental scientific research, highlights barriers and opportunities regarding regulation, technology (including platforms, sensors and integration) and data flows and provides recommendations to inform future NERC perspectives on the use of UASs for environmental research. These aim to help prioritise opportunities to deliver a programme of low-carbon UAS and sensor capability that can be linked to the NERC carbon-pathway to Net Zero by 2040.

2.3 Drivers

2.3.1 UKRI and NERC Decarbonisation Targets

UKRI and NERC are committed to achieving Net Zero Carbon by 2040. For NERC, it is especially important to show leadership in setting and meeting ambitious targets: NERC funding underpins much of the environmental evidence for the urgency of climate action that UK scientists have been collating. At the same time, collecting this evidence has come at a significant carbon cost, especially where it currently requires the use of ships and aircraft. NERC is addressing decarbonising its shipborne science through FMRI (Future Marine Research Infrastructure; formerly NZOC (Net Zero Oceanographic Capability)); the NZArC programme, of which this scoping report is a component, has been set up to facilitate decarbonising NERC's airborne science.

2.3.2 Science and Technology Innovation

New technologies open up not only moving existing experiments from crewed to uncrewed aerial systems, but also experiments and data collection hitherto not possible (for example because they are too dangerous, expensive or inaccessible using crewed systems). Pursuing those can improve the quality of science and usefulness of outputs to decision makers and contribute to achieving Net Zero targets by shifting away from research areas that use more carbon-intensive platforms.

There will continue to be a need for crewed capabilities. For some instruments, miniaturisation and light-weighting may not be achievable to the degree necessary to enable them to be flown on even the larger autonomous platforms;even for light-weight sensors, the combination of instruments required for a science mission may require a total volume incompatible with UASs currently available to the research community. Furthermore, as the technological landscape advances and the scientific needs of the community evolve, new instruments and analysis techniques will be developed. The proof of concept for new instrumentation is a critical stage before the specialist adaptations required for integration on a UAS platform can be addressed. Testbed capability that facilitates innovation and also "heavy lifting" capability sit more with advances involving crewed aircraft rather than UASs.

2.3.3 UK Government Context

Outside of the scientific context, the UK government is also investing in reducing the carbon footprint of aviation, including through airborne autonomy for commercial and societal uses. In May 2022, the government published "Flightpath to the Future: A Strategic Framework for the Aviation Sector", setting out a vision for a modern, innovative and efficient aviation sector over the next 10 years. This was followed in July 2022 by a framework and plan for achieving Net Zero aviation, "Jet Zero Strategy: Delivering Net Zero Aviation by 2050" and a policy paper "Advancing Airborne Autonomy: Commercial Drones Saving Money and Saving Lives in the UK". The latter includes several 'Calls to Action' (p. 8) which chime with the findings of this scoping study: workshops with the NERC research centre community also have identified the need for *(1)* regulatory support, *(2)* funding to ensure the development and demonstration of new operating models and frameworks, *(3)* supporting innovation and *(4)* implementation of sector-specific skills development.

2.4 Use of UASs in UK Environmental Science Research Centres

The sections below provide an overview of the research areas of eight Centres and Institutes that receive NERC funding, how they currently use crewed and uncrewed aerial systems and their strategic vision for UASs. In alphabetical order, these are: British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanographic Centre (NOC), Plymouth Marine Laboratory (PML), Scottish Association for Marine Science (SAMS) and UK Centre for Ecology and Hydrology (UKCEH) - in this report, they are collectively referred to as "NERC Centres and Collaborating Institutes". Due to the interdisciplinary nature of most of these NERC Centres and Collaborating Institutes, this is a high-level overview; details for discipline-specific systems and sensors (current state of affairs, vision, gap analysis and recommendations) will be covered in the technology section of the Findings chapter (sections 4.4.1 to 4.4.6).

2.4.1 British Antarctic Survey (BAS)

BAS delivers and enables world-leading interdisciplinary research in the Polar Regions. Through its logistic capability and know-how BAS facilitates access for the British and international science community to the UK polar research operation and provides magistrate functions for the British Antarctic Territory.

2.4.1.1 BAS Science & Service Areas

BAS covers a wide range of scientific disciplines in relation to the cryosphere, including atmospheric science and meteorology, ecology, geology and geophysics, glaciology, oceanography and space weather. Most of them currently include the use of airborne platforms, either for data collection including *in situ* and remote sensing or for logistical support for fieldwork or both. The capabilities of airborne platforms help deliver BAS's 10 year science strategy, Polar Science for a Sustainable Planet. The strategy covers the following five themes:

- Climate Change Science for Developing Resilience targets how the Arctic and Antarctic respond to and mitigate climate change.
- Conserving Polar Biodiversity focuses on how biodiversity at the poles responds to change.
- Protecting Coastal and Technical Infrastructure addresses the impact on infrastructure and societies of sea level rise and space weather.
- Sustaining Livelihoods and Societies considers environmental changes across Earth's frozen regions and how these affect societies and livelihoods.
- Safeguarding our Future addresses potential severe impacts of reaching thresholds and triggering extreme changes in the polar environment.

Continuous development of airborne capabilities, including through UASs, also underpins delivery of the BAS organisational strategy, with its priorities for change:

- **Digital innovation and technology:** integrate all areas of technology to unlock new science and new ways to deliver polar operations.
- **Environmental sustainability:** embed environmental sustainability into everything we do.
- **Modernisation:** modernise and future-proof assets and infrastructure.
- **Safety culture:** develop safe and resilient staff who can confidently and successfully assess and manage hazards and risks.

BAS's Air Unit provides a NERC community facility (also used by NCEO, see section 2.4.4.) which currently runs four De Havilland Canada Twin Otters (wheel- and ski-equipped to land on snow, ice or any other type of hard runway) and one De Havilland Canada Dash-7 (see Figure 2.1) . The Dash-7 aircraft and Twin Otters AZ and BL aircraft have modifications to allow surveying and atmospheric research equipment to be fitted. These support a range of NERC science across the globe, depending on availability.

BAS also hosts the UK Polar Data Centre, a node of NERC's Environment Data Service (EDS), the focal point for Arctic and Antarctic environmental data management in the UK. It coordinates the management of polar data from UK-funded research and support researchers in complying with national and international data legislation and policy.

Figure 2.1: *BAS's De Havilland Canada Twin Otter (top) and Dash-7 (bottom) in flight.*

2.4.1.2 BAS Current Use of Crewed Aircraft

The pressurised Dash-7 aircraft provides the air bridge between BAS's main Antarctic research station, Rothera and gateways to commercial air transport in the Falkland Islands and Punta Arenas, Chile. In addition to its role in ferrying people and supplies between Rothera and gateways, the Dash-7 also carries passengers, fuel and cargo to the blue-ice runway at Sky-Blu Field Station – a staging post for deeper forays into the continent.

The Dash-7 supports higher altitude, long-range data collection with a large 1.5m instrument bay that allows sensors to be installed externally to the aircraft's pressure body, including wingtip magnetometers and roof radiometer mountings. The Dash-7 has recently delivered radar, LiDAR (Light Detection and Ranging), gravity, reflected GNSS (Global Navigation Satellite System), radiometry and optical camera data during long-range missions over the Weddell Sea.

The unpressurised Twin Otter aircraft are the mainstay of BAS logistical support within Antarctica, carrying people and equipment into the field.

Twin Otter AZ has hard points suitable for meteorological and atmospheric sensors including wing pylons for cloud and aerosol probes, a boom for turbulence probes, floor hatch for radiometers and hardpoints with Rose Mounts and boot modifications to carry gas cylinders. This allows the installation of atmospheric sensors including a Cloud Aerosol and Precipitation Spectrometer measuring liquid water content and size distribution of droplets and a Cloud Imaging Probe measuring crystal sizes from which it derives total ice water content, as well as other meteorological and atmospheric sensors.

Twin Otter BL has been modified to carry out geophysical surveys, with wing and belly hard points to install radar antennas, a wingtip magnetometer, as well as Rose Mounts for limited meteorological and atmospheric data collection. This allows the fitting of a PASIN (Polarimetric radar Airborne Science INstrument) 150 MHz depth sounding radar as well as other radars that map the terrain hidden beneath up to 5km of ice and gravity and magnetic sensors to measure the properties of rocks deeper beneath the surface.

The Twin Otters have identical instrument bays suitable for cameras and other sensors up to the size of a full-format camera gimbal. These can be equipped with LiDAR and photogrammetry systems to map surface elevations and other surface features such as penguin and seal colonies. The aircraft also support air-drop missions using a standard sonobuoy launch tube.

Some of these sensors are too heavy or voluminous to fit on currently available UASs, but many are already small and light enough or could be miniaturised to be accommodated on future uncrewed platforms.

Hence UASs, especially those at the larger end of the spectrum, have the potential to take on some of the Twin Otter roles both for scientific survey and monitoring, supported by the wider BAS air infrastructure. Some logistical tasks, such as delivery of critical parts or medical supplies, could be assigned to UASs in future. UASs with the functionality to drop sensors or payloads could in some cases replace the use of research shipsor open up science opportunities in geographical areas or operational periods that are too dangerous for access by ship or crewed plane, such as near ice cliffs or volcanic plumes. Use of smaller UASs to inform ice navigation can also lower the carbon footprint of ship movement through ice.

Appropriately sized and configured UAS platforms have the potential to make significant (circa 70%) fuel savings in some science mission profiles if employed wisely. On the other hand, in high payload mission profiles (100skg+), current crewed aircraft may be up to twice as fuel efficient as current UAS options. In all cases, it will be necessary to properly understand and account for the logistics overhead of deploying and operating UASs to remote locations such as Antarctica. The most credible Antarctic operating models necessitate a well-considered synergy between UASs and crewed aviation to achieve the desired science and environmental benefits. The UAS situation is nuanced but has great potential. At this point accurate and balanced analysis is vital to inform strategy.

2.4.1.3 BAS Current Use of UASs

Currently, small quadcopters are being used for wildlife monitoring and local visual surveys for geological/geomorphic studies. Larger fixed-wing platforms such as the ~2kg eBee are now regularly used for visual mapping studies out to ranges of ~10km from a station or field camp. Such uses would have been prohibitive in terms of cost and logistical effort using previous traditional platforms. This quiet revolution in science observation has been developed largely outside the restrictions imposed by aircraft regulation due to the miniaturisation of sensors and platforms, allowing such restrictions to be bypassed. In addition, simplified and autonomous operation means such platforms are typically operated by the scientists/data users themselves. Examples of existing use cases from BAS can be seen in the Appendix. The use of the larger platform Windracer ULTRA was successfully tested in Antarctica during the writing of this report; see the Appendix for summary outcomes.

2.4.1.4 BAS Strategic Vision for UASs

Airborne autonomy for science observations using UASs has been identified as a strategic goal for BAS over the next five to ten years. High priority is given to transitioning from traditional platforms such as the Twin Otter to appropriately sized UASs. This not only has the potential to reduce the operational cost of science observations and reduce the associated carbon footprint but also to open new geographies and time windows for studies, such as using quadcopters to study unstable ice cliffs rather than using a ship or operating fixed wing UASs in the winter, when traditional aircraft are not available on the continent.

Four strategic science areas are identified that will likely need larger UASs going into the future: glaciology, geology and geophysics, environment and ecosystems and meteorology and atmospheric science. In addition, airborne geospatial mapping continues to be an over-subscribed and vital underpinning requirement across BAS. All these science areas need airborne observations which are typically beyond visual line of sight and often with heavier sensors, requiring larger UAS platforms.

The specific science areas for which BAS aims to develop strategic airborne autonomous capability are summarised in Table 2.1 below and overarching requirements for this capability in terms of range, payload and other operational factors are considered here. Figure 2.2 depicts the expected range versus payload requirements for those strategic science disciplines and sensors.

Payload: The sensor requirements for these science areas are generally between 1kg and 10kg, with some requirements for greater payloads of up to ~35kg. Power requirements are generally less than 200W. Some sensors fit within a standard small payload bay (~30cm x 30cm x 30cm), but there may be a requirement for larger sensors or antennas to be fitted externally to the airframe, on booms, or be structurally integrated into the airframe.

Range: The UAS range requirements are generally >10km, but typically between 100km and 1000km. Some science areas require a range of ~2000km in future. Maximum range is determined in part by the capability to position and operate the UAS in a remote location.

Altitude: Flight altitudes of 100m to500m (300ft to 1,600ft) above ground level (AGL) are expected to be optimal for most observations, but extremely low (<30m, 100ft) and high-altitude (>2000m, 6500ft) flights may be required at times. Where terrain is elevated, such as the polar plateau, operation at altitudes of greater than 3000m above sea level are required.

Other operational considerations:

- Beyond visual and radio line-of-sight operations will normally be required.
- Operation in typical Antarctic wind speeds (equivalent to Twin Otter) is desirable.
- Operation at temperatures down to -40°C is desirable, though coastal areas do not get this cold.
- Operation from snow/ice, as well as gravel strip, is required to access science targets in the deep field.
- Operation from the ship is desirable for some platforms.
- Operation from short temporary landing strips is desirable, for example on sub-Antarctic islands.
- Platform must be transportable (or fly itself) to remote field locations[1].
- Icing detection and mitigation systems are desirable.
- Operation by staff with minimal training or skill is desirable, for example over winter, or in small deployed field teams (as is possible with smaller platforms such as the eBee; large platforms require specialist operators).
- Sensor operation/quality flag in telemetry is desirable (real-time data is generally not required).

Table 2.1: *Science areas and sensors for which BAS aims to develop capability on longer-range UASs with expected payload and range requirements. Note 1: sensors already available in-house at time of writing are marked with *. Note 2: range requirement does not include any operational reserve. Note 3: operation at minimum suggested range will hit some useful science targets, but not all. Note 4: payload weight is in most cases an estimation.*

Science area	Science detail	Sensor type and weight	Typical survey altitude & total range.
Glaciology	Ice sheet deformation	Autonomous phase-sensitive Radio Echo Sounder ~10kg	100-400m AGL 10-300km
Glaciology	Ice sheet thickness, basal geomorphology, deep ice sheet internal structure (for example basal conditions for ice core site selection)	Accumulation radar (up to ~1km ice) or PASIN Depth sounding radar (up to 5km of ice), 10-40kg	100-400m AGL 20-1000km
Glaciology and Oceanography	Shallow ice-sheet internal structures, sea ice thickness	Snow radar/accumulation radar 2-20kg	100-400m AGL 10-300km
Oceanography	Ice shelf margin water column observations. Areas not typically open for ship access	Air-drop profiling floats ~8kg + weight of drop mechanism	400m AGL 200-1000km
Glaciology and Oceanography Geology and Geophysics	Regional sub-ice shelf bathymetry Geological/tectonic fabric	Gravity 7kg*	100-200m AGL 100-600km
Geology and Geophysics	Geological and tectonic fabric	Magnetic sensor 2-5kg*	50-200m AGL 10-600km

[1] This transport of both UASs and fuel/power source, most likely by ship or crewed aircraft, has a carbon footprint of its own, and requires the availability of larger crewed transport capabilities. This reinforces that autonomous systems can complement, but are unlikely to fully replace, crewed capabilities.

Geospatial mapping	Underpinning science and operations	High-specification visual camera plus gimbal and control 19 to 34kg	100-750km
Operational awareness	Visualisation of sea ice around ships and crevasses along traverses	Small cameras on quadcopters	200-300m ASL; <5km
Geology Ecology	Geological mapping and rock differentiation Vegetation mapping on all BAS-designated ASPAs (Antarctic Specially Protected Areas) Krill monitoring	Multi/Hyperspectral and visual cameras 0.5-5kg*	50-400m AGL 1-150km 50-500m AGL 2-800km 200-600m AGL 100-400km
Ecology	Higher predator population monitoring, including penguin rookeries and sea-ice seals	Multi or Hyperspectral, infrared, thermal and visual cameras 0.5-5kg*	50-500m AGL 2-800km
Meteorology	Atmospheric turbulent boundary layer observations	Turbulence probe, 0.5kg* Fast response (>50Hz) temperature sensor and hygrometer ~0.26kg Sensors for long and shortwave thermal radiation, for up- and down welling radiation and albedo, 6-12kg Inertial Measurement Unit for georeferencing, ~0.73kg	10-200m AGL 40-150km Future missions targeting the Weddell Sea require a range of up to 2000km and crossing the Antarctic Peninsula
Meteorology	Atmospheric composition and flux	High-frequency gas analysis for example CO_2, methane, H_2O 10-32kg	10-1000m AGL 40-250km
Meteorology	Aerosol observation and cloud-forming processes	Cloud and aerosol probes 0.5-10kg	200 to >5000m AGL 40-250km

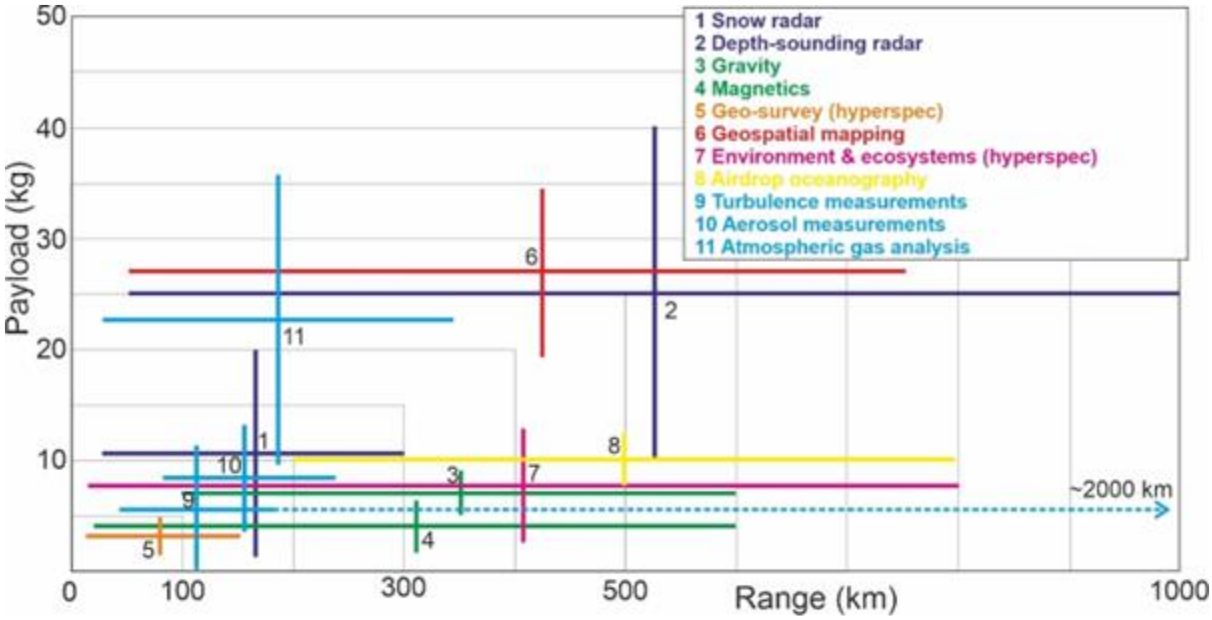


Figure 2.2: *Expected range versus payload requirements for various science disciplines and sensors. Note in some cases deployment of multiple sensors on a single platform (increasing the payload) would be advantageous.*

2.4.2 British Geological Survey (BGS)

BGS is a geological survey and global geoscience organisation, focused on public-good science for government and research to understand earth and environmental processes.

2.4.2.1 BGS Science & Service Areas

BGS research covers the study of landforms through their physical and chemical properties, the processes that have caused their development and changes through time and the understanding of how they may evolve. Our research includes core geological survey and monitoring work and other innovative projects addressing today's geoscientific challenges driven by the changing needs of our stakeholders. Research at BGS focuses at local, regional, national and global scales and conducts monitoring at multi-temporal scales using real-time to multi-decadal data. Research at BGS is often project-based but with a UK remit for mapping the surface and subsurface geology incorporating bedrock, superficial and artificial deposits as well as understanding the structures forming the geological landscape.

BGS provides objective and authoritative geoscientific data, information and knowledge to help society to use its natural resources responsibly, manage environmental change and be resilient to environmental hazards. Our outputs range from digital datasets to reports, geological maps (digital and printed), books, posters and guides and mobile applications. The BGS Strategy 2023 to 2028 – Understanding our Earth – sets out three challenge areas:

- decarbonisation and resource management
- environmental change, adaptation and resilience
- multi-hazards and resilience

Our science priorities aim to tackle challenges to the environment and society over the next five years covering the following four science priorities:

- maps and models for the 21st century
- a more secure energy transition

- improved water security
- living with geological hazards

BGS studies a wide range of complex topics covering specialist themes such as:

- volcanology (evolution of volcanic environments)
- seismology (earthquakes and seismic waves)
- tectonics (structural evolution of land surface through time)
- landslides (mass movement down a slope)
- natural resources (terrain, rocks, soils and minerals, geothermal and carbon capture and storage)
- sedimentology (sediment erosion, movement and deposition including surface sediments, bedrock and lithology as classification of rocks based on physical and chemical properties)
- stratigraphy (layering of rocks through time)
- geomorphology (creation and evolution of landforms, physical features and structures including topographic measurement)
- hydrogeology (transportation and distribution of groundwater through soil and rock)
- geophysics (relation of physical processes and properties of the Earth to its surrounding space)
- geomagnetism (variations in the Earth's natural magnetic fields from deep within the core into space)

and includes interlinking topics of:

- geodesy and remote sensing (development and application of remote detection and monitoring strategies)
- soil science (formation, use and management and classification through physical, chemical, biological properties of soils)
- engineering geology (application of geological knowledge and associated hazard and risks to engineering projects such as reservoirs and construction)
- urban geoscience (towards a sustainable and resilient built environment)
- geochemistry (chemical distribution and processes acting on rocks and minerals and their movement into soil and water systems)
- multi-hazards and disaster risk (mapping and monitoring of and vulnerability to hazards)
- astrogeology

The latter will not be covered in this report as we are focusing on terrestrial UAS applications.

2.4.2.2 BGS Current Use of Crewed Aircraft

BGS do not run or operate crewed aircraft but have in the past applied for data acquisition from the NERC Airborne Research (and Survey) Facility and commissioned surveys from commercial providers. The data from the airborne sensors, as well as access to the proprietary processing software, have been used to further our geoscience understanding. However, in recent years BGS has been limited in terms of access to new airborne data acquisition that would enhance specific geological projects. As such, BGS has developed UAS operations and looked at satellite datasets to fill the gap, although not always at the most suitable spatial, spectral or temporal resolutions for our geoscience.

BGS used to own and operate a marine vessel (White Ribbon) for marine geological applications, however, BGS no longer has this capability. BGS often hires marine vessels on which to deploy BGS-established technologies that are suitable for marine geological assessment. This contributes to the carbon impact of BGS marine operations.

2.4.2.3 BGS Current Use of UASs

BGS operate UASs in alignment with our core work as set out in published annual reviews and organisational strategies, focused on the collection of geoscience data to increase our understanding of Earth system processes.

BGS undertake UAS operations under the Civil Aviation Authority approval given in the Uncrewed Aircraft - Operational Authorisation granted by Civil Aviation Authority Permission for Commercial Operations (PfCO) Operator registration number: GBR-OP-NX2PQN84K2VB, CAA reference UAS 2700. All BGS pilots are registered, have a General Visual Line of Sight Certificate (GVC) and are fully insured to fly in accordance with the BGS Flight Operations Manual.

BGS own and operate a suite of sub-25kg rotary UAS for aerial data collection associated with filming, aerial photography, multispectral imaging, thermal imaging, LiDAR and gas detecting conducted in surveying, monitoring and mapping modes flown under VLOS (Visual Line of Sight) permissible limits for operation.

BGS conduct research using:

- DJI Matrice 210-RTK: Red Green Blue (RGB, Zenmuse X5) and Thermal Infrared (TIR, FLIR XT2)
- DJI Inspire-1 RAW: RGB (Zenmuse X5S) and TIR (FLIR XT)
- DJI Inspire-2: RGB (Zenmuse X5), TIR (FLIR XT2) and Rededge Multispectral (Micasense)
- DJI Matrice 300-RTK: RGB (Zenmuse X5), TIR (FLIR XT2) and Light Detection and Ranging (LiDAR, Zenmuse L1) and Carbon Dioxide and Methane gas detection (GasFinder2)
- DJI Phantom-3 Professional: RGB
- DJI Mavic Air (x2): RGB
- DJI Mini 3 Pro: RGB
- DJI Mavic 3: RGB

Outputs from the UAS operations are crucial datasets that underpin the geoscience research at BGS, such as:

- Terrain model generation
    - RGB – Structure-from-Motion (SfM) Digital Surface Model (DSM)
    - LiDAR – point cloud, DSM, Digital Terrain Model (DTM) and feature height
- Surface context
    - RGB – orthophoto mosaic for land cover and ground control positioning
    - TIR – surface thermal anomaly detection

Applications of UAS beyond the underpinning outputs above include (see Appendix for more detail):

- Landslide/Ground Motion
    - comparison of temporal DSM/DTM for elevation changes - matched to ground and subsurface observation systems
    - comparison of temporal DSM/DTM and TIR anomaly detection as a proxy for potential structural instability
- Coastal Erosion
    - comparison of temporal DSM/DTM for elevation changes
    - changes in the contextual surface cover through temporal repeat
    - comparison of temporal DSM/DTM and TIR anomaly detection as a proxy for potential structural instability
- Geological Stratigraphic and Basin Analysis
    - surface structure and feature mapping from RGB, Multispectral, TIR and LiDAR
    - TIR diurnal variation for near-surface volumetric delineation
- Mine activity and Near-surface anomaly detection
    - RGB and LiDAR for assessing the stability of mining environments

    - TIR for detection of thermal mine water seepage
    - TIR diurnal variation for near-surface volumetric delineation
- Gas detection – Carbon Dioxide (CO_2) and Methane (CH_4)
    - monitoring of carbon capture and storage injection, seepages relating to energy sites

Important in all UAS operations is the deployment and incorporation of additional ground control such as positional information and local meteorological parameters to better calibrate UAS measurement to at-surface observation. These are currently limited in use due to capital requirements for multiple systems for multiple UAS deployments.

The current desire is to extend UAS operations into:

- geophysical measurement to better quantify subsurface features
- gas sensor deployment to better quantify atmospheric effects from for example, geothermal areas
- night-time observation to understand the full thermal characteristics of geological near-surface structures
- hyperspectral data acquisition to identify surface minerals, aid lithological characterisation and for other purposes such as identifying and monitoring pathways of pollutants from historical mining

2.4.2.4 BGS Strategic Vision for UASs

To align with the BGS strategy and especially the science priorities 'living with geological hazards' and 'maps and models for the 21st century', BGS wish to develop the ability to deploy simultaneous multi-sensors for a full suite of Spectral Visible and Near-Infrared (VNIR), Shortwave Infrared (SWIR), Midwave Infrared (MWIR), Thermal Infrared (TIR), LiDAR, Gas and Geophysical measurements to help provide an understanding of an instantaneous 3D geoscience status for the upper geological column (surface, near-surface and subsurface).

As a core part of the BGS remit and strategy, understanding the geophysical nature of the surface and subsurface is of key importance. BGS will need to expand the sensor array to include UAS-borne geophysical sensor(s) across different geophysical techniques, such as magnetometry, radiometry, time-domain electromagnetics and ground-penetrating radar, providing measurement of different geophysical parameters. Whilst some sensors may be available, but not currently accessible within BGS, other sensors will require further development before being proven for core deployment.

For this, BGS wish to expand the sensor array to include UAS-borne hyperspectral sensor(s) across the SWIR or TIR or both spectral regions. These spectral regions are invaluable for geological investigations as they acquire reflectance in narrow contiguous spectral bands and enable differentiation of mineralisation through the extraction of diagnostic absorption spectral signatures of a wide array of surface minerals and rocks. Expansion into hyperspectral UAS systems will complement the geological information extracted from subsurface samples within the BGS core scanning facility and enhance the detailed geological mapping in exposed terrains to meet the strategic aims of BGS. Whilst access to a hyperspectral UAS sensor is possible through application to the NERC Field Spectroscopy Facility (FSF), FSF staff are required to operate the imager due to cost and complexity issues. Combined with weather windows, this places a limit on overall availability.

BGS need the ability to redeploy the full suite of UAS sensors at multiple times across a 24-hour cycle (or longer) to understand changes in the geological column and more specifically to monitor geological hazards, providing a better understanding of the predisposing and indicators of changes in the geological properties. For this, BGS may need to address the current limitation in timing within the Operations Manual (CAA PfCO authorisation) for night-time operations. Expanding the observational timing across the full 24-hour cycle will help define optimal observation programming for specific geoscience applications applicable both in the UK and globally.

Operational capability also relies on appropriate software for survey flight planning. To meet our strategic aims, BGS will need to monitor vertical surfaces along a vertical grid with oblique observation. However, current and easily accessible UAS flight planning software is limited for this style of repeat deployment. Until this survey method is fully embedded within software, accuracy in vertical surface models will be variable and will limit our ability to fully address the BGS strategy with respect to geological hazards.

2.4.3 National Centre for Atmospheric Science (NCAS)

NCAS is a global leader in atmospheric science and, through our research and innovation, we address many of the biggest questions relating to our environment and rapidly changing world.

2.4.3.1 NCAS Science & Service Areas

NCAS brings together expertise from across scientific disciplines, spanning all scales from quantifying chemical reactions in laboratories to global pollution, from detecting the smallest cloud droplets to weather systems and from local weather impacts to modelling global environmental change.

- NCAS undertakes fundamental air pollution science, focusing on the understanding required to inform policy interventions and improve public health.
- NCAS studies the processes and interactions that control the weather and how this is affected by climate change; it conducts targeted observations of the atmosphere and advances understanding to improve predictions of weather hazards and help society build resilience to climate change.
- NCAS studies the long-term changes in the atmosphere and the impact of human activities; it collects long-term observations and builds numerical models of the whole Earth System to inform policy on climate change mitigation and adaptation, including pathways to Net Zero.
- NCAS exploits the latest technologies, from laboratory measurements to observing systems and high-performance computers and develops comprehensive numerical models of the atmosphere and environment.
- NCAS collaborates widely, to advance shared research challenges and to meet societal needs more effectively.
- NCAS champions new ideas across the organisation, community and at the interface of disciplines; it continually adapts its research as new opportunities emerge, forging new partnerships and opening new fields; it can turn its attention rapidly to the issues of greatest importance to society.
- NCAS provides independent advice to national and local government, businesses and wider society; it informs and influences global and national decisions, rooted in robust science, that help to deliver a more resilient, healthy and productive environment for all.

The NCAS goal is to make discoveries that push the frontiers of current knowledge, developing an understanding of the atmosphere and the environment for the benefit of everyone. NCAS supports long-term measurement activities which generate datasets used by both the NCAS scientific programme and the wider community.

In most cases, these contribute to national and international measurement networks, with the data being provided to a variety of international databases. They inform NCAS advice to the UK Government in areas such as Air Pollution, Climate Change and High Impact Weather.

NCAS undertakes long-term measurements where *(1)* there is a clear scientific need; *(2)* the science is important in a wider context and *(3)* NCAS has unique capability.

To enhance the NCAS long-term measurement capabilities, it develops improved software and calibration methods for analysing atmospheric radar and airborne particle probes, new technologies for LiDAR and RADAR remote sensing and analytic tools for model assessment. These activities benefit the wider community and keep the UK internationally competitive.

NCAS also generates fundamental physicochemical data and supports cutting-edge measurement science. In Air Pollution, it develops the core science represented in the Master Chemical Mechanism (MCM), a constantly updated model of more than 12,000 gas-phase chemical reactions, that is the gold standard measure of atmospheric chemistry performance across the world. The experimental data validates and supports a parallel activity developing theoretical descriptions of gases and aerosols used in the development of pollution and climate models.

Key priorities in measurement science are *(i)* the validation of *ab initio*, mechanistic and experimental approaches that generate reaction schemes and parameters for the next generation of air pollution and global models, *(ii)* experimental evaluation of the emissions, properties and lifecycles of atmospheric aerosols and clouds under a range of physical and chemical atmospheric conditions, *(iii)* the development of new techniques for the traceable calibration of NCAS and UK community gas and aerosol instruments and sensors, *(iv)* support for new numerical and methodological tools for atmospheric aerosol and cloud observations, including new methods for data analysis from LiDAR and cloud probes.

Long-term ambitions include to:

- provide NCAS observations to the highest international standards of measurement quality and data, understand the uncertainty in the data and work with international colleagues to improve and develop standards
- develop automated chemical mechanism generation methodologies and experimental smog chamber techniques that will underpin the future schemes used in community models of atmospheric chemistry and aerosols
- enhance NCAS's capability by developing new technology for atmospheric measurements that will support scientific discovery and equip NCAS to meet the challenges of the future including enhanced sustainability
- embed the NCAS observational programme as a respected contributor to international networks and infrastructures such as the World Meteorological Organization Global Atmosphere Watch (WMO-GAW), Integrated Carbon Observation System (ICOS), Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS) and E-Profile - a network run by European National Meteorological Services (EUMETNET)

NCAS provides the following Services, Facilities and Tools:

- Airborne Laboratory (Facility of Airborne Atmospheric Measurement; FAAM) is a NERC Service and Facility based on and around a BAe 146-301 crewed aircraft - see section 2.4.3.2 for details on possible UAS impact - commissioned by NERC as an Advanced Research Aircraft (ARA) through Large-scale Research Infrastructure funding.
- Atmospheric Measurement and Observation Facility (AMOF) is commissioned by NERC through NERC Service and Facility funding; UASs could be used to enhance service provision and drive technology innovation and development.

- Centre for Environmental Data Analysis (CEDA) - Atmosphere (CEDA consists of CEDA - EO and CEDA - Atmosphere) is funded by NERC and STFC via NCAS and NCEO and as a node in the UKRI Environment Data Service (EDS); UAS impact arises through the need for a joined-up and cross-community approach to making data FAIR compliant and accessible to non-expert users - the Flight Finder tool, developed by CEDA, would be ideal for ensuring UAS flights could be easily found within an archive; CEDA have considerable experience in archiving and disseminating data from instruments deployed on a wide variety of airborne platforms ranging from pigeons to satellites.
- JASMIN: Funded directly through NERC, this is the hardware infrastructure on which CEDA services operate; it also hosts group workspaces (GWS) - increased demand for services (CEDA & GWS) arising from enhanced UAS use will have an impact here.
- Computer Modelling Support (CMS): Funded through NCAS, this service would be least affected by enhanced UAS usage unless there is an effort in the area of model-observation pull-through.
- FORCE is a tool developed for flight planning and comparison of ground, satellite, aircraft and model data; funded from an NCAS short-term project and further development funded through a NERC standard grant, this tool would be of use to the UAS community and would need adaptation to make available; current models support Weather Research and Forecasting (WRF) and Model for Prediction Across Scales (MPAS).
- TWINE is a tool developed for the visualisation of individual parameters from past flights and comparing them with model output; the current version uses the output from the UK Earth System Model (UKESM), but recent funding will see work to incorporate the output from other models

2.4.3.2 NCAS Current Use of Crewed Aircraft

The NCAS Airborne Laboratory, also known as Facility for Airborne Atmospheric Measurement (FAAM), is an airborne laboratory investigating atmospheric processes through the *in situ* and remote sensing measurement of atmospheric variables. It takes a user's idea and turns it into quality-controlled and quality-assured data products archived in the CEDA node of the UKRI Environmental Data Service (EDS).

NCAS delivers this capability to the UK and international science communities and consists of:
- a BAe 146-301 4-engine aircraft as shown below (Figure 2.3)
- the operational infrastructure (aircraft maintenance, safety processes, flight crew) which ensures flight operations meet regulatory requirements

Figure 2.3: *FAAM's BAe 146-301 4-engine aircraft.*

- the science infrastructure which ensures access to world-class, cutting-edge instrumentation and infrastructure ready for the next generation of instruments
- the data infrastructure which ensures the delivery of quality-assured and quality-controlled data products to the EDS (CEDA node) on a defined time scale; it also ensures products that follow a defined internationally aligned data structure and are supported by documentation and transparent processing workflows
- the deployment infrastructure, which ensures that the laboratory can operate where the science is happening no matter where that is globally and is accessible to a wide and diverse user base

Full details of the capability can be found on the EUFAR website.

UKRI, through NERC, has awarded NCAS up to £49 million of funding to undertake a Mid Life Upgrade (MLU) of the physical platform and the capabilities offered. The MLU programme intends to deliver against three primary strategic objectives of:

- safeguarding the UK's research capability
  - allowing the facility to continue to respond to domestic and international atmospheric emergencies whilst meeting the increasing demands of the UK research community and enhancing the range of services available
- providing frontier science capability
  - providing groundbreaking science capability to satisfy the UK research community's current and predicted future research needs as a world-class airborne research platform whilst enabling maximum infrastructure flexibility to cater for new and existing end-user needs
- reducing environmental impact
  - improving or maintaining the facility's environmental performance including reducing the impact of noise and other emissions from operations, increasing the science outputs relevant to carbon costs and looking at ways of enhancing operational performance including fuel and alternative resource usage

The UKRI investment and the MLU programme are transformational, delivering, in 2027, a world-leading and cutting-edge facility for global airborne atmospheric research: a global flagship.

The MLU programme is not just to look at the aircraft but at how the capability is delivered - it aims to establish a stable operational environment for the NCAS Airborne Laboratory out to 2040, one that meets and exceeds the expectations of facility stakeholders, allows the facility to continually improve the support it provides to UK science and enables UK science to be cutting-edge and world-leading. It also addresses the environmental impact of the platform through the use of sustainable aircraft fuel (SAF) and advances in technology that reduce the need to fly instrument operators. Table 2.2 below shows the carbon footprint from the fuel of FAAM. Unlike ships, reduction of carbon footprint cannot be made by simply flying slower - fundamental physics means that there is a minimum speed needed before the plane stalls. A rebalancing of the carbon footprint of the activity and science benefit comes from introducing new ways of operating, reductions in platform weight and drag and greater use of remote monitoring and near-real-time (NRT) visualisation.

Table 2.2: *FAAM Fuel data 2017-2023 (Source: Ecometrica NERC)*

Financial Year	2017/2018	2018/2019	2019/2020	2020/2021	2021/2022	2022/2023
Tonnes Carbon Dioxide Equivalent (tCO_2e): Aircraft Activity	2577.01	2192.15	1630.28	269.21	1430.89	1928.28

The choice of 2040 is not arbitrary; this is the date by which UKRI is aiming to be Net Zero and the date by which the question "Do large aircraft platforms have a role in UK science delivery?" will need to be answered.

The capability provided by FAAM to the NERC science community is not something that can be replaced by the current UAS capability. UAS-based observations complement and enhance those from the larger aircraft platform as there are places that the aircraft cannot reach (below 50m), modes of operation that cannot be supported (those with higher risk attached like flying in ash) and science aspirations that it cannot meet (intensive spatial and temporal observations, for example). It would be possible to establish a UAS community facility offering the same service coverage. To do this efficiently and safely and ensure science quality would need the same infrastructure to be established that is in place supporting the NCAS Airborne Laboratory.

There will continue to be a need for crewed capabilities: as the technological landscape advances and the scientific needs of the community evolve, new instruments and analysis techniques will be developed. The proof of concept for new instrumentation is a critical stage before the specialist adaptations required for integration on a UAS platform can be addressed. Testbed capability that facilitates innovation and "heavy lifting" capability sit more with advances involving crewed aircraft, rather than UASs.

2.4.3.3 NCAS Current Use of UASs

NCAS has only tentatively made use of UASs - being so closely involved with FAAM, NCAS has concentrated its science activities around that. Below shows how NCAS scientists have been, and currently are, able to utilise UAS platforms to address specific questions.

- Past Use
  - Global Hawk
    - Co-ordinated Airborne Studies in the Tropics (CAST) (NE/J00619X/1).
    - The unique research capability of the Global Hawk, with ultra-long flights possible in the upper troposphere and lower stratosphere, provides a major new opportunity to advance atmospheric science. In response to the NERC/STFC/NASA collaborative initiative, we have assembled an experienced UK team that proposes to execute a research programme covering fundamental science and technology development, which, by working with the Global Hawk, will radically enhance our future research capabilities.
- Hot spot Greenhouse Gas (GHG) monitoring
  - Development of analysis techniques providing regulatory-compliant estimates of emission fluxes
  - Lifting of a Teflon sampling tube connected to a ground-based sensor
  - Aeries technologies MIRA Stratos LAS: Laser Absorption Spectrometer for GHG detection
  - Community accepted best practices for determining GHG emissions flux; calibration against ICOS network instruments
- Boundary layer profiling
  - The Wessex Convection Experiment (WesCon) field campaign and use of external contractor
    - Wind Speed: Range of approaches taken including, 5 and 7-hole probes, hot wire/film sensors, sonic anemometer, GPS & dGPS, triangulation from platform rotors
    - Fundamental atmospheric thermodynamic sensors (referred to as PTU sensors): emphasis on stability and housing to eliminate dynamic and radiative effects
- Radar calibration
  - Carrying the target and holding it steady in the beam

- Insect sample collection
    - Drag nets, sticky on leading edges - radar – aerobiology
- Volcano response
    - Sensors but no platform - making package platform independent, calibration
    - Sniffer 4D: Wide range SO_2, high-resolution SO_2
    - Sniffer 4D: Wide range H_2S, wide range C_xH_y/CH_4/Lower Explosive Limit (LEL)
    - Alphasense: OPC series 30 - 100 g depending on model

NCAS has not had a specific strategy around the use of UAS in its science nor how such platforms could be incorporated into the facilities it provided to the UK science community. However, that situation is now changing through the refresh of NCAS Science and Innovation strategy that is currently underway. The next section details some of the areas NCAS intend to explore.

2.4.3.4 NCAS Strategic Vision for UASs

NCAS sees UAS use as a crucial tool in observational science. UASs come in many forms and the unique operational characteristics of each platform can be used to address the wide and very diverse needs in atmospheric science: there is no one-size-fits-all solution. There is a spectrum of needs that can only be met by having a spectrum of airborne capabilities that include both UASs and crewed platforms.

NCAS is looking to expand UAS capability and use through the development of a strategic vision - the general areas of interest are:

- Science
    - supporting the NCAS science strategies and programmes in the areas of Air Pollution, Climate & High Impact Weather and Long-term Global Change
    - pull through of observations to models, outcomes and impact
    - autonomous (‘drone-in-a-box’) monitoring for
        - GHG profiles, boundary layer profiles
        - GEMMA project
    - cloud physics capability
    - flux & turbulence measurements (gases, particles, dynamics)
    - whole air sampling
    - virtual mast
- Technology & Innovation
    - sensor development, testing, calibration and transparent data processing for atmospheric observations on UASs
    - development and testing of processing techniques through collaboration with wider communities - leading to the development of nationally and internationally recognised standards
    - development of analysis algorithms to deliver GHG emissions and fluxes for regulatory use - collaboration with Flylogix
    - collaborating with FalconWorks (FAAM delivery partner) to develop UAS platforms and sensors
- Quality & Accessibility
    - understanding and quantifying the measurement uncertainty for UAS-based measurements
    - developing best practices for airborne measurements - using skills and capabilities in the NCAS Airborne Laboratory community
    - development and implementation of globally aligned data standards that facilitate software tool development for users and providers
    - toolchain development to enable non-expert users to access UAS data

- applying ACTRIS Standard Operating Procedures (SOPs) and calibration practises and working with the ACTRIS community to develop best practices for UAS measurement

As a national science centre, NCAS believes that it must work with and lead its relevant communities. The UAS strategy developed by NCAS will be grounded in our science communities and will take advantage of our staff being both embedded in UK universities and research active on the international stage to develop a capability that is embedded in current international best practices and that is accessible to the user community.

2.4.4 National Centre for Earth Observation (NCEO)

2.4.4.1 NCEO Science & Service Areas

The National Centre for Earth Observation (NCEO) provides the UK with core expertise in Earth Observation (EO) science, along with EO data sets, data and model merging techniques and model evaluation, all underpinning Earth System research and the UK's international contribution to environmental science. In particular, NCEO harnesses the power of satellite remote sensing and its associated techniques to generate new knowledge related to couplings between the physical, chemical and biological systems of our planet, advancing our understanding of its current climate and environment and how these are changing and may change in future. NCEO achieve their significant capabilities and success through the generation, expert interpretation and blending of EO data coming from satellite, airborne and ground-based instrumentation, thereby delivering value-added environmental information that can also be used by others to deliver new scientific insights, provide a trusted source of information for non-expert users and inform future policy. NCEO's scientists work strategically with space agencies, play significant roles in mission planning and generate internationally-recognised data products from multiple different satellite instruments - and play key roles in the development, planning and exploitation of new missions as well. Overall, the work of NCEO addresses critical policy-relevant questions identified by the international environmental science community surrounding carbon budgets, ecosystem change, climate feedbacks and sensitivity, environmental threats and more.

NCEO provides the following Services, Facilities and Tools:

- NCEO Airborne Earth Observatory (NAEO): Based around a state-of-the-art remote sensing instrument suite and hosted normally on the BAS Twin Otter aircraft - the NAEO also has UAS and ground-based *in situ* measurement capabilities to support the interpretation of the airborne remote sensing data collected. UASs are already used sometimes during NAEO operations to collect complementary data for example very high spatial resolution mapping and measurement, or high temporal resolution measures obtained by rotary wing UASs hovering over the targeted ground area being probed by the NAEO.
- NERC Field Spectroscopy Facility (FSF): Commissioned by NERC through NERC Service & Facility funding, the FSF maintains and provides a pool of state-of-the-art spectroscopy instruments for use by the UK research community, as well as providing advice on their use, training in techniques and calibration expertise. FSF already provide some UAS capabilities to the environmental science community, both loaning out small UASs equipped with remote sensing instrumentation and providing more capable copter-style VLOS UASs and remote sensing equipment (for example hyperspectral imagers) along with a skilled team to undertake the data collection on more complex missions. FSF and other parts of NCEO have detailed equipment and knowledge for radiometric and spectral calibration of UAS EO instruments - and there is dedicated collaboration on this subject that links these UAS-based and NAEO crewed aircraft activities.
- NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS): Commissioned by NERC through NERC Service & Facility funding, NEODAAS provides satellite data to NERC researchers and

others, support for fieldwork activities, bespoke EO data products, operationalised algorithms produced by NERC-funded research, an artificial intelligence analysis service for EO data and advice and training in the sources and best practice in EO. They also provide an airborne data processing capability that is used by the NAEO and are collaborating with FSF to develop a similar functionality for UAS data. They work with NAEO and FSF on the calibration of airborne EO instrumentation, including that operated on the FSF UAS fleet.

- Centre for Environmental Data Analysis (CEDA) (CEDA consists of CEDA - EO and CEDA - Atmosphere): CEDA-EO is funded by NERC and STFC via NCAS and NCEO and is a node in the UKRI Environment Data Service (EDS). UAS impact comes through the need for a joined-up and cross-community approach to storing and serving data, making it accessible to expert and non-expert users.
- JASMIN: Funded directly through NERC, this is the hardware infrastructure on which CEDA services operate. It also hosts group workspaces (GWS). There is potential for increased demand if very significant UAS usage appears.

2.4.4.2 NCEO Current Use of Crewed Aircraft

The NCEO Airborne Earth Observatory (NAEO) maintains and operates the UK's national capability for airborne remote sensing instrumentation, providing a state-of-the-art commercial instrumentation suite that represents amongst the most comprehensive in the world. NAEO operates broadband and hyperspectral imagers, covering the visible to longwave Infrared. Some of these are highly specialised - for example the very high spectral resolution IBIS sensor used to estimate solar induced fluorescence or the Telops Hypercam used to derive maps of atmospheric trace gases. Some have been adapted by NCEO - for example the OWL long-wave infrared hyperspectral imager that has been adapted to operate on a tilting platform to obtain high view angle imagery and some provide more generalised data (for example the FENIX visible to shortwave infrared hyperspectral image). There is also an advanced active EO capability in terms of a full-waveform LiDAR for terrain and vegetation mapping, 3D information extraction and biomass assessment, along with a high-resolution digital camera for context imagery, 3D terrain interpretation and photogrammetry. The NAEO also integrate guest sensors from organisations such as NASA-Jet Propulsion Laboratory (JPL) - being the only European organisation known to have signed the NASA Space Act Agreement to allow this - and also test sensors from commercial companies or other research groups.

NCEO's node at King College London operates the NAEO, maintaining, calibrating and running the EO instruments, fitting them to the aircraft and providing science coordination and flight planning coordination whilst the British Antarctic Survey provide the aircraft platform and pilots, engineering and operational support and NEODAAS process the collected data to Level 1b (calibrated and geocoded data; but not yet geophysical products).

The capability provided by the NAEO to NCEO and the wider NERC science community is not something that can be replaced by current UAS capability. UAS-based observations certainly can provide remote sensing data of useable quality but they cannot fly out of line of sight except in special circumstances and cannot carry anywhere near the payload of the BAS Twin Otter (TO) aircraft currently used (see Figure 2.4). At present 100s of kilograms of EO sensing equipment and data control and storage racks are fitted to the TO for a typical campaign - and even one of the NAEO EO instruments used would be very hard to accommodate on all but the largest UASs. For maximum science reward per km flown, and also to ensure contemporaneous observations by all instruments at times of rapid change or where the environmental data collected is sensitive to time-of-day observed, the NAEO typically flies four or more large EO instruments operating in different wavelength ranges and in different ways simultaneously. However, UASs could complement and enhance those data collected from the crewed aircraft platform, as there are places that the TO cannot easily operate in (for example very low altitude or in intensely convecting smoke plumes) and data that cannot be collected with the TO capability (for example cm scale EO imagery - of a type possible to be collected with a low flying UAS). There are also science aspirations that a crewed fixed wing aircraft cannot meet (for example intensive spatial and temporal observations) - though a rotary wing crewed aircraft can do better here. It would be possible and beneficial to establish a community UAS facility and indeed FSF already provide one, hosting multispectral cameras, thermal cameras and a hyperspectral imager with attached LiDAR, along with UAV platforms providing a maximum payload of 12kg. To do this efficiently more widely, including larger, BVLOS platforms and with operations conducted as safely and legally as possible whilst ensuring science quality and science return would need additional substantial infrastructure and trained personnel with the correct licences able to operate in many places worldwide.

Figure 2.4: *The NCEO Airborne Earth Observatory (NAEO) equipment and operators housed within the BAS Twin Otter aircraft shown in Figure 2.1: (left) A series of NERC-funded remote sensing devices installed in the viewing hatch of the BAS Twin Otter by the NAEO and (right) personnel operating the sensors at night during an overflight of Canadian forest fires in 2023, whilst the European Copernicus Sentinel-3 satellite passes overhead. Notice the racks of sensor control and data storage computers at right.*

2.4.4.3 NCEO Current Use of UASs

In terms of its existing and past use, NCEO already uses UAS platforms for both its own science, as well as providing a UAS service, described above and in section 4.4.7.2, as part of its NERC Services and Facilities offering to the community through FSF. Within NCEO's science itself, UASs have been employed by the King's College London node since the mid 2000's - initially in a trial manner and now as a key component of a number of science strands. NCEO has undertaken very high spatial resolution (cm scale) mapping, including 3D mapping, of landscapes and derivation of rapid landscape change (Simpson et al, 2016). Working with Rothamsted Research (a BBSRC supported national research institute) we have pioneered the derivation of crop height and crop growth rate (Holman et al, 2016) during field phenotyping trials, NCEO have mapped land surface temperature (LST) of crops during their growing period using LWIR remote sensing and combined this with VIS-NIR remote sensing and other data to map evapotranspiration (ET) across fields. NCEO science employing UASs have generally used platforms similar or smaller in size to a DJI M200 for this work.

NCEO has also employed UASs to collect *in situ* measurements in environments not conducive to ground-based or crewed aircraft operations - specifically the near-ground plumes of wildfires burning in various countries overseas. A UAS of small size was outfitted with gas sensors, aerosol counters and a smoke bag collection system for this purpose - with the resulting data enabling the measurement of emissions factors in a way not possible before (Vernooij et al, 2022).

At the University College London (UCL) node of NCEO, a DJI Matrice M600 and Mavic Mini 2 equipped with LiDAR, hyperspectral and RGB cameras are utilised to enhance the assessment of vegetation structure and function. These UASs are specifically employed to estimate canopy structure and aboveground biomass at a detailed (metre) scale, validate surface reflectance retrievals derived from EO data and test the retrieval of biophysical parameters over typically forests and croplands.

In 2015 scientists from the University of Leicester node of NCEO were involved in the CAST-ATTREX flight campaign to track changes in the upper atmosphere. The NCEO-led GHOST shortwave infrared spectrometer was flown on the extremely capable and large NASA Global Hawk UAS during the campaign in March 2015, with retrievals of atmospheric carbon dioxide made from the resulting spectra. The unique capabilities of the Global Hawk, with high payload capability and very long duration flights at high altitudes provides a significant EO opportunity different to almost any other UAS platform.

2.4.4.4 NCEO Strategic Vision for UASs

NCEO views UASs as a unique tool for remote sensing and Earth observation science and indeed for wider environmental science. The many different types of UASs provide a suite of unique platforms capable of carrying multiple different EO sensors and also *in situ* sensors that can collect complementary data to those provided by remote sensing. However, UASs cannot - at least at present or in the near future - replace the capability provided by crewed aircraft fitted with the highest scientific quality remote sensing equipment. That equipment is simply far too large, heavy and has a power requirement unable to be provided by UASs and also generally requires a human operator. There are smaller versions of these science grade instruments available from some manufacturers, but generally their performance is significantly inferior to the full-size versions and they are still extremely expensive and thus deemed somewhat risky to fly on a UAS. The current inability to fly out of line of sight, and the UAS pilot and platform restrictions present in many nations where NCEO undertakes its fieldwork, are also significant impediments to UAS use.

However, despite their current limitations, UASs have provided unique datasets to NCEO science and the capability provided to the NERC community by FSF and the significant demand for the FSF UAS service experienced from for example the PIs of NERC grant proposals, indicates the keenness with which sections of the community view the capability. It is clear from FSF's work that many environmental scientists require help accessing a high quality, high performing UAS capability for remote sensing, with a broader scope than FSF can currently provide. This is especially true for the type of high spatial resolution, hyperspectral imaging or high performing LiDAR capability that requires significant investment in equipment, skills and training to operate. NCEO is looking to therefore continue to expand its UAS capability and use and the offering to the community through FSF, via development of a strategic vision. The general areas of interest that NCEO sees as most relevant are listed below.

- Science
  - Supporting the NCEO science and programmes in the areas of biosphere-atmosphere, carbon and energy water exchange.
  - Flux measurements (gases, particles, evapotranspiration).
  - Atmospheric sampling in for example polluted plumes.
  - "Virtual" mast for atmospheric profiles that support EO data collection (for example by the NAEO).
  - Bio-physical parameter retrieval over landscapes (including support to models).
  - Landscape change mapping, including 3D.
  - Satellite and airborne data validation and calibration and algorithm and method development for future or current satellite missions.
- Technology & Innovation
  - Sensor development, testing, calibration and transparent data processing for EO data collected by UASs.

- Development and testing of EO data processing techniques, through collaboration between FSF and NEODAAS and the wider NCEO - leading to the development of nationally and internationally recognised standards as with field spectrometer data.
  - Development of analysis algorithms to deliver biophysical parameters (for example chlorophyll content, solar induced fluorescence, evapotranspiration, land surface temperature and so on) to the wider community.
  - Collaborating with developers to prototype more "EO-capable" UAS platforms and sensors with the necessary high quality performance characteristics.
- Quality & Accessibility
  - Understanding and quantifying the measurement uncertainty for UAS-based remote sensing measurements.
  - Developing best practices for airborne EO measurements made using UAS platforms - using skills and capabilities in the NAEO.
  - Expansion of the UAS provision of FSF to enable non-expert users to access UAS data and to make high cost UASs and sensors accessible to the community.

NCEO have significant knowledge and experience with using UASs for the collection of EO data in many contexts, including in challenging environments and as such believes it can work with and lead its relevant communities on the path to improved and expanded UAS-use for both EO science and wider environmental science. The successful example provided by the Field Spectroscopy Facility, as well as in its own science, demonstrates NCEOs commitment and capability in this area of science - which is highly related to the areas of satellite Earth Observation and airborne remote sensing in which it excels.

2.4.5 National Oceanographic Centre (NOC)

2.4.5.1 NOC Science & Service Areas

The research undertaken by NOC aims to advance the knowledge needed to address global environmental challenges. The ocean is fundamental to these challenges and understanding this system can only be addressed by science over decades and across all ocean basins. NOC aims to provide the evidence that enables managers to secure and protect marine resources and ecosystems (via projects such as CLASS and SMARTEX), to protect habitats, people and property from natural disasters and climate change (example projects include BlueCOAST, CHAMFER and WireWall), to understand climate change and variability (current projects include COMICS and RAPID-AMOC).

2.4.5.2 NOC Current Use of Crewed Aircraft / Any Other Vehicles

Although electromagnetic waves can only go a few millimetres down, satellite-derived observations have always been essential for ocean colour observations and surface water characterisation. Satellite-based imaging is also advancing our understanding of shallow water habitats. However, the majority of our work remains dependent on the use of large research vessels despite a long history of greater use of autonomy at NOC. NOC supports complex, multidisciplinary research using state-of-the-art technology and instruments across all oceanographic disciplines. Because of this, the primary goal of NOC is to create new, cutting-edge technology to support the growth of scientific research carried out in the most extreme marine settings, such as the deep sea, subfreezing temperatures, variable oceanic weather and isolated coastal habitats. These technologies include the creation of marine autonomous robotic systems (Auto-Hover 1, Autosub2KUI, ecoSUB, small, low-cost Autonomous Underwater Vehicles (AUVs), Autosub Long Range 1500, BRIDGES deep glider project), the design, creation and use of novel sensors and instruments and the development of electronic, software and communication systems that facilitate the gathering and storing of data. NOC Marine Robotics Innovation Centre supports the development of technologies for platforms, components and subsystems.

NOC is committed to moving towards a 'Net Zero Oceanographic Capability' (NZOC) and supporting UKRI's goal of becoming Net Zero by 2040. However, the fabrication, building and disposal components of the UKRI/NERC marine research infrastructure were not taken into account by the NZOC scoping review because they need to be evaluated independently.

In recent years, the use of UASs has been viewed as an effective alternative for a wide variety of marine science, which has ultimately delivered evidence that supports climate change mitigation, marine spatial planning and coastal zone management. Equally, some of these autonomous platforms have been particularly useful in shallow waters, or at the interface between subtidal and intertidal systems, where the use of large research vessels is not possible or not cost-effective. In addition, the use of UASs would replace the need to use bathymetric (airborne) LiDAR, such as that used at Turneffe Atoll in Belize (see section 2.4.5.3 below) or for the Darwin-plus projects to produce a Coastal Resource Atlas 2 and Ecosystem Sensitivity and Climate Vulnerability for marine spatial planning in the British Virgin Islands.

2.4.5.3 NOC Current Use of UASs

NOC's Seafloor Ecosystems Subgroup (part of the Ocean BioGeosciences research group) has an established track record of using UASs, equipped with various sensors from multispectral and hyperspectral sensors, polarising lenses and Real-Time Kinematic (RTK) for a varied of marine habitat mapping applications. Applications include orthophotography, which can be extended to photogrammetry with the use of ground control points, shallow water habitat mapping and satellite imagery validation for habitats such as (but not exclusively) coral reefs, seagrass meadows and kelp beds. (For validation, a series of highly accurate UAS classifications offer the ability to increase the data available to train and validate satellites and improve estimates of cover within a pixel rather than generalising point-based field surveys.) The technique can be expanded to filter-feeding species such as oysters (for example Espriella et al, 2023); mussels (for example Barbosa et al, 2022); sponges, algae (for example Diruit et al, 2022), macroalgae (for example Rossiter et al, 2020, Deysher, 1993 and D'Archino & Piazzi, 2021]) and barnacles. Furthermore, approaches to integrate the use of low-cost uncrewed aerial and surface vehicles and geographic information system (GIS) processing have been considered to be an effective strategy for allowing fully remote detailed data on shallow water benthic communities (Ventura et al, 2023).

Relevant projects include:

- The generation of the first seagrass cover map at Turneffe Atoll, the largest marine reserve in Belize and a worldwide biodiversity hotspot. The project aimed to map the ecologically significant seagrass habitat at the Atoll and include it as part of a wider, national blue carbon assessment for Belize. The study included a three-tiered methodology using: (i) Sentinel-2 data in order to estimate the continuous seagrass percentage cover; (ii) UAS-based imaging to estimate mixed classes within satellite pixels; and (iii) ground-truthing using traditional *in situ* observations. It demonstrated how high-resolution UAS photography may be used to summarise seagrass cover within a Sentinel-2 pixel to train and test a model at a broad scale by merging UAS and Sentinel-2 data (Carpenter et al, 2022).
- The Manx Blue Carbon Project seeks to identify locations where carbon stores could be safeguarded and managed in Manx territorial seas by providing an in-depth examination of blue carbon ecosystems surrounding the Isle of Man, including offshore mud habitats, seagrass meadows and kelp beds. The use of UASs allowed the project to survey extensive areas around the coastline and thereby quantify the blue carbon sources and sinks within Manx waters.
- On the Island of Vanuatu, a UAS was used to generate shallow water bathymetry, using photogrammetry and contribute to a wider marine habitat mapping delivered as part of the Commonwealth Marine Economies Programme.

- The National Capability ACCORD project aimed to deliver high-quality science that supports: (i) the sustainable growth of blue economies in partner countries; and (ii) the long-term resilience of these blue economies, within partner countries, to natural hazards stemming from climate change. In 2019, sub-projects undertaken by the NOC Seafloor Ecosystems Subgroup included the mapping of critically threatened marine habitats in Malaysia and Cambodia. Both mapping studies included the use of aerial UASs to map shallow water coral and seagrass habitats (Pulau Bidond in Malaysia and Koh Ach She, Cambodia (Strong et al, 2022).
- The ongoing CHAMFER project is examining the protective ecosystem services and susceptibility of UK coastal ecosystems to climate-driven multi-hazards. The project includes an extensive fieldwork campaign that includes coastal habitat mapping, using UASs, throughout Great Britain. UASs are also being used for field validation of mechanistic controls of shoreline change from collocated habitats with a specific focus on quantification of the erosional processes, using *in situ* instrumentation, within and between habitats.

UASs have been used by National Marine Facilities (NMF) at NOC from its research vessels, mostly for operational purposes (for example the detection of surfaced autonomous vehicles away from the mother ship). However, the NMF has limited usage for UASs because of the regulatory difficulties with safely operating remotely piloted aircraft systems beyond the operator's visual line of sight (BVLOS).

2.4.5.4 NOC Strategic Vision for UASs: Desired Case

Although NOC extensively use UASs for shallow water mapping, there is no strategic vision for UAS use at NOC. However, NOC does remain abreast of the current developments in UASs and their sensor payloads, (for example miniaturised sensors, such as hyperspectral imagers, LiDAR, synthetic aperture radar and thermal infrared sensors) to understand their continued application for marine habitat mapping. NOC does see the continued value of UASs for various applications including (i) subtidal and intertidal habitat mapping; (ii) ground-truthing satellite imagery; (iii) coastal erosion monitoring through photogrammetry and repeat surveys; (iv) measuring interactions at the air-sea interface (for example CO_2, boundary layer profiling & mapping for pressure, temperature, humidity, wind speed, wind direction); (v) detecting and analysing plastics in marine environment; (vi) pollutant pathways; and (vii) characterising volcanoes (ash and gas). NOC plan to ramp up their use of UASs through the following strategies and development topics:

Integrated science technique development:

- National Marine Facilities Roadmap for the development of the National Marine Equipment Pool (NMEP): This roadmap highlights NMF's future aspirations. Of relevance to the NZArC Scoping Report, the roadmap highlights science at the air-sea interface using a variety of autonomous platforms. NOC's Marine Autonomous and Robotic Systems (MARS) intends to collaborate with the scientific community to modify the Uncrewed Surface Vehicles (USVs) so they may serve as a platform for measuring this gas exchange. For instance, to determine this exchange, the Calibrated pCO_2 in Air and Surface Ocean Sensor (CaPASOS) projects will use USVs to monitor the partial pressure of CO_2 in the air and water.
- Land-water continuum: Use of green waveform features, infrared intensities and elevations (multispectral bands (red edge - RE - and near-infrared - NIR) and digital surface model (DSM) for habitat classification based on the traditional red-green-blue (RGB) dataset) to map the complexity and distribution of coastal seascapes (collocated littoral and subtidal habitats), which would allow monitoring effects of climate change, sea level rise and hydrodynamic changes on habitats at high temporal and spatial scales (Letard et al, 2022, Andersen et al, 2017, James et al, 2020 & Collin et al, 2012).

Equipment development:

- Utilising fixed-wing UASs to cover larger areas and produce marine habitat maps with a great extent (Ellis et al, 2020) and carry heavier payload such as a multispectral camera (Markelin et al, 2021) + green/bathymetry LiDAR
- UASs capable of safe water landing (traditionally, non-fixed-wing UASs take off and land vertically from the shore). This would:
  - Develop UASs to remotely deploy ejectable payloads (i.e. dropped sensors monitoring variables such as salinity, wave direction, temperature and nutrients)
  - Suspended 'dip camera' for the ground truthing of shallow water coastal habitats

Remote sensing techniques development:

- The development of remote sensing techniques such as airborne fluid lensing can provide a clear image of the seabed by accounting for distortions caused by the movement of the water's surface in centimetre-resolution aircraft assessments of marine habitats (Chirayath & Instrella, 2019 and Chirayath & Earle, 2016)
- High-resolution UAV outputs could be used to train satellite imagery classifiers (Carpenter et al, 2022).

2.4.6 Plymouth Marine Laboratory (PML)

2.4.6.1 PML Science & Service Areas

Plymouth Marine Laboratory (PML) is committed to delivering scientifically excellent research that generates a greater understanding of marine, coastal and aquatic environments, the threats they face, the linkages and interactions with freshwater, terrestrial and atmospheric systems and the interplay with human society. Moreover, PML is also leading research on in-land waters developing new technologies to monitor water quality for human health and pioneering studies to understand changes in riverine and coastal environments and Blue Carbon initiatives that include carbon sequestration in saltmarshes restoration to the implementation of nature-based solutions.

Importantly, we seek to use this greater understanding to effect demonstrable change in the way in which marine environments are appreciated, managed, protected and valued. This is realised through a broad range of regional, national and international engagement activities and leadership roles that PML provides and supports.

We employ a combination of traditional and advanced scientific methods, utilising the latest digital technologies such as Artificial Intelligence (AI) and machine learning (ML) to help us quickly and efficiently collect, visualise and interpret increasing quantities of environmental and biological data, using Digital Twins and autonomous marine and aerial platforms.

Our research is ultimately designed to:

1. Identify how marine ecosystems are fundamentally structured and how they function.
2. Quantify the impacts of multiple human and climate induced stressors on marine ecosystems.
3. Develop solutions and approaches to support the sustainability of marine ecosystems.

In practice, PML's science is delivered through a series of interconnected 'Science Areas':

- Digital Innovation and Marine Autonomy
- Earth Observation Science & Applications

- Marine Biogeochemistry and Observations
- Marine Ecology and Biodiversity
- Marine Systems Modelling
- Sea and Society

2.4.6.2 PML Current Use of Crewed Aircraft

While PML does not directly use crewed aircraft for projects on a regular basis, PML did provide the processing node for the NERC Airborne Research Facility (ARF, 2007 - 2018) and continues to process airborne data on behalf of the National Centre for Earth Observation (NCEO). This includes a suite of instruments delivering high quality airborne remote sensing data to support Earth Observation research and is available to UK researchers via a peer reviewing process. PML was also a NERC ARF user, the last example of which was a field campaign for the remote sensing of plastics carried out over Whitsand Bay (Plymouth) in 2018 as a feasibility study to detect plastic features in the SWIR (OPTIMAL project led by Victor Martinez-Vicente).

Currently, processing of airborne data sits within NEODAAS (NERC Earth Observation Data Acquisition and Analysis Service) at PML using software developed in-house to process airborne hyperspectral, thermal, LiDAR and digital photography data. PML is able to offer data processing for new flight campaigns, exemplified by the joint NASA-Jet Propulsion Laboratory (JPL) and NERC-NCEO campaign in summer 2019 where the NCEO Specim Fenix was flown alongside JPL's Hyperspectral Thermal Emissions Spectrometer (HyTES) instrument.

2.4.6.3 PML Current Use of UASs

PML started using UASs in their research in 2018. The number of projects that rely on UAS use has grown in the last few years. UAS data has been used as a very high resolution stand-alone dataset (such as for project LOCATE) or was combined with other sensors or satellite observations for validation (MONOCLE, BETA...). PML is using or has used UASs for different studies that include:

- In-land water quality monitoring developing hyperspectral or multispectral sensors mounted on UASs (project MONOCLE) including projects focused on the quality of human health (REVIVAL , Vis4Sea).
- Monitoring changes in salt marshes and mudflats (Sharpham and Calstock). Using DEM derived from UAS imagery, sediment accretion and carbon sequestration is estimated for mudflat restorations (project LOCATE).
- Habitat mapping for seagrass and algae (BICOME) or Kelp (TALISKER). This research usually combines UAS data with ML techniques such as 'random forest' or Deep Learning for image analysis and object identification to detect and count invasive marine species (ongoing as part of PORTWIMS).
- Remote sensing of plastic marine litter over water or on the shoreline. This research is carried out either using RGB cameras or feasibility study with hyperspectral instruments mounted on a UAS (HyperDrone).
- PML also promoted the use of UASs in workshops and outreach events. For example, PhD students were able to learn about how UASs and ML can be exploited for ocean monitoring (PORTWIMS workshop) and children at key stage 4 in schools were introduced to the use of new technologies including UASs and satellites for ocean colour and water quality monitoring (EO-PI) as well as UAS displays for projects that involved citizen science (MONOCLE).

2.4.6.4 PML Strategic Vision for UASs

The very high resolution of the EO data provided by UASs has been incorporated into PML's research across several disciplines with a particular impact on coastal marine and transitional waters research. PML are actively working to expand their UAS capabilities towards microscale validation of inland water quality products derived from satellites, advancing both technical capabilities and uptake of multi-scale observation strategies with a diverse range of stakeholders, demonstrated through its co-development and leadership of the Smart Sound Plymouth and more recently, the National Centre for Coastal Autonomy (NCCA). The vision is for UASs to contribute to a seamless integration of scientific research and technology across a broad range of different scales and platforms: from microscale (such as collecting water samples with UASs for laboratory, or potentially autonomous analysis) to small scale but very high resolution (as with UAS imagery) and large scale observations, integrating satellite, *in situ* and UAS data to deliver the best available products to support regional scale models and Digital Twins capable of predicting phenomena such as harmful algae blooms or underpinning a range of decision support tools. At the same time, UAS-based research at PML is becoming more interdisciplinary, with rapid uptake in ecological and biodiversity studies with a specific focus on Blue Carbon, demonstrated by recent projects using UASs for quantifying changes in mudflats restoration and for kelp mapping. We envision that habitat research that uses ML and UASs will see rapid acceleration in development in the next five years and efforts are underway at PML to meet the challenges such developments present.

The use of UASs over open waters for scientific purposes is still in its infancy. Some of the techniques commonly used by UASs such as 'Structure from Motion' do not work well over water and as such, most of the available multispectral cameras are marketed at agricultural studies. There is current work in progress to extend the in-house Airborne Processing Library (APL) used within the NERC-ARF to UAS platforms to be able to directly geocorrect UAS images. Smart Sound Plymouth (SSP) presents the perfect platform to test and develop new UAS technologies and new protocols alongside other expert capabilities at PML and regional partners in marine autonomous systems. SSP presents a diverse and comprehensive testing environment with >1,000km^2 of authorised, de-conflicted water space with a unique private high speed marine communications network offering the potential for interconnected sub-surface, surface and aerial autonomous capability.

Also within SSP, PML offers an autonomous fleet, a range of crewed and autonomous marine vessels, autonomous buoy systems continuously collecting data including water depth, temperature, salinity, sound velocity, density and chlorophyll-a data that would allow to compare and cross-validate data taken with UAS. It is PML's vision that UASs will become an integral component of near future Smart Sound Plymouth capabilities to enable a community accessible platform for UK marine science and marine technology research.

The PML Airborne team comprises scientists with a range of backgrounds spanning mathematics, physics, computer science and geography and who have years of experience working with remotely sensed data acquired from airborne platforms. With a strong programming focus and immediate access to world leading marine science expertise, we develop our own software, tools and procedures for data processing, analysis and sensor calibration. We have experience in processing data from hyperspectral sensors in the VNIR, SWIR and LWIR as well as LiDAR and solving different problems, which more than often arise during data collection to prevent loss of data or metadata quality with bespoke processing chains. As part of the wider NEODAAS group we also have expertise in satellite data processing and integration of airborne, satellite and *in situ* data. With a background in delivering large quantities of high-quality airborne data in standard formats for scientific research we have developed a number of capabilities including sensor calibration, sensor characterisation, web-enabled processing and data quality assessment. In addition to standard products, we can offer bespoke solutions such as higher-level products, custom software for analysis (including efficient implementation of existing algorithms for large datasets) and training. PML also performs quality checks on airborne data and ensures the metadata is FAIR (Findable Accessible Interoperable and Reusable) and uploads the data to CEDA where users can access archives including over 100 Gb of airborne data processed by PML and the only NERC-FSF hyperspectral UAS data. PML's vision is that the NERC scientific community needs a centralised UAS processing service that includes state-of-the-art equipment for remote sensing and a dedicated processing team where PML will be a great fit for the latter.

To conclude, there are three main pathways to deliver the PML's UAS vision:

1. UAS data processing for state-of-the-art EO instrumentation via NEODAAS as a NERC service (very much as was the case for the NERC-ARF).
2. In-house UAS capabilities for habitat mapping, especially for Blue Carbon, pollutant pathways such as plastic detection and water quality for human health (using hyperspectral, hydrology and seamless integration across different scales and platforms – satellite, modelling, sea and society thanks to PML's already existing capabilities).
3. Plymouth Smart Sound as a technological testing ground for new marine research relying on UASs.

2.4.7 Scottish Association for Marine Science (SAMS)

2.4.7.1 SAMS Science & Service Areas

SAMS (Scottish Association for Marine Science) is an independent research, education and enterprise institute, founded by Sir John Murray in 1884 and as such is the oldest independent and dedicated marine science organisation in the UK. Its vision is an ocean in balance that is healthy and sustainable. More information can be found on the SAMS website.

For the purpose and background of NZArC, SAMS has had a strong environmental robotics footprint for marine science for over a decade, hosting the North Atlantic Glider Base, the Scottish Marine Robotics Facility and more recently, the Scientific Robotics Academy. On the specific topic of airborne robotics (UASs or 'drones'), SAMS was building their own bespoke copters and flying wings in 2012 and hosting postgraduate training courses in environmental airborne robotics from 2014 onwards. The SAMS UAS team has strong and active links with the local Oban Airport, frequently operating on air-side during (and integrated into) civilian piloted operations. During the Covid lockdown, the SAMS team introduced the Skyports medical delivery team to the opportunities opening up at the Airport: this is still evolving into a significant active beyond visual line of sight (BVLOS) UAS testing arena, a topic that we believe will be a valuable asset to the NZArC project.

Argyll & Bute Council and Skyports are also winning UK Government funding, via Levelling Up investment, to further enhance the Oban Airport infrastructure for commercial and innovative UAS operations: the SAMS UAS team are active consultants and future users on these projects.

Recently SAMS has been working toward the goal of operational "heterogenous swarms", whereby UASs can integrate with small (kayak-scale) robotic boats (Autonomous Surface Vehicles) to acquire data necessary to understand very near surface (<10m) air-sea interaction, with a focus on turbulence behaviour in both the lower atmosphere and upper ocean. In this regard, the open-source ArduPilot software (and aligned Pixhawk hardware) is delivering rapid progress to practical solutions when coordinated but dissimilar data sets are required, for example marine acoustic back-scatter, acoustic doppler current profiling and wind stress.

SAMS is, however, at heart a science institute. Our UAS operations support a range of studies from the equator (Identifying Macro-Plastic in Mangrove Swamps) to the poles (Mapping marine-terminated Glacial Discharge). UASs are either Commercial Off The Shelf (COTS) units such as DJI Mavic (for example used to study sea-weed decay on rocky shores via a 2-year photogrammetry video sequence), or DJI Phantom (for example for studying glacier/mangroves/Corryvreckan), or more frequently our own design or design+build. The latter include mounting a shortwave infrared multispectral camera on a hexacopter (for microplastic detection on rocky shorelines), designing novel water-landable quadcopters ('Skaters') for trace gas fluxes, ultra-low power powered gliders (for hydrogen fuel cell test beds) and dual-band spectrometers (for mapping harmful algal blooms).

On the broader scale, the SAMS UAS group also leads in the international atmospheric UAS community, being co-founders of ISARRA (International Society for Atmospheric Research using Remotely piloted Aircraft), with Bergen University, following the successful EU COST (Cooperation in Science and Technology) Action on the same topic starting in 2008. ISARRA is a community of scientists, albeit with links to engineering, looking at ways to modify and then instrument UAS designs to glean otherwise unavailable measurements. SAMS hosted the 5th ISARRA conference in 2017.

2.4.7.2 SAMS Current Use of Crewed Aircraft

Currently no crewed aircraft are used, although SAMS did participate in working with FAAM to test the feasibility of working below peak height in Loch Linnhe, the extension of the Great Glen of Scotland, with (SAMS-designed) robotic surface vehicles under the flight path.

2.4.7.3 SAMS Current Use of UASs

SAMS currently uses both COTS systems, such as the DJI family of quadcopters, or bespoke systems (copter and fixed wing) based around the ArduPilot/Pixhawk family of open source avionics. Focus is inevitably on the marine, near coast or shoreline environments, with launch from shore or from Rigid-hull-inflatable-boat, small day boat or ship.

COTS-based projects mostly involve using visible camera systems on gimbals, frequently with post-processed photogrammetry. Projects include:

- Year-long timelapse of kelp decay using repeat mission plans and photogrammetry (O'Dell, 2022)
- Aerial photography of glacial plume in Svalbard
- Monitoring of plastic pollution in mangrove swamps
- Visible survey of macro-plastic pollution on rocky beaches (Cocking, 2022, p. 268)

Our main focus since 2012 is on bespoke aircraft, in each case to offer a novel airborne platform for relatively standard instrumentation. These fixed wing and multicopter platforms use the professional-level open-source ArduPilot avionics incorporated into novel airframes, requiring a high degree of flight test and avionic tuning to ensure airframe reliability, safety and minimal risk to mission/project. Projects include:

- First flight of solid-fuel hydrogen aircraft: aim for very-long range operation
- Shortwave InfraRed hyperspectral survey of beach plastics (in tandem with FSF and PML)
- LiDAR measurement of glacier crevasses for assessing photogrammetry
- Long endurance flying wing (X8) for rocky shoreline photogrammetry
- Airborne spectrometer for detecting Harmful Algal Blooms
- Low impact platform for sea-bird colony survey (Bixler powered glider)
- Terrain following testbed using Optical Flow for sea-surface flux monitoring
- 'Skater' water-landable copter for simple T, RH and CO_2 profiling and survey

2.4.7.4 SAMS Strategic Vision for UASs

Our vision, via the Scientific Robotics Academy (SRA) based on campus, is to bridge the divide between the measurement needs of the environmental science community on the one hand with usable robotics platform designs from the engineering community on the other. This fusion will then address the pressing needs for climate and forecast model validation by providing a route to technology development and a school for knowledge exchange.

Specifically, we aim to develop simple-to-operate heterogenous swarms of coordinated surface, sub-surface and airborne platforms in the marine environment, working from shore or deep-ocean mother ships. Initially these small vehicle collectives will address the paucity of air-sea interaction measurement.

A second target of the SRA is to dovetail with the growing *commercial* BVLOS community in the Hebrides. Oban airport is deemed an ideal test area for BVLOS, with a number of month-long field campaigns to date delivering medical or educational packages from mainland to island. This proven capability for commercial BVLOS operation from Oban in the marine environment paves the way for research operations in the future.

Targets we have in the next five years are:

- though sea-surface turbulent fluxes of momentum, heat and trace gases
- flow fields within off-shore wind farms, to provide wind field data for Digital Twins
- heterogenous swarms, being UASs, surface vehicles and sub-surface vehicles to study air-sea interaction

Finally, the SRA will host robotics teaching through local education STEM initiatives. As part of this initiative, SRA plans to fund an all-weather, radio-transparent training facility where new pilots can work in all weathers and, being an indoor arena, without the need for CAA permissions. The radio-transparent aspect allows the testing platforms that require continual access to GNSS signal as if outside; as such the arena will be used to confirm airworthiness of novel build aircraft (or novel *payload* installation) in a CAA-safe, indoor setting. We aim that this facility be open to use by the research community.

2.4.8 UK Centre for Ecology and Hydrology (UKCEH)

2.4.8.1 UKCEH Science & Service Areas

UKCEH provides the data and insights that researchers, governments and businesses need to create a productive, resilient and healthy environment. The institute has a long history of investigating, monitoring and modelling environmental change, generating evidence-driven solutions to complex environmental challenges. UKCEH is addressing three major environmental and societal challenges:

- Creating and enhancing sustainable ecosystems
- Reducing and preventing pollution
- Mitigating and building resilience to climate and environmental change

More specifically UKCEH aims to:

- improve the process-based understanding of land-atmosphere exchange, focusing on emissions, atmospheric transport and chemical transformation, deposition and effects
- understand, predict and mitigate future threats to biodiversity
- improve our ability to forecast flood and drought events and minimise the impacts of extreme weather, taking new observations and developing new analysis techniques and models

- provide the scientific understanding needed to develop chemical hazard and risk assessment, understand the effects that pollutants have and develop effective mitigation and restoration strategies
- measure and model change in the structure, function and quality of our soil and land so we can better develop solutions to conserve and enhance these valuable natural assets
- provide insight into the relationships between the natural water resource and its dependent ecosystems, so that the impacts of pressures from exploitation of the resource can be understood

Remote sensing (RS) forms an integral part of UKCEH's science delivery and strategically UKCEH aims to further enhance and promote UKCEH's application of RS for land, water and air and their integration with ground-based measurements and modelling. These will include the development and enhancement of core RS land cover-related products; the use of RS for process understanding, through determining condition and function across the land, air and water system; RS-based monitoring and forecasting including near real-time data for integration with models as part of Digital Twins and other modelling applications; and calibration and validation bringing together our field-based and RS capabilities.

2.4.8.2 UKCEH Current Use of Crewed Aircraft

UKCEH makes widespread use of satellite remote sensing in its research. There is *ad hoc* use of the FAAM facility mostly to study convection processes and atmospheric transport and chemical transformation. In the past UKCEH regularly made use of airborne hyperspectral and LiDAR observations (mainly in the UK) delivered by the NERC Airborne Research & Survey Facility (ARSF) and it still exploits historical time-series of ARSF data for two forest sites (Wytham Woods and Monks Wood).

Boats, both crewed and uncrewed, are widely used in UKCEH's research programmes. UASs can offer major benefits to efficiency, accessibility and operator safety compared to these surface-based vessels.

Stationary buoys are used for water quality monitoring. These have the benefits of stability and continuity of monitoring, but cannot offer spatial distributed information.

2.4.8.3 UKCEH Current Use of UASs

UKCEH's current UAS fleet comprises of:

- DJI Matrice 300-RTK: Red-Green-Blue (RGB), Thermal and Light Detection and Ranging (LiDAR), Multispectral
- DJI Matrice 600: (max payload 5.9kg), Rikola hyperspectral imaging, PICCOLO hyperspectral reflectance
- DJI MAVIC 2 Pro: RGB
- DJI MAVIC 1: RGB
- DJI Mavic Air 2S: RGB
- DJI Mini 3 Pro (x2): RGB

Ecology and biodiversity

UKCEH is currently using UASs to replace the NERC ARSF airborne capability. The achievable coverage is limited compared to NERC ARSF, however, this is compensated by:

- a significant increase in spatial detail
- affordable repeat visits
- internal access and thus increased control and flexibility

This is creating opportunities for new research and discovery. Current campaigns are mainly collecting RGB & Near Infrared (NIR) imagery, structure from motion point clouds and LiDAR to characterise vegetation communities, derive habitat condition metrics and woody vegetation vertical structure. Hyperspectral campaigns are less popular as the current sensor-on-UAS setup requires expertise related to multi-band pre-processing and image analysis.

In the terrestrial environment UASs are being used in UKCEH to study:

- Land cover/ land cover change
- Habitat modelling
- Disease monitoring: for example ash dieback, acute oak decline
- Phenological traits
- Biomass/carbon stocks
- Rewilding
- Biodiversity metrics
- Floral resources
- Invasive vegetation
- Insect habitats
- Forage volume/quality
- Crop health
- Carbon mitigation
- Hydrological vegetation habitats
- Soil hydrology

Hydrology: UASs offer huge potential to improve monitoring in hydrology. Existing monitoring programmes can be greatly improved in terms of efficiency, safety and effectiveness and new insights can be gained into hydrological processes and events.

Flood monitoring: When major floods occur, observing and quantifying the peak flow and its impacts is crucial. With traditional methods, these observations are hazardous, time-consuming and in many cases impossible. However, a UAS pilot well out of the way of the flood waters can use video footage of trackable surface features of the river to give the variation in river flow across the whole width. This combined with the river cross section can give the total water flow at that point which can then be used with a high-resolution digital surface model (DSM) of the area, also produced from UAS data, to give an indication of flood risk.

Drought monitoring: Droughts can have huge impacts on people, nature, agriculture and industry and come in many forms. A hydrological drought marks the point at which a meteorological drought starts to have major impacts on rivers, streams and groundwater. UASs have huge potential to help identify the onset and propagation of hydrological drought, increasing preparedness and response to minimise impact. Huge carbon savings can be achieved if large-scale water pumping and the provision of bottled water can be prevented.

Water quality monitoring: UASs present an opportunity for new monitoring and observations, allowing access to hard-to-reach locations. UASs have been adapted to land on water and undertake measurements, but these technologies are not yet common.

Water temperature monitoring: As the impacts of climate change accelerate, understanding changes in the temperature of water in rivers and lakes is vitally important ecologically. UASs equipped with temperature probes and thermal imaging cameras can map water temperature on a regular basis.

Morphological change monitoring: Rivers and landscapes are dynamic and can be subject to both gradual and sudden, sometimes catastrophic change. UASs offer a safe and effective tool for the observation of such change in real-time and for pre- and post-event analysis.

2.4.8.4 UKCEH Strategic vision for UASs

UKCEH's strategic vision for UASs currently covers the following areas:

***In situ* systems:** The potential of UASs that are permanently situated at a fixed location and deployed automatically ('drone-in-a-box') at set intervals or in response to hydrological or other events is considerable. Such systems can deliver significant financial and carbon savings by eliminating the need for people to visit the location on a regular basis and in response to extreme events.

Satellite calibration and validation: UASs will also play a major role in providing a calibration and validation service for satellite-based observations of water quantity and quality. As new sensors and very high-resolution satellite constellations are launched, these have the potential to bring transformational benefits to hydrological observations globally. The UKCEH-led FluViSat project is one such example in which UAS-based observations of water flow are being used to develop a satellite-based method using very high-resolution optical imagery. UKCEH are Hydrology leads in the Europe-wide Copernicus *In Situ* (COINS) project that aims to improve the sustainability of *in situ* observations.

New sensors and applications: Sensors such as LiDAR and ground penetrating radar (GPR) can bring major benefits. UAS-mounted LiDAR can be used to provide quickly and efficiently very high-resolution topographic, habitat and land-cover maps which are extremely valuable for hydrology and ecology. LiDAR technology also has the potential to enable new observations and to reduce costs in existing ones. Green LiDAR can be used to generate very high-resolution bathymetric maps of lakes and rivers and standard LiDAR modules have the potential to enable new observations of flood dynamics and river hydraulics.

Real-time data creation: There is a need to improve the creation of real-time, actionable information from UAS sensors. This requires advances in onboard processing and external metadata, for example through the creation of Digital Twins of areas of interest such as rivers, lakes, wetlands and other critical landscapes.

Integration of UASs with ground- and water-based systems: In many cases, UASs alone will not answer research and monitoring questions. UKCEH's existing skills and experience with water and ground-based sensors and deployment platforms (such as the ARCboat uncrewed water survey vessel) and a strategic objective to accelerate the development of robotics and autonomous systems means it is well-placed to integrate UAS-based monitoring with other solutions.

3. Methodology

3.1 NZArC Steering Group and Report Writing

The NZArC Scoping Report has been overseen by a Steering Group which was first comprised of representatives from six NERC Centres and Collaborating Institutes invited by NERC Head Office (BAS, BGS, NCAS, NCEO, NOC, UKCEH; see Figure 3.1) and subsequently was extended to include PML and SAMS as a result of the community engagement.

Figure 3.1: *Infographic showing initial composition of the NZArC Steering Group, later amplified by colleagues from PML and SAMS and undergoing changes in representatives from other Centres - see Acknowledgements for the final composition of the Steering Group*

3.2 Community Engagement

Comprehensive community engagement was essential for the success of the first stages of this scoping programme. Engagement was sought out particularly to determine:

- Current capability & skill levels through a pre-workshop questionnaire
- What the community see as barriers to their research using UASs
- Aspirations of the community and what needs to be in place to meet these aspirations
- How a stakeholder community can be developed to deliver a joined-up approach: from science ideas to impact - providing support, innovation and development at every stage

The engagement activities included:

- First Workshop, in-person, 5 June 2023
  - Audience: The focus was placed on key stakeholders from those NERC Centres and Collaborating Institutes for whom the NZArC funding is intended. In addition, non-research stakeholders from industry and organisations such as the Civil Aviation Authority (CAA), European Space Agency (ESA) and Ministry of Defence (MoD) participated
- Second Workshop, virtual, 20 June 2023
  - Audience: A wider stakeholder group from the NERC Centres and Collaborating Institutes and from the non-research stakeholder community was invited to join the conversation and sense-check the findings of the first workshop
- Questionnaires
  - Pre-workshop questionnaire: This is introduced in more detail in section 3.2.1.

- *External* - Data questionnaire (link no longer active): This questionnaire from the NERC Environmental Data Service aimed at better understanding needs and requirements to make the data derived from UAS platforms FAIR (Findable, Accessible, Interoperable, Reusable)
- Use case study & existing resource questionnaire: This form invited stakeholders to indicate interest in providing a current use case study based on existing UAS research, or highlighting a desired use case (where stakeholders would like to, or have been unable to use UASs for their research and to highlight barriers). In addition, it provided the opportunity to
  - upload resources that should be taken into account in the NZArC Report to NERC
  - highlight any gaps from the in-person workshop on 5 June 2023 that should be covered in the online follow-up workshop on 20 June 2023
  - leave general feedback on NZArC
- Technology ranking questionnaire: This form invited individuals to rank responses given to the questions "In what areas is technology innovation needed for platforms and sensors? What are the scientific areas, new and upcoming, that could benefit from UAS activity and what is needed to make this happen?" in terms of perceived importance for progressing Net Zero Aerial Capability. The responses were grouped into 'Platforms & Training', 'Sensors', 'Integration', 'Data' and 'Other'
- *External* - CAA Innovation test sites survey: We provided this link to ensure CAA are appraised of the needs of the NERC community
- Invitation for all participants of both the in-person and online workshops to read and comment on a near-final draft of this Scoping Report

3.2.1 First Workshop

The first of the two workshops was hosted by NCAS in Leeds on 5 June 2023.

Workshop aims and preparation:

The aim was to help us gauge the current landscape across our stakeholder community. To that end we developed a pre-workshop questionnaire. In particular, we wanted to gain a better understanding of the current UAS expertise within NERC Centres and Collaborating Institutes and to capture the views and vision of researchers and employees within these Centres and Institutes and relevant others such as regulatory bodies. We asked people to elaborate on:

- current use of UASs in the environmental sciences
- experience and skills relating to use of UASs in the environmental sciences
- vision for the use of UASs in the environmental sciences
- what needs to be done to realise their vision for the use of UASs in the environmental sciences

Workshop structure and agenda:

Time	Duration	Description
09:30	mins	Registration & Coffee
10:00 - 10:10	10	Venue Housekeeping
10:10 - 10:30	20	Welcome and scene setting
10:30 - 10:45	15	Talk 1: Regulatory (Callum Holland, CAA)

10:45 - 11:00	15	Talk 2: Technologies (Ben Pickering, Menapia)
11:00 - 11:15	15	Talk 3: Data (Wendy Garland, CEDA)
11:15 - 11:25	10	Q&A
11:25 - 11:30	5	Introduction to the breakout sessions
11:30 - 11:45	15	Tea & Coffee Break
11:45 - 12:30	45	Breakout Session 1: Regulation
12:30 - 12:45	15	Breakout Session 1: Feedback
12:45 - 13:45	60	Lunch & Networking
13:45 - 14:30	45	Breakout Session 2: Technologies
14:30 - 14:45	15	Breakout Session 2: Feedback
14:45 - 15:30	45	Breakout Session 3: Data
15:30 - 15:45	15	Breakout Session 3: Feedback
15:45 - 16:00	15	Tea & Coffee Break
16:00 - 16:30	30	Open floor discussion
16:30 - 17:00	30	Wrap-up and next steps
17:00		Close

Discussion and outputs of 1st workshop:

I) Breakout session: Regulation

The questions below were posed during the breakout session:

- What influence and interaction does this community of environmental scientists want with the CAA? How does NERC show it is an informed and trusted operational partner? What might a future relationship between CAA and environmental scientists look like?
- What are the regulatory blockages that are stopping research activities? What would solutions to these problems look like?
- What support do users need to meet current regulatory requirements? How can NERC help to build a self-supporting user community?
- What is the skills gap in the user community to allow regulatory compliance? How can NERC address this sustainably?

Output: Based on the findings, Richard Dale (SAMS) composed a summary presentation from the regulation-related discussions at the first workshop which he shared at the second workshop.

II) Breakout session: Technologies

The questions below were posed during the breakout session:

- What is the current technology landscape for platforms and sensors? How can we keep up with platform, sensor and operational advances and better share this information?
- In what areas is technology innovation needed for platforms and sensors? What are the scientific areas, new and upcoming, that could benefit from UAS activity and what is needed to make this happen?
- How should the engineering and science communities come together to drive innovation? How can we continually set science-led engineering challenges that advance areas of interest?
- What infrastructure is needed to safely test and evaluate new technologies? Is there a need for places for testing individual components and integrated systems/places that are supported by experts, and if so, what would these look like?

Output: Based on the findings, Kay Smith (BGS) composed a summary presentation of the technology-related discussions at the first workshop which she shared at the second workshop.

III) Breakout session: Data

The questions below were posed during the breakout session:

- On an international level, what is happening on the data stewardship front? Who are the main players and what can we learn from them?
- How do we make this type of data inclusive to both the expert and non-expert end users? Who are the end user stakeholders and how do they want data served?
- Data needs to be archived and accessible - what data and metadata standards need to be put in place? What would a joined-up service across the Environmental Data Service for this type of data look like and how would it be achieved?
- How do we deliver a quality-controlled and accessible data product? How do we collaborate to understand the biases in measurements and develop open and transparent workflows and best practices for calibration and operations? How do we decide what data to keep and what to discard?

Output: Based on the findings, Alice Fremand (BAS/PDC) composed a summary presentation of the data-related discussions at the first workshop which she and Wendy Garland (NCEO/CEDA) shared at the second workshop.

Following the first workshop, a Technology ranking questionnaire was designed and circulated to all those invited to the workshops; it invited individuals to rank responses given at the first workshop to the questions "*In what areas is technology innovation needed for platforms and sensors? What are the scientific areas, new and upcoming, that could benefit from UAS activity and what is needed to make this happen?*" in terms of perceived importance for progressing Net Zero Aerial Capability. The responses are grouped into 'Platforms & Training', 'Sensors', 'Integration', 'Data' and 'Other'. The results of the technology questionnaire were shared ahead of the second workshop.

3.2.2 Second Workshop

The list of invitees for the second workshop included all those invited to the first workshop, plus additional leadership and science contacts from each of the NERC Centres and Collaborating Institutes.

Workshop structure and agenda:

Time	Duration	Description
14:00-14:20	20	Welcome & Scene Setting
14:20-14:50	30	Summary of Discussions from Workshop 1 (10 mins per topic): ● Regulatory ● Technology ● Data
14:50-15:50	60	Breakout Discussions for Workshop 2 ● Regulatory (15 mins) ● Technology (30 mins) ● Data (inc. Software) (15 mins)
15:50-15:55	**5**	**Break**
15:55-16:40	45	Feedback from Breakout Discussions ● Regulatory (10 mins) ● Technology (25 mins) ● Data (inc. Software) (10 mins)
16:40-17:00	20	Summary & Next Steps
17:00		**Close**

Discussion and outputs of second workshop:

The questions below were posed during the breakout session:

I) Regulation

- What have we missed? Are there any regulatory challenges and problems that have not been identified from last time?
- What could Research Councils and your community do to address any of these challenges?

II) Technology: Platforms & training; Sensors; Integration

- Which of the top three ranked challenges could be solved by NZArC Work Package 2 funding for test cases and demonstrators within the allocated funding (capital investment of ca. £3M to be delivered over 3 years via 3-4 Centre-led projects) and how?
- What have we missed? What capabilities would you like to see platforms and sensors provide?

III) Data: including software

- When using UAS to answer research questions and in the field, what are the software challenges you face?
- What have we missed? Do you think there are any challenges which could be addressed through NERC funding that we have not discussed?

Next steps following on from the second workshop – Use Case Studies:

To identify concrete opportunities from across the environmental research sector supported by NERC, we invited the community to submit existing and desired use case studies for the use of UASs in environmental science. The opportunity to submit case studies was publicised to the workshop participants and further across the different NERC Centres and Collaborating Institutes.

We provided an example case study and templates for existing and desired case studies via the NZArC Microsite.

3.3 Authorship of Report

Following from the workshops, the NZArC Steering Group undertook to write this Scoping Report, supported by additional relevant sector-specific experts from the NERC Centres and Collaborating Institutes - the list of authors is, in alphabetical order: Aser Mata (PML), Barbara Brooks (NCAS), Beatrix Schlarb-Ridley (BAS), Carl Robinson (BAS), Charles George (UKCEH), Charlotte Francoz (NOC), France Gerard (UKCEH), Hugo Ricketts (NCAS), James Strong (NOC), Kay Smith (BGS), Luke Bateson (BGS), Martin Wooster (NCEO), Nick Everard (UKCEH), Philip Anderson (SAMS), Pilvi Saarikoski (BAS), Richard Dale (SAMS), Tom Jordan (BAS), Zixia Liu (NCEO). In addition, existing use cases that had been shared by the community have been added as an Appendix.

3.4 Referencing Existing Resources

The workshop invitees were invited via questionnaires to highlight existing resources the report should make reference to; these were also sourced from the Steering Group and the authors have taken these resources into consideration in compiling this report.

3.5 Intentional Repetition

The report has been written 'bottom-up', with members of the author group taking responsibility for drafting sections aligned with their expertise areas. In this process similar points have been raised in several places of the report. We have welcomed this repetition as a clear indication of issues and opportunities that are shared between NERC Centres and Collaborating Institutes and between scientific disciplines and invite readers to pay particular attention to them. These common themes have also been captured in section 5.1 (Overarching Conclusions & Recommendations).

4. Findings

This chapter provides the findings of the NZArC scoping exercise, exploring regulation, UAS technologies and associated data workstreams within UK environmental science.

The chapter is structured to provide relevant information focusing on regulation in section 4.1, UAS technologies, specifically platforms in section 4.2, sensor integration in section 4.3 and discipline-specific sensors in section 4.4 and concludes with a section on all aspects associated with data workstreams (section 4.5). Within each section, the authors provide a review of the current state of affairs and a vision of where the NERC Centres and Collaborating Institutes would like to be in the future in terms of regulation, technology and data regarding UAS uptake for environmental science in the UK. As part of reaching that vision, each section outlines a gap analysis conducted on the barriers and challenges to reach that vision and provides potential solutions or opportunities to overcome these barriers. Each section concludes with recommendations to drive forward advancement to help UK researchers maximise the use of UASs within environmental science.

The detail contained within this chapter has been compiled by representatives from each of the NERC Centres and Collaborating Institutes, in conjunction with information gathered as part of the community-led workshop series held in June 2023.

4.1. Regulatory Factors

UAS use is expanding and finding new and novel applications in many areas; this means that in the majority of airspaces, the zone of operation has to be shared by a diverse and extensive user base. We have seen the negative impact that unauthorised UAS usage around airports can have with the closure of airspace resulting in substantial financial impact through lost revenue and passenger care costs.

Many use-cases see UAS applications in and around the general public; be that leisure usage, aerial photography, parcel delivery or situational monitoring by the emergency services, they all raise questions around privacy, consent and safety.

For these reasons and many more, the use of UASs is strictly regulated and the science community needs to show that they are responsible and trusted UAS users by complying with the regulations that are in place in their target zone of operation.

Understanding and navigating the complex regulatory landscape is a “must” for the science community. While science users have many areas of expertise, they need access to expert knowledge and support that is not readily available to meet regulatory requirements in the UK and internationally (regulations varying between counties). This section provides insight into the barriers the science community encounters concerning regulation and makes recommendations on how to overcome them.

4.1.1. Current State of Affairs

For UK operations, the Civil Aviation Authority (CAA) regulates UAS operations and a code of conduct has been developed. In the UK it is against the law to fly a UAS without having the required IDs:

- Anyone who will fly the UAS must pass a theory test to get a flyer ID. The flyer ID shows a person has passed a basic flying test and knows how to fly safely and legally.
- The person or organisation that owns or is responsible for the UAS must register for an operator ID. The operator ID is the owner's registration number and must be labelled on the UAS.

This is a rapidly changing area and the CAA develops and updates regulations as UAS use evolves. Regulation changes involve consultation with user groups. The science community currently engages with these consultations as individuals rather than as a single body: if the UAS science user group worked together, it could influence the future developments of regulations.

The CAA code defines categories of operation. Of interest to the science community are the categories Open, Specific and Certified: it is Specific that covers most of what is currently being done.

Navigating the requirements for operations under the Specific category necessitates experience and expert knowledge. For many, this requires approaching third-party suppliers of UAS services or developing a relationship directly with the CAA. It appears that the effort of developing such a relationship is being duplicated across research groups and has often to be repeated within a group due to the loss of expertise when Post Doctoral Research Assistants (PDRAs) or Post Graduate Students (PGSs) move on.

The regulations require trained and qualified pilots and these are often, but not exclusively, the PDRAs and PGSs engaged in a science programme. Training is accessed through third parties and on an individual basis. One aspect of qualification is the need for pilots to reach and maintain logged "flight hours"; the amount needed varies with the complexity of the airspace. For PDRAs and PGSs there is not always the funding or capacity (time) to train to become pilots on top of conducting their scientific research and for those that do, the host research team face loss of expertise when they move on. Achieving and maintaining the required flight hours requires physically flying the UAS and that in turn requires access to appropriate flight ranges.

Some groups (including in NERC Centres and Collaborating Institutes) have developed and retained a knowledge and expertise base, but this appears siloed and inaccessible to the wider science community. The proliferation of third-party UAS service providers is an attractive option for those starting in this arena. It is however often prohibitively expensive.

For many groups, certain regulatory restrictions exclude their area of research: for example, flying beyond visual line of sight (BVLOS) and heavy UAS systems. The CAA is currently developing policy in this area. The CAA Airspace Modernisation Strategy (AMS) presents the roadmap for the development and modernisation of UK airspace until 2040. One key element considered within the strategy is the way that UAS operating BVLOS will be integrated into the airspace system.

The use of UASs by the UK science community is not restricted to operations in the UK: capability may be developed and tested in the UK but with the intention of scientific use overseas. Each country has its version of the CAA regulations that a user must comply with. It appears that there is a knowledge base on how to do this, but it is siloed within the groups that have had to solve the problem.

In Antarctica, for example, the freedom to operate is higher, but challenges with safe integration into existing air operations remain. Unlike elsewhere the airspace is regulated by ASSI (Air Safety Support International) for UK operators but is simultaneously regulated by other national bodies. International organisations such as COMNAP (Council of Managers of National Antarctic Programs) help to coordinate the application of these regulations throughout Antarctic airspace.

4.1.2. Where We Want to Be

To move the community to a position where they are considering UAS operations as a viable option we need to make the understanding of and compliance with UK and international regulations as simple and transparent as possible. There is experience within the community which, if shared, would go a long way to minimising the dependencies on third-party UAS service providers which in turn would increase the science that can be delivered for the funding available.

Knowledge of regulation and regulatory processes is one piece of the puzzle: access to qualified pilots is the other. If the goal is to move the NERC community to a greater use of UASs then we need to be in a position where there are sufficient numbers of appropriately trained pilots. Not all training is equal and we need to consider the development of training that ensures “NERC trained pilots” are reputationally enhancing as well as meeting the legal requirements. This also means the development of “safe” places for flying: both indoors and outdoors.

We want the UK science community to be trusted operators and to have a voice at the regulatory table both in the UK and internationally.

4.1.3. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

The greatest barriers and challenges in this area are around developing and retaining the knowledge and expertise to meet legal requirements. The challenges and opportunities appear to fall into four areas: knowledge, training, pilots and central facilities. Table 4.1 below collates and summarises the gap analysis that has been performed.

Table 4.1: *Summary of barriers/challenges and solutions/opportunities for regulation regarding knowledge, training, pilots and central facilities.*

	Barrier/Challenge	Solution/Opportunity
Knowledge	● Access to CAA expertise is difficult to get other than through what is available online - new and inexperienced users do not know where to go to get support ● The complexity of the regulatory environment makes it difficult to know what is needed ● Staff gain experience but move on - knowledge and expertise is lost ● Use of third-party UAS service suppliers is costly and often prohibitively so ● The UK science community is not a coherent group operating with a single voice resulting in this community not having representation when regulations are changed and not always being seen as a trusted operator ● Lack of knowledge about international regulation; knowledge does exist but it is locked in the research groups involved ● NERC Peer Review College appears ill-informed regarding regulation requirements which impact grant success	● A dedicated CAA - NERC contact through which science-related questions can be channelled ● Central repository for information and documentation for the NERC community to access ensuring the community is kept updated on regulatory changes ● Enhanced communications and sharing between groups through the development of forums and user groups
Training	● Access to required training reliant on third-party UAS service providers - no recommended or preferred supplier ● Lack of access to indoor and outdoor training ranges	● Standardised pilot training to ensure all NERC-related operations are performed by people with the same level of training. Reduces reputational risk and raises the visibility of NERC ● A Doctoral Focal Award dedicated to UAS usage and delivering trained pilots as an output

Pilots	● Retention of trained pilots: Research groups may only have one or two trained pilots; if they are on short contracts or decide to leave then the piloting expertise is lost	● Pilot user groups to enhance communications ● Development of a pilot pool ● Pilot secondments at the CAA to learn more about the regulatory framework
Central UAS Facility		● Development of a central UAS facility providing platforms, pilots and deployment services - similar in function to FAAM; a facility that would allow a user to bring their own instrument package and have it flown on a UAS

4.1.4. Recommendations for Advancement

The following recommendations are made to advance the ease of access and lower the need for expert knowledge, resulting in greater inclusivity and encouraging greater diversity in the user base.

- Establish an environmental science UAS community to allow the development and sharing of good regulatory practices in this field
- Provide resources for setting up a UAS community and document repositor - a repository for the community to share operations manuals, risk assessments, guidelines and other related regulatory paperwork
- Develop future regulation through NERC/the research community together with the CAA, to allow for environmental science applications
- Explore a mechanism by which the UK can affiliate with EASA (EU Aviation Safety Agency) to allow UK pilots to fly in all EU countries and vice versa
- Provide a NERC-funded point of contact for the environmental research community who can assist with any regulatory or training questions for UK and international UAS usage -this would alleviate duplication of work and ease the workload on the CAA
- Provide a training course specific to environmental research or broader research communities which covers regulation and pilot training
- Form a “pilot pool” of trained UAS pilots

4.2. Technology - Platforms

There is a strong business need for lowering the carbon footprint of conducting environmental science and associated operations, to reach the UKRI target of Net Zero carbon emissions by 2040. Where it is not possible to reduce the need for flights and their associated carbon footprint through alternative ways to deliver the required functionality, it is imperative to minimise fuel use – this contributes to both environmental and financial sustainability. UASs can both reduce the carbon footprint and enhance the functionality of a spectrum of airborne science activities.

UASs come in a range of aerial platforms that differ in size and characteristics, this makes them a key asset to help deliver airborne capability: meaning the correctly capable platform can be chosen to deliver the flying efficiently and effectively, be it a UAS, a crewed aircraft or a satellite. This spectrum of platforms and their characteristics is summarised in Table 4.2. However, there are hybrid UAS developments occurring, such as larger multi-rotor UASs and also tilting rotor designs that combine some of the benefits of fixed and rotary-wing operations.

Table 4.2: *Characteristics of different aerial sensing platforms; not represented here are specialist platforms such as high altitude and lighter than air platforms that have very specific uses*

Aerial Sensing Platform Options				
				
Multi-rotor UAS	**Small Fixed-wing UAS**	**Large UAS**	**Crewed Aircraft**	**Satellite imagery and data**
· Low initial cost · Low operating cost · Small area coverage · Able to fit onboard new sensors to trial or deploy without much recourse to how they restrict airflow · Access required to target area · Limited to small camera, LiDAR and spectral systems, on some platforms standard manufacture only cameras · Operations including media tasks and local area science mapping and observations and some small *in situ* sensors (for example gas sampling/measurement)	· Low initial cost · Low operating cost · Medium area coverage · Required to be *near* target area (within several km – depending on the model) but direct access not necessarily required · Solar UAS give multiday operations · Limited to small camera and spectral systems and smaller atmospheric sensors. On some platforms standard manufacture only cameras · Sensors generally have to fit INSIDE the platform or in an aerodynamic "pod"	· High initial cost · Varying operating cost, depending on platform · Large area coverage Requires professional service provider · Remote access · A wide range of UAS sensors can be fitted including cameras, spectral sensors, magnetics, gravity, radar and atmospheric sensors	· High initial cost · High operating cost · Large/very large area coverage · Remote access · Low cost per km^2 · A full range of science sensors can be fitted in the cabin, on hard points, camera bay and boot apertures · Automated sensors possible in boot enclosure · Operations including media tasks and large scale science and mapping tasks	· High operating cost (though they are shared or not always passed on to users) · Very large area (global) coverage · Very remote access · Low to medium cost per km^2 depending on use of free or commercial satellite data · Almost all scientific satellite data products are free for users · Large range of analysis ready data, scientific data product and geophysical data products, including visual imagery, gravity, radar, spectral datasets and surface temperatures, trace gas and biophysical parameter retrievals etc

4.2.1. Current State of Affairs

UK scientists and operations staff already utilise UASs for local visual line of sight (VLOS) flying, both in the UK and overseas, including for:

- Mapping of landscape features, plants and plant species, vegetation types, agriculture (crop cover and condition), river margins, coastal/land and sea interfaces, land use and local area geology and for establishing digital elevation models (DEMs)
- Remotely sensing estimation of key biophysical parameters, such as leaf chlorophyll, crop growth rate, land surface temperature, solar induced fluorescence and so on and occasionally remote sensing of atmospheric parameters (for example CO_2 column amounts from the NASA Global Hawk flown BVLOS)
- *In situ* sampling in difficult to access areas - for example smoke sampling in wildfire plumes
- Building long or rapid 'time lapse' studies from repeated Structure-from-Motion (SfM)/photogrammetry or LiDAR data, for example shoreline kelp decay and, or identifying and quantifying changes after for example wildfires (for example depth of burn)
- Study of air-sea interface, air turbulence measurements, CO_2 and methane measurements, trace gases
- Measuring river flows, water sampling
- Assessing natural disasters (for example landslides), supporting environmental protection (for example identifying illegal waste/discharge), plastic pollution tracking
- Wildlife census and observations
- Sensor R&D and Net Zero research (for example on sustainable fuels) (Note: NERC policy is not to develop UASs, but rather use of UAS and development of sensors to fly on them)
- Operational use for communication, incident response, media recordings, infrastructure surveys, navigating vessels through sea ice, traverse navigation, snow management, route finding for field parties through dangerous (for example crevassed) terrain

Most organisations utilise quadcopters/multi-rotors for VLOS, these are readily available from manufacturers such as DJI. The DJI platforms *Inspire, Mavic* and *Matrice* and similar UASs have provided a cost effective, advanced, commercially available quadcopter capable of flying for over 20 minutes.

Some organisations also use small, fixed wing UASs such as the ready-to-fly eBee, or build-your-own systems using simple foam kits such as Bixler or X8 flying wing. These are technically able to operate BVLOS if and when regulations allow (see column 2 in Table 4.2).

NERC Centres and Collaborating Institutes have a number of platforms available as detailed in the use cases of the Appendix; they are being used in the UK, in UK Overseas Territories and worldwide, including in both Polar regions. The NCEO Field Spectroscopy Facility (FSF) provides the community with a UAS remote sensing capability, both in terms of platform and sensing equipment and operators. Supported by NERC Services and Facilities, FSF has developed this capability over around the last five years and has provided it as a service to a number of NERC grant project leads to whom it has proved extremely popular and the demand for additional sensor capabilities i.e. SIF imagery exceeds current FSF capabilities.

Regular use of larger UASs beyond visual line of sight (BVLOS) is still emerging and is limited to small case studies (some larger campaigns have also taken place, such as Global Hawk remote sensing of CO_2 column amounts[2]); the main barriers to BVLOS are regulatory (see section 4.1) and verification and validation that UASs are capable of delivering effectively and reliably. BVLOS flying for the science community, especially of larger UASs, is likely to be delivered by a service provider in most cases, the exception to this is simpler smaller BVLOS platforms in remote areas or organisations who invest in dedicated personnel to operate these

[2]however National Science Foundation have found Global Hawk in Antarctica to be more resource-intensive than crewed alternatives

platforms. Service providers in the UK are starting to emerge including Tekever, Bluebear, Windracers, Skyports and UAVE.

In remote areas including overseas Territories, Antarctica, UK Highlands and Islands and remote UK coastal areas, the use of UASs can be more pragmatically managed locally by stakeholders, this has allowed an easier route to fly UASs for science data collection. These areas therefore have become more accessible for BVLOS UAS flying and have seen several BVLOS flights. It remains hard or impossible to fly BVLOS in more densely populated areas of the UK, so the benefits of BVLOS to science and operations have yet to be fully exploited in these geographies.

The potential (in)ability for UK registered UAS pilots to fly in different countries and to operate a UAS registered in the UK in another country, is another regulatory hurdle that requires significant consideration when planning overseas campaigns and data collection efforts.

4.2.2. Where We Want to Be

Environmental science would benefit if **small quad/multirotor and fixed wing UASs** were to:

- be considered as standard tools for delivering science and be accessible to all, either through ownership with required training, bought-in service or provided from a facility
- be available via several NERC Centres and Collaborating Institutes, ideally as a complete service (including pilot) for those who cannot justify purchase or do not have the required trained staff to pilot UAS - but not excluding independent capability within NERC Centres and Collaborating Institutes where required; this is partially already in place in several centres (for example NCEO via FSF, specialising in EO)
- have longer flight endurance (currently limited to approximately 60-90 mins)
- be able to carry larger payloads or payloads capable of delivering data of the necessarily high scientific quality, which requires significant calibration and validation work; the potential to carry multiple different instruments simultaneously, or perhaps in a "swarm" of multiple UASs, should also be considered as a requirement
- be available from resilient sources: Ensure that UAS capability is in line with UKRI's Trusted Research and Innovation and encourage UK development of future-proof platforms for science, incl copters (through EPSRC, Innovate UK and industry activity)
- be modular and repairable (with straight-forward re-certification pathways) and partially or completely recyclable in the future to reduce environmental impact; small UAS models are continuously being updated and replaced, sometimes with unnecessary sensor obsolescence due to manufacturers not supporting previous sensors on new platform models, which currently creates waste that is not easy to recycle

Current VLOS flying has proven the capability for data collection; to deliver further benefit to science and Net Zero savings, BVLOS flights are needed. We require greater use of **small BVLOS UASs** to:

- replace, where appropriate, tasks currently delivered by vessels, crewed aircraft or persons on the ground
- safely fly at low altitudes (down to 20m above sea level, or even 5m with terrain-following technology)

To fulfil the potential of **large complex BVLOS UASs**, we need them to be:

- available via a service provider or NERC-owned with employed professional pilots, as flying large complicated UAS requires dedicated pilots
- capable of vertical take-off and landing (VTOL); this will enable certain science activities as well as operations from vessels, de-skilling automated take-off and landing, operation from rocky shorelines, forest clearances and so on
- capable of carrying higher sensor payloads (>> 10kg) over longer ranges (> 1000km)
- equipped with sense-and-avoid technology and accurate digital elevation models (DEM) to allow low level flying (down to 5m with terrain following)
- integrated into the airspace in the flight theatre (see also section 4.1 on regulation and Table 4.3)
- equipped with anti- or de-icing technology

Appropriately sized and configured UAS platforms have the potential to make significant (circa 70%) fuel savings in some science mission profiles if employed wisely. On the other hand, in high payload mission profiles (100skg+), current **crewed aircraft** may be up to twice as fuel efficient as current UAS options and can complete missions faster, which is significant in short favourable weather windows. In all cases, it will be necessary to properly understand and account for the logistics overhead of deploying and operating UASs to remote locations. The most credible operating models for airborne activity for example in Antarctica necessitate a well-considered synergy between UASs and crewed aviation to achieve the desired science and environmental benefits. The UAS situation is nuanced but has great potential. At this point accurate and balanced analysis is vital to inform strategy.

Where appropriate, **satellite data** should be used where possible as this means no need to transport staff or equipment.[3] However, it is appreciated that satellites are in fixed orbits and with fixed levels of spatial detail - so cannot provide all the imaging and remote sensing capabilities of crewed aircraft or UASs (equally UASs and crewed aircraft would struggle to provide some capabilities delivered by satellite - for example repeatability, year-round operation in polar regions). On the other hand, their datasets are generally of far higher quality in terms of known uncertainties, biases and performance. Generally speaking, the benefits of satellites are most obvious for large-scale, systematic observations of the highest scientific quality. To achieve this, associated rigorous calibration/validation campaigns are needed that will inevitably require ground and airborne measurements.

To achieve these aims, **collaboration** is essential:

- with industry, to allow access to UASs and novel sensor technology
- between research centres and disciplines, to access a wide range of sensors, UASs and knowledge
- with CAA through regular and productive communication, to obtain permissions to fly in a timely manner and help enabling regulation to be developed

4.2.3. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

Table 4.3 below provides an overview of the barriers, challenges, solutions and opportunities regarding platforms.

[3] We appreciate that satellite data also has a carbon footprint, and further work is needed fully to understand and weigh the relative sustainability benefits of satellite-based research. This is outside the scope of this report.

Table 4.3: *Overview of the barriers, challenges, solutions and opportunities regarding platforms*

Barriers/Challenges	Solutions/Opportunities
Flight time is limited by battery life on small UASs; whilst larger capacity batteries are available, these pose a barrier to working overseas due to restrictions of carriage on commercial airlines	Most small UASs have a limited battery size of 99Wh due to safety regulations for batteries over 100Wh, restricting their flight time. Carriage of larger batteries on commercial flights is possible, but only in consultation with the specific airlines, therefore a simple (maintained) directory of airline operator battery restrictions would be of benefit. Battery technology is continuously advancing, requiring regular repurchasing of UASs to achieve better flight times. Retiring old platforms ensures UAS safety and avoids spare parts obsolescence, but also adds to waste. However, as battery energy density improves, shipping these UASs becomes more challenging. For localized VLOS with extended flight time, power tethers such as Elistair's or DJI Docks for automated 24/7 flying can be considered with proper permissions. Where transporting larger capacity batteries pose issues for commercial airlines, in some geographies purchasing or hiring these batteries in the country of use may be possible, however each country will have its own set of restrictions on availability.
Flight time on larger BVLOS UASs	Longer flight times require a larger UAS capable of carrying more fuel. Potentially solar UASs can be used but these currently have very small payload capabilities. Potentially hydrogen is a viable fuel (via fuel cells running electric motors) for gaining enhanced endurance. Energy density (how far you can fly) depends on pressurised canisters and these are evolving.
Larger payload is strongly linked to UAS size	The physics of flight dictates that to carry more payload or fuel for longer flight the UAS will need to be larger or require repeat flights to carry all the required sensors. At this point the efficiency of fully utilising a crewed aircraft is likely to have a lower carbon footprint for this scenario. To achieve larger science payloads on UASs (circa 50kg for systems such as bathymetric laser, high specification terrain mapping cameras, ice penetrating radar, complex air sampling systems, some science grade hyperspectral imagers) a larger platform is required, capable of carrying this plus the required fuel (overall payload of max 50kg would likely only leave <10kg for sensors). Continued miniaturisation of sensors will help and mean potentially small UASs can be used in some cases.
Limitations of miniaturising sensors	Miniaturisation potentially allows for easier integration onto UASs but may compromise key sensor characteristics (resolution, accuracy, sensitivity, stability, range and so on). These may be still as good as older sensors, but not as good as the newer state-of-the-art sensors. It is for science users to decide what sensor characteristics are required, whether miniaturised sensor on a small UAS or full-sized sensor on a large UAS or crewed aircraft meet the requirements. In many cases the sensors simply don't exist for UAS deployment - and they are only available for crewed aircraft where a human operator and sufficient payload, power and duration characteristics are available. For certain applications, (at present squall gusts, wind farm wakes and turbulence measurements) the miniaturisation of the quadcopter platform itself lends the UAV to be a wind sensor: broadly, the avionics records the change in 'effort' of the motors to retain position and attitude.

Power for sensor payload: Power from UASs with batteries is often limited as the batteries have been sized for the UAS only; for UASs with combustion engines the spare power off the alternator could also be similarly limited, the larger the UAS the more potential power for sensors there is	Using smaller low powered sensors helps but this may not meet science requirements. Ultimately power-hungry sensors need to be flown on larger platforms with larger batteries or engines/alternators. If the UAS has payload weight spare, an extra battery could be used to power the instruments.
VTOL on larger BVLOS UAS is key for use on vessels and in areas without runways, though choice of large VTOL BVLOS is limited with only a few manufacturers offering such UASs; HTOL (Hybrid Take Off and Landing) also potentially provides longer duration with VTOL capabilities	Larger BVLOS UASs with VTOL capability are available but often by niche UAS manufacturers, so could be purchased or provided as a service. NERC could influence or collaborate with Innovate UK to incentivise companies to develop platforms.
Maintaining airworthiness	UAS are aircraft and should be serviced and maintained in line with crewed aviation practice. Small quadcopters have simpler and easier maintenance requirements, though sometimes still time consuming, but large BVLOS UASs require an organisation capable of aircraft standard maintenance meaning that this will be either a bought-in service or a specific NERC facility (or facilities).
Reliability (redundancy, robust autopilot) - meeting minimum equipment and build standards required by regulators	UAS reliability is crucial to avoid injury, damage to infrastructure or the environment and reputational damage. As this is an emerging market, caution is needed when selecting UASs and service providers. Advanced UASs with triplex and redundant systems offer higher reliability. Industry standards and certification will eventually weed out unreliable manufacturers, making it easier for users to purchase UASs or UAS services.
Environmental (weather) conditions limiting when UAS can fly	Current UAS flying limitations include IP (Ingress Protection) rating, wind tolerances, temperature ratings and icing conditions. Future UAS designs aim to overcome these limitations to enable operation under a wider spectrum of conditions.
UAS engines and propellers have altitude limitations	If study locations are too elevated for currently available UAS platforms crewed aircraft may need to be chosen.
UK pilot and UK UAS registration limitations	It is the case that in many nations, both the pilot and the UAS need to be registered in that nation to operate - posing a potential barrier to rapid deployment of a UK-based UAS and pilot on an overseas campaign (and much NERC-supported fieldwork occurs overseas). Foreign pilots can be hired as a potential solution to the first issue, or the UK-based pilots undergo registration in the country of interest.
Overseas restriction on deployment of UAS manufactured by specific countries	Some countries restrict the use of UASs and sensors manufactured by specific countries, this may prevent deployment in a desired country or require lengthy regulatory discussions for their approval. A maintained directory of known country requirements/expectations with regards to permitted country of UAS/sensor origin may assist in rationalising overseas deployments.

Inaccurate or low-resolution DEM means low level flying may not be realistic in some areas, also making terrain following impossible	DEM accuracy in the UK is high due to extensive surveying by Ordnance Survey, but other geographies, especially polar regions, often have less accurate or low resolution DEMs. The issue is being addressed through additional surveys or by conducting an initial DEM survey at a safe altitude before the main survey, albeit this doubles the flying time. Terrain following/avoidance systems are being developed to allow real-time low level flying over unknown terrain.
Lack of ownership limits length of deployment; when there is a long shipping period, UAS service providers/owners are not keen to deploy assets and have them inaccessible	Ownership of actual UASs will allow NERC to ship equipment on research vessels for extended periods of time and use in remote international locations. UAS service providers have various models of access, purchase and pilot training, this allows NERC to flex its capability and use the right model to provide the required UAS capability.
Funding for UASs: small quadcopters are now both affordable and advanced, but larger UASs are still expensive	Small quadcopters are affordable for most organisations. However, adequate funding is also needed for staff training and ongoing maintenance to operate UASs safely in-house. Where this is not possible, a UAS loan or service provision from a NERC facility is a good solution. Larger BVLOS UAS are costly and complex to operate. Significant NERC investment is required for both purchasing the UAS and employing pilots or using a UAS service provider. Initial collaborative opportunities exist as the marketplace evolves.
Sensor cost, accuracy and ease of use	Beyond the simplest Red-Green-Blue cameras, many UAS-based remote sensing systems require dedicated and detailed radiometric and spectral calibration activities in order that the data provided can be of the most relevance to science. Whilst instruments like hyperspectral cameras and thermal imaging systems exist for UASs - they are generally either not at all easy to operate, require significant expertise to extract useable data from, or are 'calibrated' by the manufacturer such that the measurement accuracy in use can be quite some way below what would be desirable. Expertise in sensors is just as important - and in some cases more so - as expertise in platforms. It is the sensors that actually are used to provide the dataset that the science will be undertaken with.
Limited commercial availability of large BVLOS UASs	The marketplace is still developing, but there are a few companies emerging that may achieve long term success. Opportunities exist through funding like Innovate UK Future Flight Challenge for science users to collaborate in providing use cases and joining collaborative teams. NERC does not fund UAS development but supports the use of UASs as sensor platforms for collecting science data. However, caution should be exercised when selecting collaborators in the emerging UAS marketplace, as some may have poorly thought-out business models. Access to Ministry of Defense UASs tends to be cost-intensive due to the requirement for large operational teams. The previous use of Global Hawk for the National Science Foundation (NSF) failed due to high deployment costs, as conventional aircraft could achieve more with the same expenditure.
Large complex BVLOS require qualified full time professional pilots	Manufacturers/service providers can provide pilots as a service or train pilots. This would mean NERC would need to either buy in this service or employ staff as pilots.

Airspace integration	Currently, UAS in airspace are managed by segregating them based on time, area, or height. However, in the future, aircraft systems and regulations will allow for airspace integration. Until then, segregation remains the operating model. Large BVLOS UASs equipped with ADSB (Automatic Dependent Surveillance Broadcast) and Mode-S transponders provide electronic visibility to crewed aircraft and other UASs. Future sense and avoid systems, including visual and radar capabilities, will detect, identify and react like a crewed aircraft pilot would. These systems are currently in development and require certification and adoption by regulators, but they will eventually lead to airspace integration. In Antarctica, ADSB-out is mandatory for all BVLOS UASs. There are opportunities for early adoption and testing of these systems in some of the remote areas NERC operates in, as well as proving Concepts of Operations (CONOPs). In the UK a number of commercial groups are exploring BVLOS models for working efficiently within CAA regulation. These groups (and others) are trail-blazing, NERC should make efforts to build partnerships with them at an early stage to develop planning for BVLOS Standard Operating Procedures for NERC science.
Larger BVLOS UASs need to have CAA approval to fly	The manufacturer or service provider (which depends on 'class', i.e. weight) must meet CAA standards and obtain permits for UAS flights (depending on UAS class), which are limited by the CAA in terms of who, what and where they can fly. Professional expertise and CAA approval are required for applicants. As technology and CAA policies develop, more flying opportunities will arise, but adherence to standards is crucial. In Antarctica, with its minimal air traffic and vast airspace, routine BVLOS use may be possible early on. Collaborating with the CAA to establish BVLOS-friendly areas could lead to more opportunities.
Concept of Operations (CONOPS): All flying activities need to have well developed operations procedures and experienced and qualified pilots to deliver the flying	Organisations either need to train staff to acquire both the knowledge and expertise or rely on a service provider for UAS flying.
ITAR (International Traffic in Arms Regulations) and other export/import restrictions: UAS have dual civil and military use so many countries impose restrictions	If no alternatives to ITAR-controlled UASs are available, users may need to absorb the additional administrative burden. Opportunities might be created by working more closely with a UK manufacturer.
UAS platforms need to be available from resilient sources	Ensure that UAS capability is in line with UKRI's Trusted Research and Innovation and encourage UK development of future-proof platforms for science, including quadcopters (through EPSRC, Innovate UK and industry activity). It may be an opportunity to work more closely with manufacturers in the UK. ISARRA (International Society for Atmospheric Research using Remotely piloted Aircraft) 2023 discussed this topic. Previously the Euro/US atmospheric science community used Paparazzi (for example SUMO) but the community now sees ArduPilot, which is open source as the world leader. However, additional due diligence is needed for verification/validation to appropriate aviation standards. Contact between NERC users of ArduPilot (and derivatives) and UK experts in modifying coding would be useful for (a) enhanced large-platform capability and (b) very small UAVs such as gust swarms.

4.2.4. Recommendations for Advancement

To develop the opportunities for enhancing low-carbon environmental science through uncrewed aerial platforms, we make the following three key recommendations:

Ownership

Strategic purchase of small quadcopter and fixed wing VLOS UASs would improve access and use of UASs in an organisation. We stress that this needs to be strategic and preceded by careful review, to assure the capability is not a duplication of what could be accessed in a timely manner from elsewhere, that the platform is useable in the required context (technologically and operationally, including regulation) and has evident advantages over current data collection methods.

Exploration and potential purchase of UAS technology from resilient sources in line with UKRI's Trusted Research and Innovation is recommended and of UAS designs that align with the European Green Deal for industry will reduce waste. Links to strong expertise in aviation, robotics and engineering can open doors for designing platforms. Purchase of larger UASs will allow these to be shipped and utilised at flying locations with long shipping/deployment times so as not to incur high service cost during transit time. This is particularly relevant for Antarctica and Overseas Territories. Current methods and processes need to be reviewed to establish if UASs are an effective replacement for existing higher-carbon methods of data collection, if so, further assessment should identify whether NERC should own or buy in a service.

UAS facility (or facilities)

It would be beneficial for NERC to fund a UAS facility (comprising equipment, staff and ongoing activities); this could be spread across several organisations and should provide:

- smaller UASs for loan, including option to include a pilot
- larger future BVLOS UASs and pilots to deliver flying
- access to test areas and facilities to test UASs fully prior to deployment
- expert single point of contact between NERC and CAA to streamline approval of UAS operations in UK airspace.

The NERC Field Spectroscopy Facility (FSF) already provides a UAS remote sensing service to the UK environmental science community, including platforms, sensors and operators and can provide advice on certain of the issues faced from their *ca*. five years of experience performing this service. Larger, more complex BVLOS UASs are closer to piloted aircraft and will need to be managed in a similar way as BAS or FAAM aircraft, either by a service provider, or by adding to current specialist aviation departments where they exist, or by creating a dedicated specialist team.

Collaboration

Shared UAS (and sensor) registers should be created to enable all NERC organisations using UASs to share their knowledge and indicate what UASs can be loaned or provided as a collaborative service to others. Collaboration and shared knowledge between groups using UASs will help speed up adoption, as the most effective platform can be identified from the experience of others. Collaboration will also maximise access to UASs and prevent platforms being stored for sole use thus maximising return from NERC's investment. This collaborative knowledge-sharing needs to extend beyond the NERC family, to accelerate transition to low-carbon ways of working by sharing experience of what works and what doesn't.

Industry collaboration in the short term can provide beneficial access to UASs. This is realistic while the commercial UAS marketplace continues to mature and various funding mechanisms are available, such as Innovate UK's Future Flight Challenge. Providing requirements and use case examples to industrial collaborators may lead to development of more suitable future platforms for science sensors and would build longer-term relationships.

Due to the importance of regulation in aviation, it is essential to engage with CAA to help make UAS policy and regulation suitable for scientific use.

4.3. Technology - Sensor Integration

Sensor – platform integration is a key part of collecting environmental data using UASs. We consider three key aspects of sensor integration most relevant to remote sensing/earth observation: mechanical and power; positional; and sensor triggering.

Each influences the ease with which a platform/sensor combination can be deployed. There are many solutions to these integration issues, which are used both in traditional airborne surveys and in the emerging area of environmental UASs. Here we provide a high-level review of these key aspects of sensor integration which should be considered when designing/specifying integrated UAS sensor systems.

When considering *in situ* measurements from UASs, such as atmospheric sampling or electric field measurements, the aircraft itself becomes an active part of the sensor and airflow (or airframe conductivity) can modify the exposure and thereby the behaviour of the sensor. This is an active research topic in itself, bridging environmental sciences with fluid dynamics engineering and leads to highly integrated airframe sensor designs. However, the details are beyond the scope of this report and we list below topics that focus on the more familiar needs of integrating remote sensors on aerial vehicles.

4.3.1. Mechanical Fit and Power

Mechanical and power considerations are largely defined by the platform as discussed in the previous section. However, it is recognised that, especially for larger platforms, which may carry multiple distinct payloads at different times, simple mechanical interfaces, such as a single standard mounting plate, or payload bay with easily accessible mounting points, are an advantage. In some cases, sensors require a more complex mechanical fit to make measurements outside the immediate environment impacted by the UAS. This requires the fitting of booms, or carrying sensors tethered below platforms, which adds complexity to both UAS design and operation, but is possible. In a similar manner to providing a standard mounting interface, provision of power to the sensor via a robust and simple connector interface (with multiple voltages available) is desirable. For the largest UASs, where flying multiple sensors together is an option, self-contained pods, or easily removable payload floors which can be pre-populated with sensors and tested, enable sensor development distinct from both the UAS and the rapid change of role in the field. In such cases a separate power conditioning/distribution system for the instrumentation taking a single feed from the UAS may be considered a worth-while option.

4.3.2. Integrating Position

Positional information is key to both flying the UAS and georeferencing the collected data. As such, it is a key part of any UAS/sensor system. Two methods are available: (i) using a user's fusion of external navigational data such as a feed of satellite (GNSS), altitude (pressure) and ground control points and (ii) using the data from the internal Ekman Kalman Filter (EKF), a mathematical method of data fusion used by all aircraft avionics to estimate its position (x, y and z) and attitude (roll, yaw and pitch). Even in manual control of a 'copter-style' aircraft, it is the avionics that are controlling the platform at sub-second intervals and centimetre accuracy and precision. To do this, the avionics uses EKF software to perform the data fusion of multiple on-board accelerometers, gyroscopes, compasses and GNSS. The results (position, attitude) are logged and can then be available to the user post hoc to derive sensor position and attitude. Fusion with sensor data is usually via an accurate clock feed in the sensor package.

External positional information comes from GNSS satellite data, potentially augmented with local real-time kinematic positioning (RTK) base stations. This positional data can be provided to the sensor for recording via a feed from the UAS, often using the NMEA (National Marine Electronics Association) data format, which is a simple ASCII (American Standard Code for Information Interchange) string provided to a serial port. Positional information from the UAS can be further improved by integrating attitude and acceleration information using extended Kalman filtering techniques, which gives precise location information accurate to ~2cm and is often logged at a rate of ~40 Hz. Alternatively the recorded position of the UAS can be merged with the sensor data after a mission using a timestamp, assuming the sensor has an internal clock with sufficient precision. Both these methods are limited to the quality of the real time UAS positional information, often quoted to be ~5m or a good time synchronisation between the UAS and sensor. In addition, taking the UAS positional information does not permit post mission re-processing of the GNSS data, required to obtain the highest quality positional information. To by-pass these limitations, it is becoming more and more common for each sensor to have its own internal GNSS receiver and if required, its own raw GNSS data logging system. In this case an independent GNSS antenna with a clear view of the sky, or a feed from the UAS GNSS antenna is required. For the highest precision studies, for example LiDAR scanning, a full inertial navigation system (INS) will be required and lever arms between sensors, mounted GNSS antennas and INS should be recorded in meta-data files to facilitate post processing.

4.3.3. Triggering the Sensors

The final term in sensor integration is triggering, that is to say turning on/off sensors only at specific times, or carrying out actions such as deploying a payload. There are many reasons that triggering is required. Some sensors, such as high-powered LiDARs or radar systems, can be hazardous if operated very close to people. Other sensors may be collecting sensitive information such as imagery where privacy of people outside the environmental target area is a consideration. Some systems, such as hyperspectral sensors, collect huge volumes of data, meaning data collection on the transit to/from a study area is inefficient and may exceed memory limitations of the sensor. Two types of triggering methods can be used. Either a waypoint-based trigger, or a geofence trigger. In the case of a waypoint trigger this is typically associated with the UAS navigation/mission planning system. As the platform reaches a specific trigger waypoint (or comes within a pre-determined distance) a signal is sent to switch on/off data collection with the appropriate sensor, which is typically set in a stand-by mode prior to the flight. The advantage with this method is that sensor operation can be tightly controlled, but a distinct trigger interface with the UAS must be maintained. Where the geofence method is used, the sensor switches on every time it enters a specific geographic area. This method works well where the sensor has its own on-board GNSS system, as it removes the need for an external trigger/UAS interface. However, it has some limitations, for example, when overflight of the take-off area is required. Use of altitude to geofence an operational volume of space, rather than a 2D area can solve this issue, but it requires creation of a more complex 3D geofence geometry.

4.3.4. Where We Want to Be

The ultimate goal is that the sensor(s) for a desired survey can be quickly (within ~15 minutes) mounted on a UAS platform with an appropriate payload and range and high-quality data collected. This installation process should be fool-proof, allowing non-expert/minimally trained science users to do this. For some applications integrated sensor-platform packages, such as the eBee, may be a better solution. However, for more advanced and novel sensor systems, sensor/platform integration will remain a challenge to consider.

4.3.5. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

There is currently no standard procedure for interfacing sensors and UAS platforms. One solution to this issue would be to maintain a library of CAD models of mechanical fit, along with system specifications (power, GNSS or trigger availability), in a library of NERC provided UAS platforms/sensors. Such a library would allow rapid and simple consideration of sensor-UAS integration early in the project planning phase and facilitate engineering solutions to enable the ultimate goal of installation by a non-specialist. Engineering solutions to UAS-sensor interface problems should be logged and recorded allowing for repeated use by future projects.

Another factor is that where more complex mechanical fit requires modification of a UAS airframe, there is no standard procedure for testing/certifying the fit. Working with the CAA to create a designated civilian/research UAS testing range[4] and procedures for certifying platform modifications, without re-certifying the entire platform, would be advantageous.

4.3.6. Recommendations for Advancement

We recommend development of a facility to maintain records of all available NERC UAS platforms/sensors and the methods of integration. This should include a library of CAD models of sensor/platform interfaces. Where UAS platforms or sensors are purchased for specific projects, we suggest that there should be an expectation that, in consultation with the facility management, they are placed on the NERC register for wider use at the end of the project. Platforms/sensors placed on the register should be considered as part of the NERC facility and funding to operate and maintain them for future projects should be covered by the facility. Such a facility could be based across multiple centres, but a central hub to share knowledge of sensor/platform integration will be required.

We suggest that associated with the facility an area of dedicated airspace for UAS testing should be developed to facilitate testing and certification of UAS modification, as well as testing and calibration of sensors. To facilitate testing of sensors the test area, or areas, must be well characterised in terms of all potential observable parameters and be of a reasonable scale to allow testing. This would for example include detailed ground based magnetic and EM surveys to determine sub-surface structures, hyperspectral characterisation of the surface properties and a detailed LiDAR model of the topography, as well as masts to provide base-line physical and chemical observations of the atmosphere. Such areas could be new, or built on existing calibration facilities.

Maintaining expertise and knowledge within the NERC facility on platform certification for novel sensors will be a key advantage for UK researchers going forward. It is important to note that the NERC Field Spectroscopy Facility (FSF) already provide a UAS capability as part of their NERC Service and Facilities remit, giving access to UK environmental science to UAS platforms, sensors and operators (including pilots) as well as expertise in data processing and instrument spectral and radiometric calibration. However, this service is focused not on platform integration or sensor prototyping, but on use of commercial off-the-shelf (COTS) hardware and the deployment of smaller VLOS systems for remote sensing missions in support of NERC and wider UK environmental science - albeit with sensor calibration done to a standard far exceeding that mostly conducted elsewhere.

---

[4] or with commercial providers who already have their own testing ranges, for example BLUE BEAR SYSTEMS in Bedfordshire

4.4. Technology - Discipline-specific Sensors

UK environmental scientists strive to gather the most appropriate, accurate and relevant data from the suitable sensors on reliable and quantifiable platforms in order to conduct their scientific studies. Whilst the range of combinations of airborne scientific sensors and platforms may be vast, there are relatively few sensors that can be deployed on reliable UAS platforms for accurate environmental science measurement. The developing nature of UASs as a method through which to conduct environmental science gives UKRI an opportunity to lead and push innovation to advance UAS sensor development and for their integration on platforms to become a routine method for UK environmental scientists to address their scientific study.

Whilst previous sections have provided detail on UAS platforms (section 4.2) and sensor integration (section 4.3), this section focuses on the sensors that are of greatest importance in environmental science. Detail is structured by the individual environmental science disciplines, providing an overview of each discipline and outlining the sensors that are currently available to help UK environmental scientists to gather the most appropriate data for their discipline. Each discipline also outlines a vision of what needs to happen to advance the uptake of UAS technologies within their science. This is coupled with a gap analysis on the barriers and challenges that each discipline currently faces together with potential solutions and opportunities in order to reduce or remove these barriers and challenges. The final section for each discipline provides recommendations to UKRI and the scientific community to drive forward the uptake of UASs within UK environmental science as part of the UKRI aim to achieve Net Zero.

4.4.1. Atmospheric Science

4.4.1.1. Introduction to Atmospheric Science

Atmospheric Science is the study of weather analysis and predictability, climate and global change, the circulation of the atmosphere relating to weather systems and their impact on the Earth, air quality and other atmospheric processes that affect us. Discovery and understanding in Atmospheric Science is critical to our resiliency and preparedness - so that we may meet the most pressing challenges of our atmosphere-dependent systems.

The main branches of Atmospheric Science are:

- Meteorology and Atmospheric Dynamics involves the study of air motions that lead to thunderstorms, frontal systems, hurricanes and tornadoes
- Micrometeorology is the study of the atmosphere of near-surface atmospheric phenomena and processes at spatial scales less than 3km and time scales of 1h or less
- Atmospheric Physics applies principles of physics to study atmospheric processes such as cloud formation, light scattering and energy transfer
- Atmospheric Chemistry applies principles of chemistry to study atmospheric processes such as air pollution, ozone depletion and aerosol formation
- Climate Science studies changes in the statistics of weather from seasons to millennia and longer, addressing phenomena such as El Niño, global warming and the ice ages

In addition to the scientific drive for the fundamental understanding of the processes occurring in our atmosphere there is a regulatory aspect to this area:

- Enabling informed decision-making in setting emission targets and air quality standards
- Monitoring compliance with targets and standards
- Monitoring the impact of climate mitigation measures

In all areas, there is a pull-through of the observations to modelling activities. With the public interest in atmospheric science, driven by the air quality and climate change conversations, there is a focus on understanding the biases in data and transparent data processing workflows - be the data observational or arising from modelling.

4.4.1.2. Current State of Affairs

The wider science community (the science community outside of NERC Centres and Collaborating Institutes that are eligible to apply for UKRI funding) has access to a range of crewed aircraft platforms. In the UK BAS offers access to their instrumented Twin Otter. The MASIN-equipped Twin Otter can carry 500kg of payload (including 2 operators) on approximately 5 hrs missions: combined duration and payload capability is considerably more than that any current UAS can provide, while NCAS manages the FAAM Airborne Laboratory: world-leading and cutting-edge capability that supports science on the world stage. Further afield UK scientists have also been involved in projects that make use of the crewed aircraft platforms offered by NCAR at NASA, University of Wyoming, DLR at Météo France/CNRS and NORCE, Norway.

There is no comparable UAS facility accessible to UK scientists. The use of UASs in UK research is often elitist and insular. It lacks collegiality and leadership and part of this fragmentation is due to the lack of UK travel and subsistence funding for emerging atmospheric science UAS teams to attend international meetings. EGU (European Geosciences Union) and ISARRA are key meeting points for atmospheric science UAS researchers and practitioners.

Activities are occurring but these are based within the UK Met Office (UKMO), NERC Research Centres and Collaborating Institutes, University groups or in collaboration with commercial organisations offering services. They comprise:

- UKMO: the UK Met Office are making use of UAS-based observations for operational purposes but are becoming increasingly interested in developing the capability to address research needs in areas including fundamental atmospheric science, air quality and GHG (greenhouse gas) monitoring, volcanic emissions (gas and ash) and satellite remote sensing calibration and validation. They are also actively looking for collaboration in sensor and analysis development.
- NERC Research Centres and Collaborating Institutes: Details of these activities have already been provided in chapter 2.
- University groups: The examples provided are not comprehensive
  - University of Manchester: Greenhouse gas sampling and flux quantification methods
  - University of Reading: Atmospheric Electricity, cloud particles and precipitation
  - University of Hertfordshire: The Unmanned Systems Research Laboratory (USRL): A New Facility for UAV-Based Atmospheric Observations
  - University of Highlands and Islands, Thurso: CO_2 fluxes
  - University of East Anglia: Greenhouse gas observations using UASs as part of the UK GEMMA project
  - There is much activity in University groups around platform engineering and operation, but not so much in the application of technologies to atmospheric science itself
- Collaboration with commercial partners:
  - Collaborative opportunities are being developed with FalconWorks: Arising from their work around the FAAM mid-life upgrade project, FalconWorks are keen to engage with the scientific community in the development and integration of sensors and in the development of platforms - they have developed a solar powered platform: the PHASA-35 high altitude pseudo satellite platform that is capable of carrying a modest payload; they are reaching out to the science community to help develop the nature of this payload

  - NCAS collaboration with third-party developers and providers: monitoring of emissions from North Sea oil platforms, training the next generation of atmospheric scientists
  - WesCon project & Menapia: boundary layer profiling (PTU, winds)
  - SAMS collaboration with local authorities in the development of operational "airport" capability
  - Environment Agency & National Physical Laboratory: GHG Emissions
- Specific sensors currently in use:
  - Aeries technologies MIRA Stratos LDS: Laser absorption spectrometer for GHG detection; 2kg with battery
  - Sniffer 4D: Wide range SO_2, high resolution SO_2; 0.3kg
  - Sniffer 4D: Wide range H_2S, wide range C_xH_y/CH_4/LEL; 0.3kg
  - Alphasense: OPC series 30 - 100 g depending on model
  - Wind Speed: Range of approaches taken including, five and seven hole probes, hot wire/film sensors, sonic anemometer, GPS & dGPS, triangulation from platform rotors
  - PTU sensors: Emphasis on stability and housing to eliminate dynamic and radiative effects
  - ABB Hoverguard carbon dioxide and methane analyser

4.4.1.3. Where We Want to Be

The UK is a world leader in all areas of atmospheric science and to remain in that position it needs to be able to utilise all the tools available for new and routine observations. Development of sensors and platform capability needs to address end data user needs - there is no point in investing in capability if at the end of the day, the data produced is not used. There needs to be pull-through of observations to modelling and impact. This is true for all observations but for UAS-based observations of atmospheric parameters there is substantial work to be done around building the "trust" in the final product: that is understanding and quantifying data uncertainty, demonstrating that integrated sensors are neither biased by or adversely impacting the airflow around the platform, ensuring transparency of deployment and analysis process and providing a data product in a standard documented format preferably with software tools for both users and providers.

Where possible we should be aiming to collaborate with external service providers, but the emphasis has to be again on the data quality and transparency of all processes. For this engagement to result in the uptake of data by the modelling community there has to be trust in that data and openness as to how it is derived.

We want all UK scientists to have equal access to UAS platforms, integrated sensor technologies, sensor and platform development support, operational support and training. We want to aim for a landscape where researchers are in a position to make informed decisions as to the most appropriate platform (UAS, crewed aircraft, ground observations, satellite observations) or combination that provides the innovative environment that allows them to address their particular research question, with the lowest possible carbon footprint.

4.4.1.4. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

A great deal of skill in atmospheric science (measurement, modelling and interpretation) exists within the community, the community being not just the scientists based in NERC Centres and Collaborating Institutes, but also in the wider UK and international groups with which we work. These people are experts in their field but lack the experience and skills necessary to adopt and develop the UAS technologies required for their particular application.

The lack of comprehensive, easily accessible support that encourages instrument development (new and miniaturisation of current capability), platform development and integration alongside a fragmented methodology for dealing with all aspects of the resulting data (from QA (Quality Assurance) and QC (Quality Control) to archiving and visualisation) represent a significant barrier to the uptake of UAS-based activities. With community access to well-supported crewed aircraft platforms that provide the full project lifecycle support, there is no driving incentive to invest time and resources in UAS-based observations - this is a competitive field and PIs balance the risk of investing in innovation (UAS platforms) that might not deliver against crewed platforms that have a track record of delivery but are less innovative.

Barriers and challenges include:

- Funding for capital but not for the resource to operate - this may lead to loss of expertise as the resource is lost or moved to other activities
- No access to CFD capability to ensure correct placement of instrumentation
- The lack of capability for eddy covariance based flux measurement - fast wind measurements decoupled from platform motion
- No calibration, deployment, or operational best practice agreement within the community
- No standard data output format around which new software tools can be developed (for both user and provider)
- Requirement of expert knowledge and skill needed to make use of UAS capability
- Sensors do not exist for use on UAS for many areas of interest
- Skill base tends to be in the science the observation supports rather than in the development of platforms/platform integration
- No provision for autonomous routine observations - 'drone-in-a-box' capability (i.e. UASs that deploy from and return to self-contained landing boxes where charging and data retrieval can occur without operator input)
- No auditable trail of sensor/platform combinations, sensor calibration and performance

Solutions and opportunities include:

- New techniques combining the capabilities delivered by UAS and crewed platforms
- "Swarm" technologies
- Linking the scientists with the platform- and sensor-developers - a continuous cycle of development: platform and sensor engineers respond to the challenges the scientists come along with - scientists respond to the new capability provided
- Greater collaboration between engineering and science: platform and sensor development is driven by science challenging current capability, but equally to challenge the current capability scientists need to know what that capability is
- Community leadership provision - community development of best practise leading to greater "trust" in data (a key theme in UKRI Digital Infrastructure Strategy)
- Provision of training
- Development of software for users - reducing the need for expert knowledge to visualise UAS-derived data and that from models, satellites, ground-based observations
- This should not be about the activities in the Centre but about using Centre-based activities to demonstrate what can be achieved to the community and engaging with the community over how we can get them to use the capability - is there a wider community need for a UAS Laboratory - as for FAAM but using UASs - or just access to knowledge and technical support?

4.4.1.5. Recommendations for Advancement

UAS usage has great deal to offer in Atmospheric Science but to advance uptake access to both the physical capability and a reliable data product need to addressed. There is need for the centres to show community leadership and to do this by example. It is recommended that the following steps be taken by and with the community and funding stakeholders:

- Provide access to a capability that can be readily configured to meet a user's needs. A capability which a user need only "know" what it is they want to measure and one that delivers a trusted data product.
- Develop the capability to model airflow around platforms – enabling optimal sensor placement and a key step in understanding measurement bias,
- Develop collaboration with aerospace facilities to test model results in a controlled environment.
- Development of field calibration capability. Understanding, mitigating and quantising measurement bias through the comparison of the integrated system against characterised static instrumentation.
- Develop the relationship between scientists and engineers – development and innovation driven be challenges set and opportunities opened.
- Develop Persistent Identifiers (PIDS) for platform and sensors and schema for combining - enhances traceability of measurements and eases archiving.
- Identify and focus on several key activity areas - develop UAS capability in those areas and be proactive in demonstrating capability to the wider community.
- Engage with the community to demonstrate new capability and what it would take to get them to use it.
- Develop and implement a common data & metadata format
- Develop and implement standard operating procedures suitable for Atmospheric sampling.
- Develop software tools for visualisation and multisource (data stream) comparison.
- Develop software tools to aid providers in the delivery of a data product.

4.4.2. Ecology and Biodiversity

4.4.2.1. Introduction to Ecology and Biodiversity

Biodiversity is part of the evolutionary, ecological and cultural processes that sustain life. For those engaged in biodiversity-related sciences—such as population biology, ecology, systematics, evolution and genetics—biodiversity refers to "the variety and variability of biological organisms" on Earth.

Ecology is the study of the relationships among living organisms, including humans and their physical environment. Ecology considers organisms at the individual, population, community, ecosystem and biosphere level.

Among other things, ecology is the study of abundance, biomass and distribution of organisms in the context of the environment; life processes, interactions and adaptations; movement of materials and energy through living communities; successional development of ecosystems; cooperation, competition and predation within and between species; and patterns of biodiversity and its effect on ecosystem processes.

Ecology has practical applications in conservation biology, wetland management, natural resource management, urban planning, community health, economics, basic and applied science and human social interaction.

4.4.2.2. Current State of Affairs

Traditionally, ecology- and biodiversity-related observations have been measured operationally through labour intensive field surveying, limiting sample sizes and revisit frequencies. This has limited our ability to capture large scale patterns and changes and understand the processes behind these patterns or changes. Combining satellite remote sensing (RS) with citizen science observations and modelling has worked successfully to study landscape scale processes; however for many organisms and processes the spatial detail or temporal frequency of the RS and citizen science data does not suffice and traditional surveying still plays an important part in many studies. The community has started to use fixed camera or camera-on-UAS remote sensing (RGN, NIR or thermal) combined with AI to for example, survey animal population densities and monitor animal movement through the landscape, quantify floral resources or fruit densities in a landscape to evaluate forage potential for pollinators, birds and small mammals. The use of point clouds derived through structure from motion (from camera-on-UAS) or LiDAR-on-UAS to measure woody vegetation structure is still limited to ecologists collaborating with expert RS groups (i.e. use of UASs in UK research is elitist and insular). Similarly, using UAS RS to study plant photosynthesis, stress and phenology relies on correctly calibrated spectral observations which require more expensive UAS-sensor setups and RS expertise.

There are no recommended standardised protocols for flying and collecting UAS data, limiting opportunities for data sharing and re-use.

Ecology-relevant sensors currently in use:

- RGB for context, mapping cover, feature, plant community, plant diversity, individual plants and animals; also for point cloud modelling (Structure-from-Motion) for topography, woody cover, structure and biomass
  - GoPro (Phantom-2), Zenmuse X5S (Inspire-1 RAW)
  - UAS-integrated (Phantom-3)
- RGB and NIR for same as above but also for vegetation chemical traits, stresses and phenology, water quality
  - Multispectral (NDVI): AgEagle MicaSense RedEdge-MX (DJI Inspire-2, M100, M200, M600 series), AgEagle MicaSense-MX Blue, Phantom-4 Multispectral, Parrot Sequoia
  - Integrated with RGB and TIR: AgEagle MicaSense Altum-PT (potential @ 460g)
  - Hyperspectral: Headwall Micro-Hyperspec Extended VNIR (potential @ 0.9kg)
- SWIR (0.9-2.5 µm) for soil moisture and plant chemical traits
  - Hyperspectral: Headwall Micro-Hyperspec (potential @ 1.6kg), SPECIM FX17 (potential @ 1.7kg)
- TIR (7.5-13.5 µm) for thermal mapping of animals, locating surface hotspots, water presence in streams, estimating surface temperature
  - Broadband mounted: Zenmuse XT (DJI Inspire-1 RAW), FLIR Tau2 (DJI Inspire-2 and DJI M200 series), Zenmuse H20N (DJI M300 RTK)
  - Broadband inbuilt: DJI Mavic-2 Enterprise Advanced, DJI Mavic-3
  - Integrated with RGB: Zenmuse XT2 as FLIR Tau2 with RGB (DJI Inspire-2 and DJI M200 series), FLIR Hadron 640R (potential @ 56 g but ±5°C accuracy)
- LiDAR for high detailed topographic modelling and (woody) vegetation vertical structure
  - Zenmuse L1 (DJI M300 RTK)
  - DJI M600 Pro LiDAR quadcopter
  - others in existence Draganflyer Commander; Riegl RiCopter LiDAR UAV, Harris H4 Hybrid HE UAV, VulcanUAV Harrier Industrial, VelosUAV helicopter, Robota Eclipse fixed wing UAS, DJI Matrice 200 Series quadcopter, OnyxStar Xena UAS LiDAR, OnyxStar Fox-C8 HD quadcopter, GeoDrone X4L LiDAR quadcopter, Tron F9 VTOL fixed wing LiDAR, Boreal long range fixed wing UAS, Vapor 55 UAV helicopter

4.4.2.3. Where We Want to Be

We want scientists to have equal access to UAS-sensor platforms.

Routine use of affordable sensor-on-UAS setups, uniquely providing very fine spatial detail and complementing (or replacing) traditional field surveying would reduce time spent in the field. This would in turn reduce the field work-related carbon footprint and risk to staff. Easy and fast deployment of small UASs would enable more frequent and widespread surveying of plants and animals, allowing scientists to study large-scale biodiversity and habitat changes and the underlying processes. It would also facilitate scalable monitoring for, for example, nature restoration, rewilding and environmental impact studies.

Artificial Intelligence (AI) is helping scientists to collect and interpret large data volumes that are not possible using traditional methods alone. The combined use of UASs with AI will be essential for upscaling UAS-based surveying. But also, to democratise sensor-on-UAS usage, scientists would need to (i) have access to easy to install (by non-experts) sensors and (ii) be able to use and adapt UAS data processing pipelines that enable UAS data pre-processing, labelling for AI and running of AI algorithms. This would also open up citizen science opportunities: amateur UAS pilots could contribute to wide scale vegetation and biodiversity surveying and monitoring.

For studies that require well-calibrated observations for multi-temporal, multi-sensor sensing or from specialised sensors (for example, hyperspectral with inclusion of shortwave spectrum, narrow fluorescence bands, thermal, LiDAR), scientists would need to have access to suitable UAS-sensor setups and standardised protocols and receive support from experts during data collection and pre-processing. Specifically for multi- and hyper-spectral observations, an ability to reliably derive reflectance from observations taken in changing illumination conditions would transform multi-site and multi-temporal spectral surveying.

A UAS data repository, enabling easy data discovery and access, would facilitate UAS data re-use.

4.4.2.4. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

Barriers and challenges in this area include:

- a lack of expertise to access, edit and run available non-proprietary software designed to pre-process and label imagery and apply AI algorithms (i.e., no provision of user-friendly software pipeline to enable processing of UAS collected imagery)
- a lack of calibration, deployment, operational best practice agreement within community
- funding for capital but not to operate, maintain and update UASs and sensors
- limited access to UAS pilots
- the requirement of expert knowledge and skill needed to make use of UAS capability
- that the skill base tends to be in the science the observation supports rather than in the development of platforms or software
- a lack of provision of autonomous routine observations – 'drone-in-a-box'
- a lack of community data repository with auditable trail of sensor/platform combinations, sensor calibration and performance
- the transportation of batteries for overseas work: quota per person on flight is limited; couriers are extremely costly; inability to hire equivalent overseas
- transporting equipment outside of the UK (import - VAT documentation)
- transporting larger UASs to location when access is difficult (mountain, wetland, tropical forest)
- limited battery flight-time reducing survey time

Opportunities and solutions include:

- renting UAS equipment in the country where field work is taking place (only possible for affordable more standard sensor-on-UAS setups); collaboration with local UAS teams
- developing standard procedure for interfacing sensors and UAS platforms to enable for example, use of rented UAS platforms
- collaborating with academics and engineers focusing on precision farming and crop phenomics (BBSRC) as there is a lot of overlap with respect to UAS sensor and AI development
- linking up with iNaturalist and similar citizen science initiatives that have already developed AI for image-based recognition from handheld cameras. This will speed up AI and software development for UAS collected imagery and point cloud data
- incorporating existing open source software and linking up with existing grassroots initiatives: Opendronemap offers free UAS image pre-processing software; OpenAerialmaps is a UAS community driven data repository enabling data to be easily found and shared
- 'drone-in-a-box' (UASs that deploy from and return to self-contained landing 'boxes') which would enable repeat visits of permanent plots for studies that need to capture temporal changes, patterns or trends (for example, phenology)
- community based UAS data processing pipelines that are user friendly and easy to adapt and improve which will democratise and accelerate UAS use

4.4.2.5. Recommendations for Advancement

UAS technology has the potential to transform ecology and biodiversity research by providing new types of information or by scaling up what is currently achievable through field surveying. Effective usage within this research community will be accelerated by:

- ensuring access to the technology (including expert support for more sophisticated platform-sensor setups)
- developing agreed data acquisition protocols
- creating UAS data processing pipelines that are easy to use and adapted by non-coding experts
- providing training

For automated plant and animal recognition, mapping and monitoring, we suggest supporting research in AI (EPSRC) and linking up with UAS-based crop phenomics research (BBSRC).

An easily discoverable and accessible repository of UAS data and AI training data will facilitate re-use.

4.4.3. Geosciences

4.4.3.1. Introduction to Geosciences

Geosciences is the study of landforms through their physical and chemical properties, the processes that have caused their development and changes through time and the understanding of how they may evolve in the future. Geoscience is a complex topic covering a wide range of specialist disciplines (such as those outlined in section 2.4.2.1), the interlinking of which allows us to advance our scientific knowledge of the complexity of geological environments and conduct in-depth assessments towards more sustainable natural resource management, environmental change adaptation and multi-hazard risk, reduction and resilience whilst building towards informing environmental policy and sustainability strategies for the benefit of communities.

4.4.3.2. Current State of Affairs

It is well known that UASs provide relatively low-cost and time-efficient tools for acquiring detailed data in areas that are often inaccessible to 'normal' field investigations. The structural and compositional complexity of the earth's surface and subsurface are well suited to observation from UASs, such as for reconnaissance to better understand new sites and define targeted surveying and to perform scientific surveying of sites using defined and structured flight patterns with specific spectral or radar-based systems to gather detailed surface or subsurface characterisation with the added advantage of repeatability for monitoring of changes. Data collected by the sensors are being integrated into workflows and models and used as a key dataset for machine learning to help address our geoscientific goals.

Geoscience-specific sensors currently in use in BGS geoscience include:

- RGB (400-780 nm) for context, feature mapping and topographic modelling (Structure-from-Motion)
    - Integrated RGB: Phantom-3
    - Mounted RGB: Zenmuse X5S (Inspire-1 RAW), Zenmuse X5 (Inspire-2)
    - Mounted coupled RGB: Zenmuse XT2 (Matrice 210RTK); Zenmuse L1 (Matrice 300)
- NIR (780-14000 nm) for vegetation with spectral properties and stresses as mineral and subsurface proxies
    - Mounted multispectral NIR: AgEagle MicaSense RedEdge-MX (DJI Inspire-2, M210)
- NIR (780-1400 nm) laser for gas monitoring
    - Mounted single-band: Boreal Laser GasFinder2 (CO_2) and Boreal Laser GasFinder2 (CH_4)
- TIR (7500-13500 nm) for geothermal, cooling volcanic terrains, soil moisture, structures, mining (incl. contamination) and silicate mineralisation
    - Mounted single-broadband: Zenmuse XT (DJI Inspire-1 RAW), Zenmuse XT2 (DJI Inspire-2 and DJI M200 series), Zenmuse H20N (DJI M300 RTK)
- LiDAR for high detailed topographic modelling and ground motion (i.e. landslide assessment, inland and coastal surface collapse) and soil moisture
    - Mounted: Zenmuse L1 (DJI M300 RTK)

Importance is also placed on:

- RTK for accuracy in geopositioning
- Ground-based measurement for calibration
- Atmospheric measurement for calibration

4.4.3.3. Where We Want to Be

In many cases, geoscience research would benefit greatly from access to a full suite of *HYPERSPECTRAL OPTICAL* UAS sensors, which can provide highly detailed spectral measurements for specific geoscience aspects across defined spectral regions:

- NIR (780-1400 nm): Currently there are no UAS-borne hyperspectral NIR sensors available within BGS, although through NZArC collaboration we now understand that NERC FSF have such a capability, to conduct geoscience research on vegetation spectral properties related to stresses from mineral and subsurface geology. However, there is potential instrumentation available in the industry suitable for UAS-borne research such as Headwall Micro-Hyperspec Extended VNIR.
- SWIR (1400-3000 nm): Currently there are no UAS-borne hyperspectral SWIR sensors available within BGS, although through NZArC collaboration we now understand that NERC FSF have such a capability, to conduct geoscience research on alteration mineralisation or mineral contamination from mining and their related characteristics such as soil moisture contamination from associated geological

structures. These areas of research are crucial to help provide a fuller understanding of the surface composition, separated through their SWIR characteristics and provide a better understanding of the complexity in their evolution. There is potential instrumentation available in the industry that would be ideal for such studies, such as that from Headwall Micro-Hyperspec or from SPECIM FX17 (900-1700 nm), both of which are light-enough for deployment on sub-25kg UASs (limit before additional CAA regulation is required).

- MIR (3000-5000 nm): Currently there are no UAS-borne hyperspectral MIR sensors available to BGS to conduct geoscience research in high temperature volcanic fields on aspects such as lava heating/cooling rates and lava evolution. However, operation of UASs in high temperature environments is extremely dangerous and potentially UASs are not able to cope with the higher temperatures and potentially corrosive associated volcanic gases so this is not currently sought by the BGS team.
- TIR (7500-13000 nm): Currently there are no UAS-borne hyperspectral TIR sensors available to BGS to conduct geoscience research on surface mineral composition for mineral resource management and for understanding crustal evolution. There is potential instrumentation available for such studies, such as that from Teledyne FLIR, although this is currently more suitable for much larger platforms due to the larger and heavier instrumentation required by the increased internal coolant for the sensor.
- Gamma-ray radiometry: Currently there are no UAS-borne gamma-ray spectrometers available to BGS to conduct science research on measurement of potassium, uranium, thorium or a range of other man-made radionuclides in mineral exploration or for monitoring mine tailings ponds. Potential instrumentation is available in the industry such as Terraplus D230A (<5.2kg depending on configuration).
- LiDAR: Currently there are no UAS-borne bathymetric LiDAR sensors (green-LiDAR) available to BGS to conduct geoscience research in deep fluvial channels, inland water bodies or in shallow coastal areas. These measurements can provide valuable information on both physical structures (landslides, faults and so on) and potential sediment or bedrock changes on the terrain at the base of the water body and can extend the current timing restriction from low-tide-only coastal geoscience. Potential instrumentation is available in industry such as ASTRELite edge or Fugro RAMMS/RIEGL VQ-840-G (larger UAS).
- LiDAR: Currently there are no UAS-borne full waveform LiDAR sensors available to BGS to conduct geoscience research in densely vegetated terrain. Having a detailed topographic model is a crucial layer within geoscience research particularly when understanding the location of potential emergence of subsurface structures, mineral veins or locating areas of unstable ground for potential landslide susceptibility. Whilst airborne full-waveform LiDAR systems are available, UAS-borne versions are still in development.

In addition to the optical aspects, detailed above, geoscience research would benefit greatly from access to a full suite of *GEOPHYSICAL* measurements to enable geoscientists to fully understand subsurface structures and characteristics.

- Ground-penetrating radar (GPR): Currently there are no UAS-borne GPR sensors available to BGS to conduct geoscience research, although through NZArC collaboration we now understand that BAS have such a capability. Whilst there are a few UAS-borne GPR sensors in existence there are additional issues with the sensor mounted below the UAS platform and having to fly at a low consistent altitude above the ground so in complex terrain this can be problematic.
- Gravity: Currently there are no UAS-borne Gravity sensors available to BGS to conduct geoscience research, important for mapping subsurface structures, including crustal thickness, intrusions, salt structures, sedimentary basins and large-scale faults. The minimum resolvable wavelength (depth of measurement) will depend on the speed and altitude of the platform so whilst there are only a few

sensors available in the industry, there is a trade-off with the requirement for larger UASs (fixed-wing or Windracers Ultra) for instruments such as iMAR iCORUS Strapdown Airborne Gravity system (7-16kg). These sensors are mounted internal to the UAS platform.

- Magnetic: Currently there are no UAS-borne Magnetic sensors available to BGS to conduct geoscience research, important for mapping subsurface structures, including intrusions, sedimentary basins and faults. Through NZArC collaboration we now understand that BAS have such a capability. As the signal falls away with an increase in altitude, terrain-following missions at low altitudes are preferred, but these can be problematic in complex terrain. There are UAS-borne magnetometry sensors available in industry such as the GEM systems GSMP-35U/25U (towed on larger UAS), SENSYS MagDrone R4 (3kg), Geometrics MagArrow II (1.2kg), SCINTREX CS-VL (890g) cesium magnetometer or the Geometrics MFAM development kit (<300g). These sensors are mounted below the UAS platform either as a fixed or tethered system.
- Time-domain electromagnetic (TDEM): Currently there are no UAS-borne TDEM sensors available to BGS to conduct geoscience research, important for detecting variations in subsurface electrical resistivity which directly relate to the shallow subsurface composition and therefore useful for mineral and geothermal exploration and hydrogeology through if induced currents. Sensors suitable for TDEM on UAS are still in development, although some are very close to market.
- Atomic Dielectric Resonance (ADR): Currently there are no UAS-borne ADR sensors available. This technology is very much in its infancy but would be of great future benefit in geosciences as the scanner transmits and receives micro and radio electromagnetic waves across material boundaries in the subsurface, the change in dielectric resistance providing a measure of the shape and depth of specific identifiable materials in the subsurface.

Whilst it is acknowledged that many of these systems exist, the barrier to their use within our geoscience research is mainly due to cost and the size of the sensors, requiring BGS to expand the current suite of UAS platforms and enhance our technical expertise in order to deploy this instrumentation on potentially larger UASs with additional time required to ensure parametric measurement and calibration workflows are robust for quantitative outputs for use in geoscience.

4.4.3.4. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

Having addressed the status of where we want to be in the field of UAS use in geosciences, there are still challenges to be addressed for them to become more mainstream in geoscience applications. Table 4.4 below outlines some of the challenges coupled with potential solutions, whilst it is acknowledged that this will not be exhaustive of either potential challenges or solutions.

Table 4.4: *Overview of the barriers, challenges, solutions and opportunities regarding platforms*

Challenge	Solution
• Limited number of experienced trained pilots that understand the survey requirement with a specific sensor	• Train more pilots (commercial operations requirement for BGS insurance purposes) to understand the requirements of each sensor
• Limited number of suitable sensors deployed to answer a specific geoscience application	• Encourage central repository of information for other geoscientists to ensure reduction in 'wasted' valuable survey time by using the wrong equipment for the wrong purpose • Encourage standardised 'best practise' procedures for UAS

	deployment and technical specification appropriate for each sensor • Encourage sharing of equipment through a centralised pool (potentially similar to the NERC FSF or GEP (Geophysical Equipment Pool))
• High cost in sensor reduces ability for redundancy if lost in complex/extreme environments	• Encourage development of cheaper sensors
• Limited battery flight-time when sensor uses UAS power thus reducing survey area extent	• Improve efficiency in UAS battery life or provide a back-up sensor battery to ensure data is not lost or both • Investigate option for regenerative power (i.e. solar, wind, friction) • Reduce UAS/sensor weight to reduce thrust requirement
• Unable to transport UAS batteries with larger capacity on commercial flights limiting international survey potential (especially when batteries cannot be sourced overseas)	• Improve efficiency of lower capacity batteries to remove requirement to ship larger batteries overseas, which currently leads to potential delays on equipment arrival in country and custom clearance, also taking equipment out of availability for a prolonged period of time
• Lead time required to work in new international countries with often lengthy legal documentation requirements	• Potential for a 'contact database' for international UAS responsibility in countries (i.e. equivalent to CAA) • Some countries are less willing to have new untested or unknown UAS/sensors and require lengthy customs conversations or in-country partner permissions
• Requirement for additional meteorological instrumentation for improved data calibration of sensor data	• Enable sensor to link more directly with UAS telemetry on wind speed, wind direction, humidity and air temperature during flight to ensure greater detail for calibration of specific images/data measurements
• Poor UAS handling or inability to fly in high/turbulent wind in complex environments that can affect data measurements	• Improve aerodynamics to with-stand stronger wind gusts • Provide information on sensor performance characteristics in certain conditions (i.e. TIR cooling fronts)
• Data lost if UAS lost	• Enable quicker data download across survey area in case UAS is lost
• Limited to using costly proprietary software	• Encourage sensor/software developers to work together to generate basic data format outputs that can be used in other systems
• Poorly documented deployment/technical and data processing procedures meaning repeat surveying of an area to produce comparable outputs is difficult	• Encourage standardised 'best practise' procedures for UAS deployment and technical specification appropriate for each sensor
• Poor understanding of limitation of each UAS/sensor - what worked, where and when	• Encourage central repository of information for other geoscientists to ensure reduction in 'wasted' valuable survey time

4.4.3.5. Recommendations for Advancement

Advancement in UAS-borne sensor technology has the potential to provide geoscientists with detailed measurements of the surface and subsurface that cannot be achieved through field reconnaissance and detailed field surveying alone.

Whilst the deployment of a single UAS with multiple mounted sensors would be ideal in order to provide a full suite of measurements of the area of investigation, due to sensor size and increased operational power requirements, this is currently not possible and there are additional potential issues arising from unknown interference effects between sensors that are yet to be fully explored.

Miniaturisation of sensors coupled with improved efficiency of UAS batteries would enable longer and larger survey deployment with potential for doubling up on sensor mounting, thus reducing the need for repeated surveys to be performed on the same day and potential issue with landowner access or from time-restricted measurement. Of the Earth Observation technologies routinely used by BGS it is geophysical sensing that is not represented on the UAS platforms. Geophysical sensing offers the unique opportunity to better understand the geological variability of the shallow subsurface, the zone where much of the infrastructure is located and therefore of great importance to stakeholders. Miniaturisation is starting to mean that new geophysical technologies for <25kg UASs are almost market ready. It is important the BGS can use its experience of ground-based systems (for example PRIME geophysical ground-imaging technology) to further develop UAS-based systems.

Aligning UAS-borne sensor deployment with ground-based and meteorological-based sensor measurements can help more accurately calibrate the UAS sensor data, however there must be agreed data acquisition and calibration standards in order for the acquired data to be useful, usable and used in the long term for geoscience research. In addition, a full understanding of exactly what auxiliary measurements are required is needed in order to ensure the UAS-borne sensor measurement is as accurate or best calibrated as possible.

As part of this approach, we recommend detailed documentation and a training programme on sensor suitability for geoscience research is generated, to ensure that sensors are used appropriately and the best possible data is acquired.

To advance UAS technology in geoscience the community must work together to develop tools for data processing (free from proprietary software) and data visualisation and integration so that products and knowledge can be shared in an effective manner with robust knowledge that the data has been quality assured and can be comparable to future investigations.

4.4.4. Glaciology

4.4.4.1. Introduction to Glaciology

Ice is a fundamental part of the water cycle, its formation, flow and return to the ocean has a global impact, through water resources and global sea level in response to melting ice caps. To understand how ice will behave in the future warming world requires observations of the internal structure and basal conditions of ice sheets and glaciers. This will constrain the processes involved in ice flow and identify regions susceptible to change. Radio-glaciology uses reflections of transmitted radio waves to image the hidden internal structure of ice and the shape of the land beneath, providing the required key information.

4.4.4.2. Current State of Affairs

Radio-glaciology can be conducted from both the ground and airborne platforms. Lower frequency and higher power radar systems are used to image the full thickness of the ice sheet (up to ~4.5km), while smaller, lighter, high-frequency systems reveal information about surface processes and shallow hidden objects or voids. Ground based systems are often used to survey smaller areas, or to check for crevasses to ensure safe travel. In contrast airborne systems on platforms such as the Twin Otter or Basler aircraft, or helicopters, can survey much wider areas and can access regions which are too dangerous for ground travel, for example close to the coast, or in areas of highly crevassed fast flowing ice. Airborne and satellite photogrammetry also provides valuable measurements of glacier and ice sheets, including surface elevation, changes in calving fronts, location of crevasses, plus derived velocity and volume dynamics. Many hundreds of thousands of kilometres of airborne radar data have been collected over the Greenland and Antarctic ice sheets and other glaciers, constraining regional scale ice sheet models. However, significant data gaps remain; for example much of the Antarctic coast has no radar observations within 5km and data gaps of 50-100km are common in the continental interior.

4.4.4.3. Where We Want to Be

UASs equipped with depth sounding radar or aerial cameras equivalent to those on traditional platforms are likely to be large (payload 10-60kg) and will require a range of hundreds up to a thousand kilometres. Such platforms will transform the ability to survey the most remote sectors of Antarctica as well as other glaciated regions. By drastically reducing the logistical overheads for operation due to positioning aviation fuel they will allow the high resolution surveys (1km line spacing or tighter) required to constrain models of future ice flow near the grounding line and search for indicators of past ice flow variability in the continental interior. High frequency radars on smaller UASs, including quadcopter platforms, will also play a significant role in both scientific understanding of ice formation and in safety related roles such as crevasse detection.

4.4.4.4. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

Barriers to deployment of depth-sounding radar on UASs in Polar Regions include:

1. Lack of suitable light-weight low-power radar system of the correct frequency to measure different thicknesses of ice, from thin sea ice (few centimetres) up to deep plateau ice sheets (up to 5km), requiring C-band, S-band, Ka-bad and Ku-band frequencies. Such depth sounding radars are typically research-grade systems and not available off the shelf.
2. A suitable research (rather than military) type UAS with the required payload/range is currently not proven for routine operation in Antarctica or other glaciated regions, meaning the default platform of choice is often a traditional one, despite its high carbon overhead.
3. Operation of UASs alongside traditional aircraft is not proven in Antarctica or other glaciated regions, meaning UASs can be grounded for days while other aircraft operations are prioritised.
4. Larger physical size is required for low frequency antennas, or for larger antenna arrays.

Miniaturisation of components associated with advances in mobile communications technology mean that decreasing the weight of a radar system from >100kg to 50kg or less is now theoretically possible. This presents a clear opportunity to move to operation from UAS platforms for some survey missions. There is a limit to how small radars can become due to power requirements and the physics of radio antennas. However, larger civilian UASs are becoming available and will soon be tested in Antarctica. Furthermore, use of swarms could be considered as an alternative to create larger antenna arrays. This will pave the way for routine radar deployment on UAS platforms, but additional funding for UAS (single or multiple as a swarm) adaptation for the polar operating environment may be required, as there is little commercial need for this.

Barriers to deployment of higher frequency radars for traverse safety include:

1. Lack of experience interpreting real-time data while operating a UAS
2. Poor trust in/difficulty interpreting radar output by non-expert field guides. Although these barriers are significant they can be overcome by training and collaboration between operational groups and scientists. The use of small UASs for route finding provides clear opportunities for improved safety, as they can both check a route days in advance and provide real time information from further in front of a moving vehicle. For example, current systems used by the US traverse teams use a ground based radar on a ~5m pole in front of the lead vehicle, giving operators just 2 seconds to respond to a sighted crevasse, while a tracking UAS could be 10s to 100s of metres in front.

For aerial photography, currently available camera systems are sufficiently small and low-power to operate on a large UAS. However, the systems currently do not support a live data feed which allows control of the camera in flight. This gap could also be solved by the development of new autonomous flight control systems (supporting cloud detection and image quality control) designed for aerial photogrammetry surveys. Alternatively, a high bandwidth satellite link, such as SpaceX Starlink, transmitting data to a ground station can mitigate this issue.

4.4.4.5. Recommendations for Advancement

For UAS depth-sounding radar surveys to become a reality, a suitable depth sounding radar system must be designed. This will include taking advantage of the latest advances in hardware miniaturisation of signal generation and processing, together with designing suitable antennas/antenna arrays compatible with deployment on a UAS. This development will also include the design of new strategies of data collection, taking advantage of UAS manoeuvrability, like vertical motion, to give an enhanced data product. The optimum system will likely be platform agnostic, ultimately allowing deployment on a range of UASs, as well as initial testing and deployment from traditional aircraft. To ensure successful deployment, large UASs with suitable range and payload must be tested and adapted for operation in polar environments, including operating from snow (likely ski equipped). The newly developed radar system will need to be tested over thick ice masses to prove it works, for example in Greenland or Svalbard. Finally, the radar system and UAS will need to be deployed to Antarctica and used in field locations and in conjunction with traditional aircraft to fully demonstrate the system is capable of replacing traditional airborne survey platforms there.

To develop UASs as a tool for field safety, robust processing algorithms must be developed for clutter rejection to give confidence that crevasses can be detected and to minimise the number of false readings. This will require collection and analysis of test data in a range of known crevassed regions, under various operating conditions. Subsequent assessment of the success of the developed algorithms will be required before such systems can be deployed. In addition, methods for quadcopter or other small UASs to track in front of a vehicle and transmit images in real time, already developed for example in the film/TV industry, must be embedded in routine operational procedures. Knowledge exchange between scientists developing the radar systems and field guides using them is vital to ensure correct use and confidence in the system.

To develop aerial photography capability on UASs, the development of new tools for in-flight data control and assessment are required.

4.4.5. Hydrology

4.4.5.1. Introduction to Hydrology

Water is our planet's most critical resource and hydrology is the science of measuring its presence, abundance and processes in the environment.

The accurate and timely monitoring of water in the environment is therefore essential to the effective management of water for people, nature, agriculture and business and as a growing threat in the form of flooding.

The need for extremely effective monitoring of water extends far beyond the domain of science and research and is perhaps greatest amongst national regulatory bodies such as the Environment Agency (EA) in England, Natural Resources Wales (NRW) in Wales and Scottish Environment Protection Agency (SEPA) in Scotland. These organisations operate several thousand water monitoring sites and as such can be the largest beneficiaries of advances in hydrological monitoring.

The EA and SEPA have both committed to achieving Net Zero by 2030, so will be actively seeking to cut carbon emissions from their monitoring and construction activities. Budgets in these organisations tend to be under considerable pressure, meaning that innovations that can deliver savings are always welcome.

Safety is of paramount importance for all forms of environmental monitoring and rivers, in particular in times of flooding, can present a significant risk to those engaged in making measurements and observations. It is important to note that, if used in accordance with guidance, UAS technologies can deliver major benefits to operator safety.

4.4.5.2. Current State of Affairs

Currently, the vast majority of hydrological observations are made at a network of thousands of permanent or semi-permanent monitoring stations, using ground-based equipment. The majority of these observations are made by the regulatory bodies, the EA, SEPA and NRW. One-off and less regular observations are made at locations outside of this core network.

Telemetry is widely used at primary monitoring locations to allow near real-time access to information, but automation of monitoring beyond regular scanning of installed sensors is rare. Where telemetry exists, site visits are required for calibration, validation and maintenance activities. The most critical of these for river monitoring sites will be during times of exceptional low flows during droughts and most problematically, at the height of a flood.

The science and monitoring capabilities of UKCEH and other hydrology scientists and researchers can benefit greatly from accelerated development of UAS-based technologies, enabling observations to be made more quickly, more safely, with fewer staff and decreased travel requirements.

The effective monitoring of river flood flows and extent is of critical importance to the nation, as flooding is the UK's most costly natural hazard. However, while existing tools and techniques can work well in lowland rivers and moderate flows, in extreme events such as 2015's Storm Desmond, the capability and resilience of established monitoring methods and sites can be left severely lacking.

River bathymetry information, where it exists, is obtained with surface deployed sensors. For the majority of rivers, no bathymetry information is available.

The following observational methods are currently in use:

- Precipitation – ground based sensors, wide coverage radar
- Snow cover, depth and melt – ground based sensors, some cameras
- River levels – ground based sensors, often in-stream, most with telemetry
- River flows fixed locations – ground based sensors, often in-stream, most with telemetry
- River flows non-routine – in-stream and surface-deployed sensors, few/none with telemetry. Use of UASs with RGB cameras for river flow monitoring just starting
- Flood monitoring – in-stream and surface-deployed sensors, few/none with telemetry
- River and lake bathymetry - surface deployed (boat mounted) sensors (for many rivers, little or no data exists)
- Soil moisture – ground based sensors, most with telemetry
  - COSMOS network for national soil moisture monitoring

4.4.5.3. Where We Want to Be

UASs offer huge potential to improve the quality of and decarbonise hydrological observations. Some will involve the development of new sensors or techniques, others simply realising existing potential. Many of these should ultimately be able to operate remotely and unsupervised in a full range of weather and illumination conditions (including at night). Recognising the widespread use of hydrology monitoring tools by non-scientists, it is essential to ensure that those suited to operational monitoring applications are easy to use and do not require significant new hardware, software or functional skills.

It is important to note, for river observations, conditions can change dramatically in a few hours or less, meaning that the ability to operate responsively, in a range of conditions, at night and unsupervised will be essential looking to the future.

The following provides an overview of opportunities and desired use cases for hydrology:

UAS-based river quantity monitoring:

- Measure water speed in a full range of conditions (slow flow, fast flow, extreme flood) using a range of technologies – RGB and TIR camera, radar and LiDAR
- Measurement of floodplain inundation and flows - RGB and TIR camera, radar, GPR and LiDAR
- Measurement of water depth (green LiDAR for clear water, UAS-mounted GPR for turbid water)
- Determination of water surface height - radar, LiDAR, RGB and TIR camera
- Ability to operate in all weathers (resistance to rain and snow, tolerance of high winds)
- Ability to fly river observation missions autonomously and unsupervised, on regular basis or in response to conditions both during the day or night – 'drone-in-a-box', BVLOS
- Thermal cameras to allow the observation of groundwater exchanges with watercourses

UAS-based water quality monitoring and mapping:

- Sediment monitoring – Green LiDAR, RGB and multispectral imagery
- Thermal and multispectral cameras to allow the observation, classification and quantification of pollution entering watercourses. RGB, thermal and hyperspectral cameras, or multispectral with dedicated bands
- Optical sensing of water quality parameters – RGB, thermal and hyperspectral cameras, or multispectral with dedicated bands

Other hydrological parameters:

- Snow cover and snow melt monitoring – UAS-based tools to observe, classify and quantify snow cover, snow depth and snowmelt. Potential for unsupervised deployment
- Soil moisture – UAS-mounted multi- and hyper-spectral cameras for soil moisture. Potential for unsupervised deployment
- Water quality – satellite-borne optical sensors are widely used to observe water quality parameters in a network of some 4200 lakes worldwide (out of 117 million). Optical sensors on UASs offer an excellent calibration and validation solution.

Satellite Calibration and Validation (Cal/Val)

Calibration and validation (Cal/Val) of satellite EO products relating to hydrology is a growing need, as demonstrated by the Copernicus *In Situ* (COINS) and WaterForCE projects. UASs are seen as having great potential to aid with this. UAS-based observations of water quality and quantity are currently sought in support of Cal/Val of satellite derived products (COINS, WaterForCE and so on).

Innovation topics

- LiDAR – Advancements in UAS-mounted LiDAR would allow new insights into the hydrological cycle – for example optimisation to allow accurate sensing of water surface roughness, slope and bathymetric mapping.
- UASs that can fly collaboratively or in small swarms would allow swifter time-sensitive data collection and permit new insights by decoupling transmitters and receivers.

Training

A lack of knowledge and skills can be a major barrier to the adoption and successful use of new tools in hydrology. A comprehensive, but accessible (i.e. not too complex) training programme will be essential to enable widespread uptake.

Making results available in real-time

Real time sharing of data and results will be essential for effective operational monitoring and extreme event monitoring in particular. This demands advances in the availability of sometimes complex metadata (for example a digital twin of a river or lake), as well as onboard processing of sensor data to deliver results in real-time. An example requiring both of these advances is enabling a fully operationally effective real-time flood monitoring solution, to improve intelligence and resilience relating to the UK's (and the world's) most costly natural hazard.

UAS development centre – river-based

A key requirement in enabling these innovations will be a suitable development and test centre, an essential component of which will be a suitable river within the site. Such a river will need to have a large range of flow conditions, including rapid, turbulent flows and out of bank flows in times of flooding. Such a development centre should also be designed to be useful for the development and testing of many other UAS-based tools and techniques unrelated to hydrology.

4.4.5.4. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

Below we provide an overview of barriers, challenges, solutions and opportunities for the use of UASs in hydrology.

Barriers:

- Regulations – CAA regulations, BVLOS, proximity to roads/railways and so on
- Land ownership – knowing who owns land & gaining landowner operating permissions can be challenging
- Lack of funding for equipment and, more significantly, development of new tools and techniques
- Technologies and software are not always user friendly, some are not yet reliable
- Lack of a location/facility on a river to enable testing of solutions on rivers
- Software for data processing pipelines
- Lack of meta data to enable effective UAS-based observations – bathymetry, floodplain DEMs (hi-res) and river hydraulic information
- Monitoring agencies (see also opportunities) – the need to maintain operational monitoring activities on tight budgets precludes significant investment in development of innovation in monitoring tools and techniques amongst the regulatory monitoring agencies.

Challenges:

Many challenges relating to hydrology and ecology applications relate to a need to operate at low altitudes and in environments with a diverse range of land cover and landforms. These can present challenges to the safe and effective operation of the UAS, but all should be resolvable.

- Low flowing rivers are hard to measure with existing UAS technology.
- River bathymetry information is needed to enable UAS-based river discharge measurements.
- There is a lack of sophisticated flight control (trees, valleys, water surface) to allow flying low over water surface and complex habitats.
- Battery capacity and endurance is not adequate.
- Systems need to be weather resilient (rain, strong winds).
- Changing illumination conditions are difficult – this is a particular issue for water as it is reflective.
- Practicalities and quality of results when operating at night time pose problems.
- There is a possible lack of trust by users in data derived from UAS technology.
- There is poor access to metadata to enable effective river science.

Solutions:

- low flows - bringing sensor closer to river surface, UAS-deployed ADCP (Acoustic Doppler Current Profiler) river flow sensor
- river bathymetry – UAS-mounted bathymetric (green) LiDAR and Ground Penetrating Radar (GPR), use of a base station for ‘perfect’ geolocation
- flight control – evaluation of existing, constantly improving off-the-shelf technologies
- battery capacity and endurance – improving sensor and airframe technologies with lower take–off weights, combined with advances in battery technology
- weather resistance – UASs should be tested appropriately
- changing illumination – explore different sensor technologies (radar, LiDAR and so on) and different EM wavelengths

- operation at night – new technologies (even at the bottom of the commercial market) are advancing night-time operation capabilities – DJI's new 249g £700 Mini 4 Pro offers night mode video and a downward facing light to improve positioning and take-off and landing
- lack of trust – undertake validation programmes in a range of conditions to demonstrate the effectiveness of UAS-based monitoring methods
- metadata – develop a digital twin to hold river bathymetry, floodplain topography and related information (discussions are underway with STFC)

Opportunities:

- development of a UAS Development Centre based around a river and a wide diversity of habitats
- enabling flow measurements on fast flowing rivers, river flow monitoring making operationally useful observations for monitoring agencies (EA, SEPA etc)
- thermal aeration to track emergence on surface combined with thermal video
- water detection for intermittent streams (thermal, multi-spectral)
- working with the regulatory monitoring agencies to develop and test new solutions in field settings and against established reference measurements and stations
- calibration and validation of satellite missions, water quality and quantity – for example Copernicus through 'COINS' project
- weather resistant UASs – waterproof and high wind resistance
- operation at night - detecting the (monitoring) signal and flying safely
- development of river digital twin with STFC

4.4.5.5. Recommendations for Advancement

To progress Net Zero Aerial Capability for hydrology, we recommend:

- development and implementation of hyper-accurate smart terrain following and obstacle avoidance
- development of positioning technologies that are resilient and reliable above water (which will often be moving which can confuse optical sensors)
- 5G network RTK correction in real-time on UASs to improve positioning, geolocation
- permanent UAS on-site in a charging and downloading box for regular monitoring to reduce site visits by UAS pilots and enable ongoing and exceptional event monitoring
- enabling onboard processing of information to provide real-time river flow information (and other parameters)
- relative soil moisture retrieval algorithms using UAS technology (thermal, radar)
- testing water quality with hyperspectral retrieval algorithms (chlorophyl) and dealing with specular reflectance of water; water quality sample collection – manual and automated
- developing links to satellite calibration and validation programmes

4.4.6. Oceanography

4.4.6.1. Introduction to Oceanography

Oceanography is a multidisciplinary scientific field dedicated to the study of the physical, chemical and biological aspects of the Earth's oceans. The overall scientific objective of oceanographers is to understand the influence of the oceans on climate, ecosystems and global biogeochemical cycles. Concerning Earth's climate system, oceanographers focus on observing circulation patterns, heat transfer mechanisms and carbon cycling dynamics. This information contributes to the development of accurate climate models, fostering a deeper comprehension of ocean-atmosphere interactions and their implications for global climate variability.

Oceanographic research is also important for understanding the distribution and cycling of chemical elements within oceanic environments. The study of nutrient fluxes, trace elements and isotopes provides insights into marine productivity, carbon sequestration (i.e. the biological carbon pump) and the interaction between biological and chemical processes. This knowledge supports our understanding of the impact of anthropogenic activities on oceanic ecosystems and the feedback mechanisms that influence global biogeochemical cycles. Finally, biological oceanography focuses more on determining the diversity, distribution and ecological dynamics of pelagic marine organisms, with a specific emphasis on planktonic assemblages. Related lines of inquiry include the mapping of species and habitats on the seabed (marine habitat mapping).

4.4.6.2. Current State of Affairs

The current state of affairs within oceanography is characterised by a confluence of technological advancements, collaborative international initiatives, large and complex modelling efforts and an increased awareness of the urgent need to address societal challenges, such as climate change.

Much of the technical advancements have been through advanced: (i) remote sensing platforms and sensors, such as satellite, aerial imaging (plane-based) and UASs; and (ii) *in situ* observations from modern instrumentation, long-term moorings and autonomous platforms (surface, sub-surface and seabed). These advancements facilitate our ability to monitor large-scale ocean processes in real time.

International collaboration plays a pivotal role in contemporary oceanographic research. Recognizing the global nature of ocean systems, scientific organisations and consortia collaborate to pool resources, share data and collectively tackle complex research questions. Initiatives like the Global Ocean Observing System (GOOS) and the Argo Program, involving a network of autonomous profiling floats, exemplify the cooperative efforts within the oceanographic community.

The rise in computational power (i.e. super-computers) and 'big data' oceanographic datasets has facilitated the development of advanced numerical models that simulate a greater number of oceanographic variables, at higher resolutions, over greater areas.

The current state of oceanography is also marked by a heightened focus on climate change impacts and the vulnerabilities of marine ecosystems. Rising sea levels, ocean acidification and extreme weather events profoundly threaten natural and socio-economic systems. As such, oceanographers are actively engaged in interdisciplinary research to assess the resilience of marine ecosystems, predict the consequences of climate-induced changes and propose adaptive strategies to minimise the ecological and socio-economic impacts.

With regard to UAS-based observations, these have found favour for shallow water habitat mapping in tropical waters and as a census tool for large mammals and marine animals returning to shore (for example penguin colonies). For marine habitat mapping, imagery collected from UASs can be used to detect the distribution of seabed habitats (for example corals, seagrass and kelps). Furthermore, the same imagery can be used to estimate shallow water bathymetry through photogrammetry methods.

4.4.6.3. Where We Want to Be

The future trajectory of oceanography is closely linked to technological innovation, specifically the development of advanced autonomous platforms, artificial intelligence applications and state-of-the-art sensors. However, due to poor penetration of optical systems through the water column, most of these developments will be *in situ* platforms and sensors. Satellite-based sensors operate at an appropriate scale for oceanographic investigations of surface conditions. UAS-based sensors are limited to small-scale surface observations or very shallow seabed observations in clear, tropical waters. For shallow water marine habitat mapping, advances in UAS technology that are particularly beneficial include (i) battery duration and therefore survey extent; (ii) optical resolution (both pixel size and band resolution; and (iii) the inclusion of additional passive and active optical instruments (i.e. LiDAR) alongside visual imagery capture.

A counterpoint to the limitations of purely observing studies is provided by the arena of process studies, specifically air-sea interaction. Atmosphere-surface fluxes over ocean are less studied and their parameterisation schemes less tested against accurate data than for the terrestrial equivalent, due to a combination of expense, a fluid surface and that most measurements are affected by the deployment (a ship rather than a thin lattice mast). UASs in conjunction with other emerging robotic technology can address these issues.

4.4.6.4. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

Despite recent advancements, there are still technological barriers hindering comprehensive oceanographic research. Remote and extreme environments, such as the deep sea and polar regions, pose challenges for data collection. Developing and deploying more advanced and robust technologies capable of sustained observation in these environments is necessary. Making greater use of technologies, such as advanced sensors, autonomous vehicles and satellite systems, presents an opportunity to overcome the difficulties of operating in these environments.

The vast amount of oceanographic data generated by different instruments and platforms often lack standardised formats, impeding efficient data integration. Addressing this challenge requires the establishment of standardised data formats, metadata protocols and interoperable systems. This will facilitate greater collaboration and analysis across diverse datasets including AI-based systems.

The drive towards Net Zero for oceanography also means that many of the traditional oceanographic tools, such as the diesel-electric research ship, are likely to be phased out over the coming decades. As such, there is a great need to replace this capability with shore launch autonomous platforms (both aerial, surface and sub-surface). Using remaining existing research vessels and motherships for robotic fleets will (i) greatly extend the physical reach of these vessels for data collection, (ii) enhance the data quality for microscale process studies and (iii) gain experience and progress towards future Net Zero or Low Carbon operations.

4.4.6.5. Recommendations for Advancement

Due to inherent optical properties of water, aerial platforms with optical sensors will be of limited value within oceanography. However, imagery collected from UASs has been particularly important for distributional studies of marine mammals and species returning to shore. Furthermore, UASs are a particularly important tool for the mapping and monitoring of shallow water habitats. For improving climate and forecasting models, the coupled ocean-atmosphere combination of UAS- and ASV (Autonomous Surface Vehicle)-based measurements, deployed in deep ocean, offers to improve understanding of the processes that in part mitigate climate change.

Recommendations here include the need for units with additional or enhanced optical sensors (for example LiDAR and specifically bathymetric LiDAR, airborne fluid lensing for enhanced optical resolution in aquatic environments). For deep ocean, platforms that can operate effectively from ships are required; key requirements are BVLOS, VTOL and Terrain Following, all of which are emerging technologies.

UASs are also useful logistical tools in oceanography. The industry-wide development of UASs that can carry heavier payloads further will also generate opportunities to develop *in situ* sensors further afield without the need for expensive, carbon emitting platforms such as traditional research ships.

4.4.7. Earth Observation

4.4.7.1. Introduction to Earth Observation

Earth Observation (EO) involves the collection of information about Earth's environment using remote sensing technologies and techniques relying on the sensing of electromagnetic radiation (EMR). The instruments used to perform remote sensing can be carried by satellites or by airborne systems such as crewed aircraft or UASs, or can be operated from ground- or water-based platforms. These sensors are either Passive in that they sense natural electromagnetic radiation - either shortwave radiation emitted by the sun and reflected or scattered by the target; or longwave or passive microwave radiation emitted by the Earth itself; or Active - in that the sensors themselves contain a source of EMR that is used to illuminate the target and which is then reflected from the target or partly scattered or absorbed by the intervening atmosphere - with some arriving to be detected back at the sensor. Often these remote sensing data captures are more than point-based observations, with for example most remote sensing systems present on satellites or aircraft being able to produce 2D arrays of data covering a geographic region at multiple different wavelengths (akin to recording “imagery” of a target area in different wavelengths of EMR).

Mathematical formulations enacted in computer code (‘algorithms’) are generally used to generate environmental information from the received EMR signals captured by remote sensing technologies. Three examples are listed as follows. Firstly, the amount of light recorded over areas of vegetation captured at fine spectral detail in the near infrared (NIR), which can be used to generate a measure of ‘solar induced fluorescence’ which in turn is related to the photosynthetic rate of the plants. Secondly, a similarly fine degree of spectral detail is required in the shortwave infrared (SWIR), whose measurements can be used to infer the column amounts of certain trace gases (for example methane) present between the sensor and the surface. Active technologies enable this capability to be potentially utilised at night and in locations/times where there is limited SWIR radiation coming from the sun and being reflected via the surface. A third example is longwave infrared (‘thermal’) measurements which provide information on the temperature of the surface and, when combined with other data and with visible-to-NIR wavelength EO information, on the rate of evapotranspiration of water from the soil to the atmosphere. There are a huge range of different EO applications and retrieval methods for geophysical data products and the examples provided here represent a small fraction.

Earth Observation serves a multitude of purposes driven by scientific, environmental, societal and economic needs. For environmental science and environmental monitoring, satellite EO provides systematic, repetitive and large-scale observations at a very high degree of scientific quality and trustworthiness across the whole Earth - providing information of a type and quality unable to be obtained in any other way. EO operated from non-satellite platforms can also provide highly spatially detailed and repetitive observations at specific places or specific times. Together these types of EO datasets and the geophysical data products developed from them underpin many aspects of Earth System and environmental research, as well as providing a ‘routine’ monitoring capability for Earth’s environment that is akin to the one developed for operational weather monitoring and forecasting. Some form of remote sensing data or derived information, most commonly that derived from data collected from satellite platforms, is used in almost all areas of environmental science and a high proportion of NERC grants include some form of remote sensing data use.

4.4.7.2. Current State of Affairs

The UK environmental science community who are eligible to apply for UKRI funding have access to a range of crewed aircraft platforms, which includes the BAS Twin Otter (TO) aircraft. Two of these TO aircraft are adapted with a viewing hatch and various other adaptations necessary to carry remote sensing payloads and are the primary platforms used for the NCEO Airborne Earth Observatory (NAEO, see Figure 4.1 below and section 2.4.1).

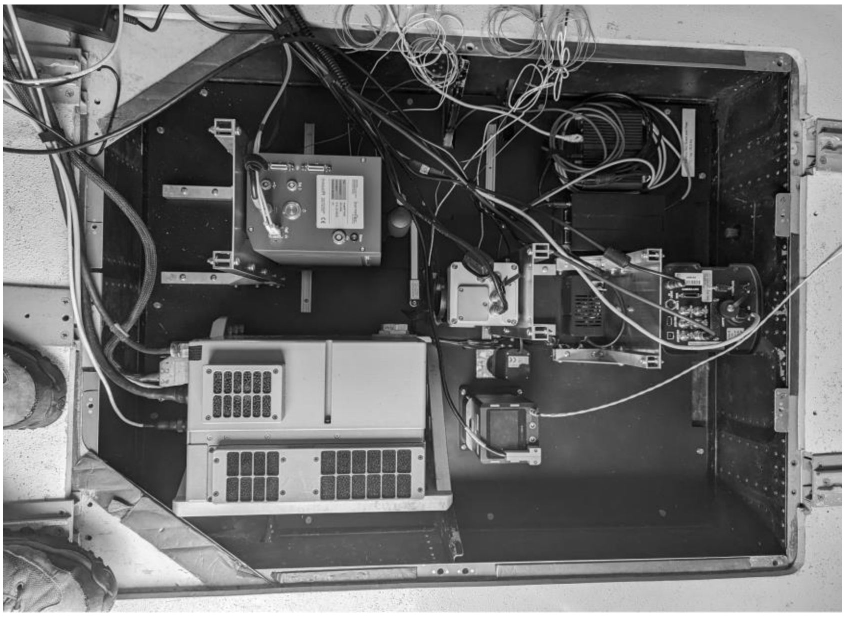


Figure 4.1: *A series of broadband and hyperspectral imagers installed in the viewing hatch of the BAS Twin Otter aircraft by the NAEO. Each sensor is generally operated by an independent computer that has its own control and data storage requirements. Note boots at far left for scale. See Figure 2.1 for the actual aircraft this installation is hosted within.*

As a complement to the remote sensing capability offered by the NAEO and the BAS Twin Otters, the Field Spectroscopy Facility (FSF) offers the most comparable UAS facility accessible to UK scientists. The FSF offers UAS platforms, well calibrated and characterised remote sensing instruments and trained operators - all accessible to the UK research community for the past approximately five years. However, the quality and range of sensors carried by the UAS platforms and the scale over which the capability can be operated, is rather different to that from the NAEO. For comparison, the NAEO operates a series of sensors costing approximately £4M when new, whereas the FSF sensors were £100,000s. The NAEO sensors and associated computers weigh hundreds of kilograms, whereas those of the FSF capability are in the low kilograms ran. The NAEO sensors measure to a far greater degree of scientific breadth and depth than the sensors able to be carried by the relatively small UASs operated by FSF and the duration of the BAS aircraft is around 4 hrs, that of the FSF UAS platforms tens of minutes. The Twin Otters can fly most places from which one can access a suitable airfield, whilst the FSF UAS platforms can only be flown within line of sight (though they have VTOL capability). Therefore the crewed and uncrewed aerial capabilities provided to the community are of different scale and resourcing and are fully complementary rather than duplicating.

The FSF, operating as part of NCEO, currently provide access to the following technical UAS related items to the community.

- Headwall Photonics Co-Aligned VNIR-SWIR Sensor with integrated LiDAR
- SAL Maia S2 Multispectral Sentinel 2 matched camera
- SAL Maia WV Multispectral WorldView-2 matched camera
- MicaSense Altum and RedEdge-M Multispectral cameras

- Zenmuse XT2 from DJI and FLIR - Radiometric LWIR thermal camera
- Piccolo doppio solar induced fluoresence point spectrometer

FSF also offer full complementary UAS ground support equipment, including:

- Calibrated Spectralon reflectance panels (25 x 25cm)
- Calibrated ground targets to support vicarious radiometric calibration and atmospheric correction
- Calibrated sunphotometers, both handheld and automatic, for use in atmospheric correction
- Spare battery & power options
- Safety and fire equipment
- All required flight hardware and software

FSF furthermore can supply the instrument operator and pilot for the required research project, greatly simplifying the requirements coming from the project itself.

Outside of the FSF provision, NCEO science does make use of UAS capabilities as well. Generally these have been small to medium sized multi-rotor platforms carrying generally the following range of sensors:

- Thermal cameras for land surface temperature
    - FLIR Vue Pro thermal camera
    - FLIR Duo Pro R thermal camera
- Spectral sensors for agriculture and vegetation observation
    - Parrot SEQUOIA+ Multispectral Sensor
    - Headwall hyperspectral camera
- RGB cameras for structure from motion (SfM) processing, photogrammetry and mapping
    - Adapted RGB and NIR digital cameras
    - UAS-integrated (Phantom-4, Mavic Mini)
- Atmospheric sensors for atmospheric composition sampling
    - Gaslab pro cm-1000
    - Customized aerosol counter
    - Customized smoke sample collection system

- LiDAR for upscaling vegetation structure and function
    - Riegl minivux LiDAR

Importance is also placed on:
- RTK system for accuracy in geoinformation
- Ground-based measurements for vicarious calibration and atmospheric correction
- Laboratory characterisation of the EO instruments prior to use to ensure data quality

4.4.7.3. Where We Want to Be

The UK is a world leader in Earth Observation, having roles in and in some cases leading, many international satellite missions and science teams. A key National Capability role of NCEO is to ensure the UK has the capacity and capability to deliver high quality, value-added EO data and information, can interpret these data in the most effective and efficient way to gain the knowledge it needs and continues to develop the advanced mathematical techniques needed to integrate and exploit these observations to maximise their scientific and societal impact. NCEO currently operates the NCEO Airborne Earth Observatory (NAEO) that provides a highly effective scientific grade remote sensing capability that can operate in many environments and across nations from the BAS Twin Otter (crewed) aircraft. The quality and significance of this capability is evidenced by its frequent use by the European Space Agency (ESA), as well as by UK national users. Alongside the NAEO capabilities, NCEO wishes to expand on its existing use of UAS in its own science, but also in its provision of UAS capabilities to the wider UK community. The latter is building on the fact that NCEO is - to its knowledge - the only NERC Centre to have provided a UAS capability to UK Environmental Science users and UKRI Grants through the NERC Services and Facilities route and has gained significant experience and expertise in UAS operations, data processing and quality control whilst doing so.

To deliver UAS-based remote sensing observations of sufficient 'science quality' there is generally a substantial effort needed in order to deliver any dataset beyond the simplest RGB imagery useful for high spatial resolution mapping and 3D digital elevation model reconstruction. Instruments need proper radiometric and spectral calibration, as well as geolocation. Whilst the latter might be easily apparent if it is not done well, the former can be completely "invisible" to many users and this can result in non-optimum, high uncertainty and even biased datasets being exploited for science without knowledge of any problem. Calibrating and validating the quality of the sensors and data and understanding and quantifying the data uncertainty, is key to a wider trust in these datasets. Providing data products in the same type of standard file formats, documented and easily read into software, is another requirement for efficient and effective use of the data. NEODAAS and FSF are collaborating on some of this type of work and the NAEO is also collaborating with them in terms of sensor radiometric and spectral calibration.

NCEO see UAS platforms as a key component within the range of remote sensing platform capabilities - and these UASs include High Altitude Platforms (HAPS) which offer pseudo-satellite or very long duration loitering capabilities in some cases. We foresee a future where researchers are supported and in a position to make informed decisions as to the most appropriate platform (UAS, crewed aircraft, ground observations, satellite observations) or combination that provides the innovative environment that allows them to address their particular research question. We envisage researchers not to have to become UAS 'engineers' in order to collect data with UAS platforms, nor software specialists to actually process the data, nor sensor experts to ensure proper data quality is obtained - but rather picture a situation more akin to the current very advanced state of affairs operating in the satellite EO world - where "analysis ready data" and "EO data products" recording the key environmental variables of interest together with their uncertainties is increasingly the standard of provision.

4.4.7.4. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

Below we summarise barriers, challenges, solutions and opportunities for UASs in EO.

Barriers and challenges to UAS take-up:

- Regulations - CAA regulations, BVLOS limitations, proximity to built-up areas, roads/railways and so on and "people not under the control of the UAS operator"
- Land ownership and operating in protected areas – knowing who owns land & gaining landowner operating permissions, restrictions on UAS use in protected areas which can be exactly those where UAS use might be some of the most useful
- Lack of funding for equipment and, more significantly, development of new tools and techniques
- Hardware and software are not always user friendly, some are not yet reliable and often scientists need to become "mini-engineers" to operate these systems and keep them running
- Well tested and easy to use, trustable software for UAS remotely sensed data processing and data products are needed
- Battery capacity/endurance/payload capacity mean that useful applications of UAS in remote sensing and EO science are often limited to relatively special cases
- Difficulty in accessing an electricity supply for battery recharging in remote environments

- High enough quality sensors, operating with the right characteristics, that are capable of being carried and operated on UAS platforms to deliver “science quality data” (beyond relatively simple RGB and thermal imagery); this may include sensors for trace gas column retrieval for example – like a UAS version of the GHGSat type approach
- Radiometric, spectral and geometric calibration and validation of the data from those sensors
- Lack of sophisticated flight control to allow flying in harsh environments and complex habitats (e.g within a forest or automatically targeting and flying within a pollutant plume)
- Weather resilient systems (rain, strong winds)
- Changing illumination conditions – a particular issue for EO applications wanting to measure reflectance rather than just a picture or spectral radiance
- Operation at night time – practicalities and quality of results
- Possible lack of trust by users in data derived from UAS technology, including because of a lack of metadata and data uncertainties

Solutions and opportunities:

- Calibration of EO sensors is a known and well-studied capability from the satellite and ground-based remote sensing areas. Geocorrection is supported by differential geophysical satellites but also requires much additional knowledge on sensor geometric effects etc
- Knowledge exchange with those operating crewed remote sensing capabilities – who have great experience in the calibration of sensors (spectral, geometric, radiometric) and in the actual real world operation of quite expensive (typically many £100’s k) airborne EO sensors to collect science grade information; such operations need to take into account safety, weather, terrain, aircraft endurance, maintenance and scientific quality of the payload and so on – all things that are common to crewed and uncrewed missions
- Flight control – evaluation of existing, constantly improving off-the-shelf technologies. Use of “UAS Swarms” to carry multiple different sensors simultaneously, or multiple copies of the same sensors to collect data over a wider area at the same time
- Battery capacity and endurance – improving sensor, airframe and battery technologies
- Work with instrument developers to provide “science grade” but UAS-capable versions of EO instruments operating with the necessary geometric, spectral and radiometric performance
- Weather resistance – UASs should be tested and certified where possible
- Changing illumination – ensure downwelling light measurements simultaneous with the UAS data collection; ensure these are of sufficient quality
- Operation at night where required – new technologies (even at the bottom of the commercial market) are advancing night-time operation capabilities
- Lack of trust – undertake validation programmes spanning a range of measurement conditions to demonstrate the effectiveness of UAS-based monitoring methods and provide written reports and publicly available datasets to provide the quality
- Metadata and data formats – develop standards akin to those in satellite data and products
- Calibration and validation of satellite missions, both level 1b data and derived products: We know how to do this using crewed aircraft and ground-based sensors; UASs can in theory easily fit into the effort provided they are able to collect data of the necessary quality and in the correct spectral regions and with the necessary characteristics at the locations targeted - they provide the potential for very frequent observations made at and around the time of satellite overpasses and at very high levels of spatial detail; these are not identical characteristics to those provided by the other solutions
- Collection of remote sensing data to support new mission development and new algorithm development or testing: This is a key role for crewed EO data collection and one that UASs could assist with should they be able to collect data of the necessary quality and in the correct spectral regions and with the necessary characteristics – however in general the commercial COTS UASs and

sensors currently available to the community are not really adequately performing in one or more of these areas and the BLOS restriction is a severe limit to much of the science

4.4.7.5. Recommendations for Advancement

UAS technology and EO capabilities are inherently extremely well suited to one another. Indeed, the collection of digital imagery from UAS platforms is one of their key application areas - and one where there are many commercial UAS providers as well as commercial operators. Expanding the use of UASs in the area of EO science offers major potential to contribute to UK environmental science - especially as many of the basic requirements for processing, curating and exploiting the data from UAS-based EO sensors share many of the same characteristics as doing so with EO data collected from crewed aircraft platforms, ground-based remote sensing devices and even satellites. Effective usage within this research community will be accelerated by:

- ensuring access to cutting-edge technology through provision of national EO infrastructure (including expert support for more sophisticated platform-sensor setup, building on what the NERC Field Spectroscopy Facility has started to provide to the community over the last five years)
- having a dedicated focus on the capability, with sufficient resourcing and documentation, as is the case with the crewed airborne EO capability operated by NCEO
- the development of science-grade EO sensors able to be operated from UAS platforms in a useful manner and with measurement characteristics informed by scientific need - this includes EO for probing the atmosphere (for example GHG column amounts via NIR/SWIR spectroscopy) as well as the surface - and coupled with platforms (and ideally policies) providing the capabilities needed to usefully deploy them
- developing agreed data acquisition and data quality protocols and having appropriate data repositories with quality checks to address the lack of research community trust in UAS data, whilst considering the sustainability implications of increasing dataset sizes
- extending data collection capabilities to BVLOS and enabling UK registered UASs and operators to operate overseas and in areas away from mains power ideally
- creating UAS data processing pipelines that are easy to use and adapt to user needs or which produce “analysis-ready data” and derived data products rather than “raw imagery”
- supporting pioneering approaches to the use and analysis of large EO datasets derived from UAS
- harnessing use of transformative technologies (AI, Machine Learning, Digital Twins) to support handling and analysis of large EO data for example by predicting future trends and automating identification and extraction of key observations
- developing skills in areas such GIS and data analytics to effectively interpret and utilize UAS-derived EO data

4.5. Data

The widespread sharing of data enables researchers, empowers citizens and conveys academic, economic and social benefits. Publicly funded research data:

- are a public good, produced in the public interest
- should be reusable to contribute towards Net Zero
- should be openly available and easily accessible

This has been recognised on the global stage to the extent that the science ministers from the G8 group of nations stated in 2013 that data should be “easily discoverable, accessible, assessable, intelligible, useable and wherever possible interoperable to specific quality standards, while at the same time respecting concerning privacy, safety, security and commercial interests": the G8 endorsed what would become the FAIR guiding principles for scientific data management and stewardship in 2016.

The FAIR principles refer to three types of entities: data (or any digital object), metadata (information about that digital object) and infrastructure. The principles aim to make data:

- **F**indable: To be of use data first has to be found - metadata and data should be easy to find for both humans and computers; machine-readable metadata are essential for the automatic discovery of datasets and services
- **A**ccessible: Once data is found the user needs to know how it can be accessed
- **I**nteroperable: Data usually needs to be integrated with other data streams and to interoperate with applications or workflows for analysis, storage and processing
- **R**eusable: To optimise the reuse of data, the metadata and data must be well-described so it can be replicated or combined with different settings

Traditionally, scientists have focused on the publication of their research findings rather than the archiving of reusable, well-described data products, but in the modern research environment there are now increasing requirements and drivers to document, disseminate and publish code and data in open, citable literature and to demonstrate research 'impact' - funders are requiring demonstrable usage and impact while publishers are requiring data set DOIs (Digital Object Identifiers) and links to supporting processing code and documentation. Whilst the requirements and drivers are clear, the engagement of data providers is poor and a gap is developing between funder expectations and the providers' capability to deliver.

Stating a requirement that data has to be FAIR compliant will not automatically result in the re-use or even the archiving of data - there has to be a supporting infrastructure. Figure 4.2 shows the interactions between users, providers, storage and services. The interactions are complex and nuanced and each community will have its own vocabulary.

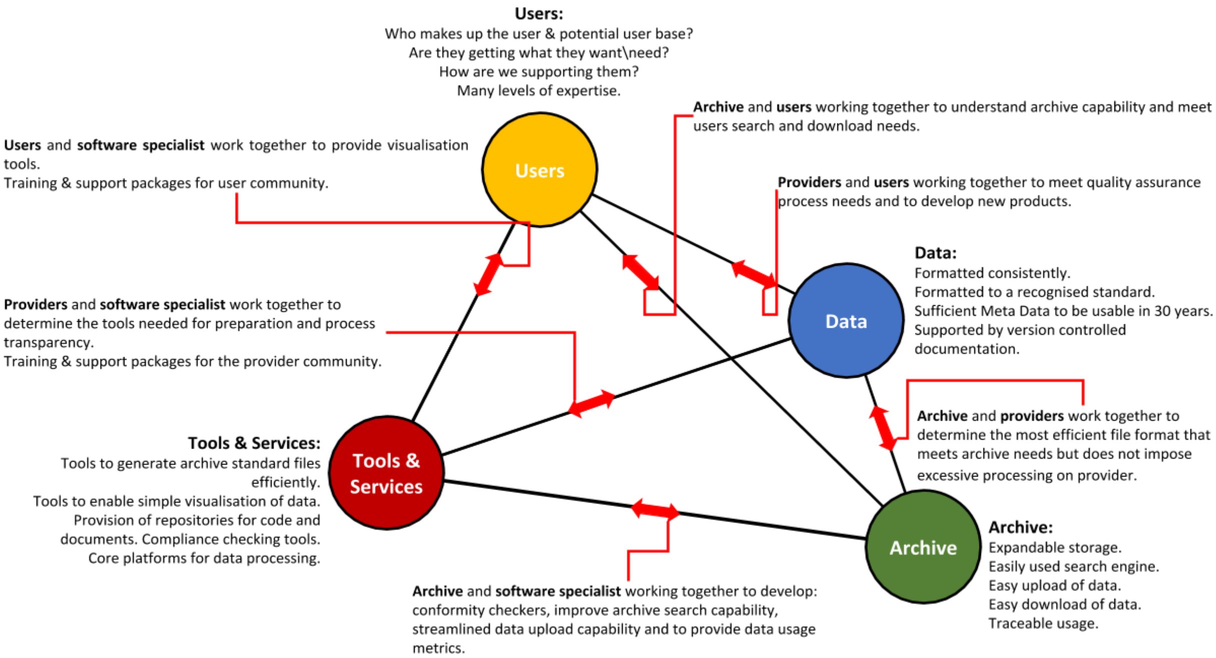


Figure 4.2: *The data pyramid. Users are at the apex but are diverse in scope and capabilities. To truly understand and cater for their requirements they must be engaged with corridors of communication established and conversations started.*

Maximising the potential of UAS-based data streams will need careful engagement with each community: the starting of conversations that establish common vocabularies enabling all parties to understand each other, developing supporting services for both user and provider and clearly articulating the benefits of adopting a "joined-up" approach to delivering FAIR-compliant UAS data. We need to bring the provider communities along with NERC expectations rather than take a punitive approach and impose ways of working. We need to engage the data user communities to ensure the data delivered is structured in a way that is of use to them and where they trust the veracity of what is provided.

4.5.1. Current State of Affairs

When considering the current state of affairs in the data area it is important to remember that many of the problems that are being encountered in the UAS data sphere have been encountered before and actions have been taken to rectify them. There is a danger of "reinventing the wheel" and wasting resources on the development of protocols and approaches and we should be open to learning and building on what is already in place.

NERC has a well-established data policy setting the ground rules for managing data that applies to all those funded by NERC. The data policy details our commitment to support the long-term management of environmental data and outlines the roles and responsibilities of individuals involved in collecting and managing environmental data.

Central to the policy is that NERC-funded scientists must make their data openly available within two years of collection and deposit it in a NERC data centre for long-term preservation. The aim is that all NERC-funded data are managed and made available for anybody to use without any restrictions.

The UKRI-NERC Environmental Data Service (EDS) provides a focal point for scientific data and information spanning all environmental science domains: atmosphere and climate, earth observation, polar and cryosphere, marine, terrestrial and freshwater, geoscience, solar and space physics. It is a distributed service of five data centres managed by six NERC Research Centres - each focused on a particular area of domain expertise:

- British Oceanographic Data Centre (Marine, NOC)
- Centre for Environmental Data Analysis (Atmospheric, Earth Observation, and Solar and Space Physics, NCAS & NCEO)
- Environmental Information Data Centre (Terrestrial and freshwater, UKCEH)
- National Geoscience Data Centre (Geoscience, BGS)
- UK Polar Data Centre (Polar and Cryosphere, BAS)

Airborne data sets from the FAAM Airborne Laboratory, balloon soundings, not to mention pigeons are held at the Centre for Environmental Data Analysis (CEDA) and data sets from BAS Masin Twin Otter and UAS-based data sets are spread across CEDA and the UK Polar Data Centre. Searches for UAS-based data on any of the archives are currently not straightforward or intuitive - this does make finding such data without prior expert knowledge challenging. Although UAS-based activities are occurring across NERC Centres and Collaborating Institutes, the data arising does currently not seem to be deposited in any regular manner.

Across the board, there is as yet no standard approach to metadata, file format and structures and following protocols or documenting activities appears to be a haphazard. This means there can be no coordinated approach to developing user tools or for these data streams to be included in activities such as the UKRI-NERC Data Hub being developed through the Digital Solutions programme at the University of Manchester.

Internationally the situation is comparable. The International Society for Atmospheric Research using Remotely-piloted Aircraft (ISARRA) provides a forum for the exchange of knowledge, experience and ideas on the various aspects of atmospheric and related environmental research using remotely piloted aircraft but does not seem to have addressed the data question. The European Cooperation in Science and Technology (COST) is a funding organisation for the creation of research networks, called COST Actions. COST is bottom-up, which means that researchers can create a network – based on their research interests and ideas – by submitting a proposal to the COST Open Call. Although there have been COST Actions around UAS use, again these have focused on platforms and sensors, not on an approach to data. ACTRIS (Aerosol, Clouds and Trace Gases Research Infrastructure) is a pan-European research infrastructure producing high-quality data and information on short-lived atmospheric constituents and on the processes leading to the variability of these constituents in natural and controlled atmospheres. Among its activities are the standardisation of data and calibration and operational best practices SOP development and it appears that UAS usage is included. ACTRIS is a "members club" and to access the infrastructure and services a country has to be a signatory contributing a membership fee - the UK is due to join at some time in 2024.

Having standards for UAS data is essential in addressing the current need for expert knowledge required to utilise the data. In short, the current situation is neither equitable nor inclusive - use is restricted to an exclusive elite. Without a standard approach to how data is archived, no progress can be made in developing software tools for either users or providers.

At the start of this section, it was stated that we do not want to "reinvent the wheel" and the community should be open to building on the work that has been done in other areas to address similar problems. Initial steps on the path towards developing a UAS data standard have been taken by the EDS (as part of Work Package 4 of the EDS UKRI Digital Research Infrastructure Phase 1b grant: Frémand, Alice (2023) UAV data management handbook & Towards a data commons: Imagery and derived data from autonomous and remotely piloted aerial vehicles) and extensive work has been undertaken by NCAS to establish a suite of internationally aligned standards for the FAIR-compliant archiving of observational data that meet the needs of the user communities across the extensive portfolio of NCAS activities.

4.5.2. Where We Want to Be

We want to develop a "gold standard" for the UK UAS data – one that is aligned with international practices but is world-leading and one that allows providers to say what they do and do what they say. We should enable equal and equitable access to data for expert and non-expert users through the training and provision of visualisation and comparison tools. We should also support our providers with tools as well as clear processes for the development of data products.

We are aiming to:

- lower the bar for expert knowledge to access data
- enable pull-through of UAS-derived data to models – are we providing the end user with the data they want in the way they want it?
- ensure centres and communities upload UAS data within a defined period after collection – following a defined protocol
- define the roles and responsibilities of individuals involved in collecting and managing environmental data including support for a data management plan
- provide focused user engagement - getting the community to help develop new data products and ways of analysing the data.
- have a joined-up approach across NERC data centres:
    - data products are delivered in the same format to their EDS node

        - common archive structure of UAS data at each EDS node
        - no need for a special data centre if this is done
    - Comprehensive software suite for providers
        - combining different sensor streams
        - make it easy to deliver the final data product
        - compliance checkers
        - training
    - Comprehensive software suite for users
        - flight finder tool
        - visualisation code
        - comparison of data in multiple files
        - community workshops and support surgeries
        - training

A key factor in the take-up of data by third parties is the trust those users have in the data being provided. Alongside defining data and metadata we also need to take a look at data uncertainty. There is a need to

- agree on an approach to evaluating measurement bias - grounded in scientific literature
- deliver uncertainty alongside the measurement data
- develop SOPs and best practices for data processing
- develop open repositories for non-proprietary processing code
- develop an open repository of calibration and service data

4.5.3. Gap Analysis (Barriers/Challenges and Solutions/Opportunities)

In and around UAS data there needs to be more community cohesion, collaboration and agreement on best practices. This situation has arisen from a combination of a fast-moving technological field and the need, by community members, to be seen to be the first to publish something novel. There is a clear opportunity for UKRI-NERC to provide leadership and to collaborate with the wider science community to develop processes, structures and protocols that are grounded in best practice and are traceable not only to international stands but to relevant science references. There is an opportunity here to position the UK as a leader in UAS data delivery and usage on the global stage and it is the NERC Centres and Collaborating Institutes that are pivotal in this: to lead by example and work together to develop initial protocols and put them into practice.

The current barriers/challenges include but are not limited to:

- researchers are mostly working in isolation and little is documented
- lack of standard file format, structure or metadata definition
- lack of common and documented approach to data processing practices, Quality Assessment, or Quality Control
- lack of agreed and documented best operational and calibration practices
- lack of understanding and representation of measurement bias
- lack of software tools being developed for either the user or the provider
- communities are not sufficiently collaborating or communicating
- no “data pyramid” exists in the UAS arena

The current situation may look dire but it does offer a wide variety of opportunities and some solutions may make a substantial difference to improving the situation. These include but are not limited to:

- EDS nodes working together to develop a common approach
- EDS nodes intensifying dialogues with users and providers to develop the data pyramid for each area
- aligning with best practices internationally
- NERC Centres and Collaborating Institutes putting best practices into action
- strategic and focused user community engagement and consultation: this will be different for each science community

4.5.4. Recommendations for Advancement

There is a danger of "reinventing the wheel" and wasting resources on the development of protocols and approaches that already exist for data from existing airborne platforms: many of these problems have been encountered and actions have been taken to rectify them. For example, there are activities underway under the banner of the Mid-Life Upgrade of the FAAM platform that will introduce standard data file formats, structures and best practices which will lead to data products having a legacy beyond the lifetime of a particular project, enable the development of user tools that allow comparison and integration with other data streams including model streams and are accessible to machine learning tools.

In the UAS sphere, it is recommended that to start the journey from where we are now to where we want to be, as discussed in section 4.5.2, the following specific actions be taken:

- Internally to UKRI-NERC, NERC Centres and Collaborating Institutes and EDS
    - NERC to indicate that this is the direction of travel and provide the necessary resources to deliver it
    - Review of data formats and approaches available or under development that could be adapted
    - EDS nodes work together to develop a common approach to archiving and define what they require from providers
    - Development of UAS data standard(s)/format(s) and metadata
    - Development of exemplar tools for users and providers
    - Development of training and support material for the standard and the tools
    - NERC Centres and Collaborating Institutes to deliver UAS data in the developed format to their EDS node within a defined period

- Wider Science Community
    - Starting dialogues with users - what do users want and how do they want it delivered - what would encourage third-party take-up and pull-through to impact. The starting point would be what has been put in place through the above actions by the NERC Centres and Collaborating Institutes.
    - Proactive engagement with international bodies in the same area – sharing best practices – aligning approaches – taking a lead
    - Establishing forums and being proactive in engaging with both user and provider communities
    - Starting community consultation and engagement showing the benefits of a joined-up approach

5. Conclusions and Recommendations

UKRI has set itself the ambition of becoming a carbon-neutral organisation by 2040 and as part of that, NERC is working to identify options for developing a world-class aerial capability with a reduced carbon footprint through the increased use of Uncrewed Aerial Systems (UAS) capability. The scoping work that NERC has commissioned its Centres and Collaborating Institutes to conduct, and that culminates in this report, has seen extensive user engagement in the form of workshops, forums and surveys to deliver a comprehensive information source and a series of recommendations. These aim to enable NERC to effectively plan for future opportunities in this space.

Regulation, technology and data have formed the three broad themes explored during the community workshops and consultations: Technology is further divided into platforms, sector-specific sensors and how they are integrated; the data section focuses on standards, archiving and tools for both user and provider. The engagement of the community and their enthusiastic response have delivered a wealth of information. Although there are very specific conclusions and recommendations associated with each of the themes, conclusions and recommendations common to all themes also emerged. In this chapter, we first present the overarching conclusions and recommendations and then give an overview of those that are theme-specific.

5.1 Overarching Conclusions & Recommendations

The use of UASs is a powerful mechanism by which the carbon footprint of airborne scientific research can be addressed. It also opens up the opportunity for new science: at the moment research is constrained by the limitations of the current crewed aircraft capability. For example, there are extreme, sensitive (i.e. easily damaged by more intrusive methods of observation) and remote environments that are inaccessible to larger platforms. Furthermore, where work is needed at high spatial resolution or in close proximity to vertical and horizontal surfaces, slow flying platforms or high temporal resolution measurement capability are required. Table 5.1 below shows some of the areas that a UAS capability could open up and enhance.

Table 5.1: *Areas which could be enhanced through UAS capability*

Sampling ● Whole air samples of the atmosphere in precise locations ● Insect, pollen and spore sampling ● Rapid air averaging in low winds or calm conditions	Clouds and fog ● Fog formation ● High spatial resolution of cloud properties
High-altitude applications ● Satellite instrument test bed, calibration and evaluation ● Iron layer sampling	Situational response ● Fast and agile response to developing situations (including floods, landslides, sinkholes, crevasses) of interest to the scientific community and for operational benefit ● Improved navigation and Search and Rescue
Extreme and difficult operational environments ● Polar Environment & ice-covered areas ● Steep-sided valleys, cliffs & quarries ● Operations within the forest canopy ● Reaching remote locations and offshore stations ● Filling in the gap below crewed aircraft	Routine observations and monitoring ● More options to cover greater areas ● Automated greenhouse emissions gas accounting (horizontal fluxes) ● Boundary layer profiling ● Crops, livestock, biodiversity

● Air-sea interactions & remote marine boundary layer ● Sea surface temperature ● Shallow water bathymetric surveys and mapping seabed habitats ● Sensitive flora and fauna	● Harnessing Citizen Science for the benefit of data collection, with the caveat of quality control

The platforms currently in use and those required to meet the needs of new and emerging science indicate that there is a need for a spectrum of capabilities: ranging from UASs the size of bees, that can be used in swarm formations to rapidly observe changing phenomena, to platforms that are capable of long duration, high altitude operations and heavy lifting. There will, however, likely continue to be a need for crewed airborne science capabilities: for some instruments, miniaturisation and light-weighting may not be achievable to the degree necessary to enable them to be flown on even the larger autonomous platforms. Furthermore, as the technological landscape advances and the scientific needs of the community evolve, new instruments and analysis techniques will be developed. The proof of concept for new instrumentation is a critical stage before the specialist adaptations required for integration on a UAS platform can be addressed. Testbed capability that facilitates innovation and "heavy lifting" capability sits more with advances involving crewed aircraft than UASs.

Reaching the 2040 Net Zero goal requires the wider science community to increase their use of modern platforms such as UASs. There are many barriers to overcome here, such as (i) "trust" in the measurements being taken, (ii) access to technology, (iii) support around regulation both for national and international operations, (iv) the provision of specialist training, as well as (v) the uptake of data for use by third-party researchers. More information on each point is provided below:

- **Building Trust:** To build "trust" in the veracity of measurements requires understanding, minimising and characterising all the areas of bias to the extent that each datum is associated with a quantified level of uncertainty. As with any cutting-edge and rapidly evolving technology, there is the fear of missing out or not being the first to publish. This leads to a situation where the emphasis is the "doing", rather than on the quality of what is being done. To overcome this there needs to be greater emphasis on calibration of platforms and sensors both in the laboratory and in the field.
    - *Key recommendation:* Develop and adopt proven, transparent and if applicable internationally recognised best practices for calibration, operations and data processing.
- **Technology:** There is a substantial amount of rapid development in both platform and sensor development, but these activities are not joined up: not between fields and not between groups. Development in isolation of either sensors or platforms increases the risk of duplication/missed opportunities and wasted resources. To be of scientific use both the platform and sensor(s) have to be integrated, the entire package characterised, calibrated and the measurement uncertainty estimated. This is a skill in itself with the associated problems of finding, developing and retaining staff. There is substantial activity in this area within the military sector but costs for access are often prohibitive to scientists. There are three communities engaged around UASs: (i) the scientists wanting to make a particular measurement, (ii) the sensor developers and (iii) the platform developers. Innovation and development come from the interaction of all three and the challenges they can set for each other.

    - *Key recommendation:* Work towards cross-council leveraging of expertise to facilitate the rapid development of compatible sensors and platforms.

- **Regulation:** There are restrictions to some flight modes, such as BVLOS, in many key geographical areas of interest that are proving prohibitive to the types of science that the community aims to undertake. The CAA are in a continuous cycle of regulation development and for the needs of UK science to be met, the united voice of the science community needs to be heard. To establish a respected voice, the science community needs to build a case to show that it is a trusted partner in the use of UAS platforms through the adoption of best practices.

    - *Key recommendation 1:* Introduce a single CAA-NERC point of contact: NERC acting as a responsible officer, proactively building a relationship and managing requests to minimise duplication of effort: i.e. preventing the bombardment of the CAA with the same requests for help and information from the environmental science community.

    - *Key recommendation 2:* Establish and maintain a central documentation repository and FAQ database. It is envisaged that the repository would include, but not be restricted to, regulatory paperwork, central operations manuals/SOPs, predefined risk assessment and templates, links to information sources, a central log of incidents and outcomes lessons learned (evidence of building a culture of Safety and Trust with CAA) and a central list of existing equipment and pilots.

- **Training:** One aspect of the regulations is the need for pilots (compliant with CAA registration requirements and local or host institution insurance and operational procedures) to maintain logged hours of flight experience; the more complex the mode of operation the more hours that are needed. This means that pilots need regular access to areas where pilot-hour maintenance flights can be undertaken; these are not readily available or easily accessed. The majority of pilots in the NERC community are also the scientists involved with the research which leads to retention issues as research projects end and this can be costly both in terms of finance and time for longer-term programmes. One solution would be for the development of a "pilot pool": pilots with the required hours on a range of platforms that could be "hired" by a programme. It has been highlighted that there is a need for the pilots to form a community network and establish a forum where they can share expertise and experience. The community identified the need for training to address the skills gap in regulatory knowledge and operational capability. It is recommended to organise a general overview workshop for all wanting to use UASs, giving non-pilots an overview of the processes and regulations and providing stakeholder understanding. Training is an integral and important part of any enhanced effort to increase UAS usage.

    - *Key recommendation:* Develop one or more geographically accessible or discipline-focused CAA-approved training centre(s) and programme(s).

- **Data Uptake by Third Party Users**: The deployment of cutting-edge sensors on cutting-edge platforms making new measurements in new places all result in the production of data. This data is valuable, not just to the individual or group collecting it, but also to the teams collaborating on a project and in the longer term to third parties. At the moment teams and individuals are producing raw data sets that are stored and processed in-house following their bespoke processing tool-chain and are not necessarily following FAIR guidelines. The file structure and format of the processed data uploaded to data archives (if at all they are) varies, with no consistency. This hampers discovery and automated pull-through to models, excludes use by researchers not having the appropriate expert knowledge, prevents access to AI and ML algorithms and removes potential data sources critical from near-real-time decision-making.

- *Key recommendation 1:* Develop and adopt standard file formats, aligned with internationally recognised best practices, and resource data centres appropriately to facilitate the development of user and provider tools and enhanced useability and inclusion.
- *Key recommendation 2:* Integrate UAS data sources into planning for Digital Research Infrastructure.

The barriers to UAS usage have resulted in the proliferation of companies offering UAS-based services ranging from just a platform to fully integrated sensor/platform packages that deliver an end data product. Partnering with such service providers has many advantages in that resources needed to develop a new UAS activity can be used in doing the measurement. In some applications, this may appear the best option but for a significant fraction of use cases the lack of transparency around sensor calibration, post-processing and the uncertainties in the final data product results in a lack of trust in the veracity of the product.

In effectively planning for future opportunities in this space, NERC has a real opportunity to not only address many of the obstacles that are preventing the greater use of UASs but to establish the UK as a world leader in the overall area of UAS usage for science and align activities with those internationally. It is also an opportunity to train the next generation of scientists in the responsible use of this technology through the development of a dedicated CDT that brings together science, sensor & platform development, integration engineering, data stewardship and pilot training. It also offers a chance to support scientists through the full project lifecycle, from concept to impact and lower the need for expert knowledge and ensuring inclusive opportunities to a diverse use base.

To encourage adoption of UASs where they would provide lower carbon options compared to the use of established crewed facilities, a review of NERC grant funding mechanisms may be advisable: Presently many grants use less efficient and higher carbon delivery methods because national capabilities are free at point of use for a grant, while use of novel, lower carbon methods has to be accommodated within the funding ceiling of the grant application.

Table 5.2 below summarises the key overarching recommendations for the community (NERC Centres and Collaborating Institutes and wider) and those specific to NERC that have been identified through this work.

Table 5.2: *Key overarching recommendations for the aerial autonomy community and for NERC*

A. **Key Overarching Recommendations for the Community**
Best practice: A1. Quantify and reduce bias and variance in UAS-based measurements. A2. Co-develop, share and adopt open and transparent data processing protocols and open licence UAS data processing pipelines. A3. Develop and adopt recognised best practice operational protocols. **Coordination:** A4. Create a network to work together more extensively and share experience, knowledge and capabilities. A5. Convene expert working groups to establish feasible development pathways and to build mutual understanding. A6. Improve access to both UAS capability and UAS-derived data. **Wider engagement:** A6. Make the best use of Citizen Science, with the caveat of quality control. A7. Encourage UAS and sensor suppliers to maintain backwards compatibility. A8. Be proactive in engaging with international bodies working on data standards, guidance, formats and approaches.

B. **Key Overarching Recommendations for NERC**
Strategic steer: B1. NERC to develop a strategy on science and innovation in remote data collection, autonomous and robotic capability, leveraging synergies across aerial, marine and terrestrial sectors. **Funding:** B2. Focused calls for development of UAS sensors and application of innovative UAS technologies relevant to the natural environment, including the understanding and quantification of measurement biases. B3. Drive innovation across NERC by developing joint programmes and initiatives across UKRI (challenge areas) and across institutions. **Resources:** B4. Develop a "pilot pool" both for regular surveying of proven systems and test pilots for first flights of novel configurations, linked to a NERC UAS training centre/programme approved by CAA. B5. Provision of dedicated field test/flying areas for sensor and airframe synergy development and training of pilots. **Data recommendations:** B6. Develop and maintain a central resource to gather, store, disseminate and communicate information across the sector. B7. Have a joined-up approach across the NERC Environmental Data Service to negate the need for a new dedicated data centre for UAS data. **Skills and knowledge recommendations:** B8. Establish UK forums to encourage collaboration and sharing of skills, fabrication capability and experience within and between UAS specialist groups. B9. Provide funding support for the development of a NERC Doctoral Focal Award specific to encouraging UAS usage in environmental science, training the next generation and breaking down barriers to access. B10. Facilitate UK-wide travel support and community building/knowledge transfer to engage with the global community.

5.2 Sector Specific Conclusions & Recommendations

In the previous section, the conclusions and recommendations that were found to be common across all the focus areas were introduced. Engagement and consultation with the community unearthed a rich stream of information from which the sector-specific conclusions and recommendations, presented below, have been developed. Regulation is addressed throughout this chapter and in Tables 5.2 and 5.3, hence is not presented in a dedicated subsection.

5.2.1 Technology

The technology sector evolving around UASs is developing rapidly with ever more complex systems coming to market with the appearance of many new suppliers of off-the-shelf capability that often proves unreliable. Keeping current and taking advantage of the advancing technology is a challenge. This rapidly changing landscape also brings with it issues around hardware lifecycle management, backwards compatibility, obsolescence and environmental sustainability. In this area, there is a need for UK-based green technology development to drive sustainability from the full-cycle pathway from source materials to the recycling of UASs and sustainable operations (fuel and automated charging).

Technology innovation is driven by current capability being challenged by novel end-use cases, while science can only come up with novel end-use cases if it is confident the capability can be developed. Science and engineering need to meet and drive innovation and development forward through collaboration. A clear understanding of the UKRI landscape and a coherent aspirational strategy could drive innovation across UKRI leveraging cross-council expertise. Areas where there is a clear need for innovation include, but are not limited to:

- **Platforms:** There is a huge variety and diversity of platforms available for the user. These include multiple-rotor and fixed-wing platforms and in some cases these cost less than the sensor a user wants to deploy. The proliferation of platforms is not supported by a full suite of information regarding environmental limitations, flow distortion, stability, battery life and duration of operation. Making the right choice of platform can be a minefield and a serious challenge to a user and a barrier to UAS user uptake. Experience and expertise exist in the community and this needs to be shared to a far greater extent. There is a great opportunity for innovation within this field; to bring the scientific and engineering communities together to develop platforms that fully meet the needs of the science community and push the boundaries for novel applications (see also 'Integration of platform and sensors' below).
    - *Specific recommendation:* Facilitate more collaboration between platform developers and science users
- **Sensors:** Stand-alone and bespoke sensors are being developed to meet specific scientific needs, but do not always take account of requirements for deployment on a UAS. Introducing compatibility retrospectively is high-cost and often done in isolation. Making sensors UAS-appropriate requires sensor miniaturisation without compromising the quality of the measurement. Cost is a significant barrier that has resulted in the community looking to exploit the explosion in low-cost sensors that has been seen in the last decade, sometimes with implications on measurement quality (see also below). Sensor operation may impact both the platform, for example through electrical interference and regulatory certification, for example when using a camera, LiDAR or more complex sensors. Current BVLOS regulations, a mode of operation of significant interest to the community, do not allow for changes to operations or platform and payload specifications once a mission is underway.
    - *Specific recommendation:* Collaborate with CAA to develop clear guidelines around the regulatory impacts of sensors and facilitate the sharing of experience and advice
- **Integration of platform and sensors:** In many areas, the working concept is that a sensor package can be developed, put in a box and that box can then simply be "strapped" to a platform. This is not the case. Adding any payload to a platform will impact the platform's performance: This may have minor but noteworthy effects for example on operational duration or manoeuvrability. However, any novel integration of an electronically active payload may have a severe, unexpected effect on the platform due to, for example, Radio Frequency Interference (RFI). Test flights of novel integration require additional pilot skills and safety awareness, knowledge which at present is not easily shared within the NERC community. Integration also impacts the flow of air around the platform and hence some sensors. For a subset of sensors for atmospheric science, understanding flow distribution is critical to the placement of sensors and the understanding of measurement uncertainty. There is also the area of integration of data streams. Physically connecting a sensor to a platform could be simplified by the adoption of a plug-and-play approach, i.e. modularisation and the development of sensor pods with standard mounting and connectors which would result in minimising the need for recertification. Both the platform and the sensor package create a data stream. It would be more effective for there to be a mechanism by which these could be fused for example to develop an Application Programming Interface (API).
    - *Specific recommendation:* Enable closer collaboration between sensor developers and platform developers/manufacturers, informed by science users

- **Measurement quality:** A recurrent theme is the need for a greater emphasis on the quality of the measurements being made. Uptake of UAS capability by the community depends on building "trust" in the data product. This requires systematic validation and calibration of the platform sensor and the integrated system and this needs to be done in both controlled laboratory conditions and in the field. Field calibration requires designated areas to be developed which are supported by appropriate instrumentation against which the UAS is compared. Development of new sensors is time-consuming and expensive but there has been a proliferation of the availability of low-cost sensors. It is unclear if these sensors are fit for purpose in the scientific arena.
    - *Specific recommendation:* The community to start a consultation to determine what is "fit for purpose" and hence develop a list of which sensors are appropriate to use
- **Operations:** To be of use to the science community, UASs need to be capable of operating in environments that are often outside the original design envelope for example requiring higher flight speeds, higher altitudes or operations in complex and extreme environments. This means the integrated sensor and platform need to be reliable and stable and collaboration between the platform and sensor developers is needed to achieve this. Operations in extreme environments are not just restricted to the consideration of weather conditions, such as mitigating the effects of intense heat, cold and icing, but it also applies to working in crowded airspace and in areas that are congested by obstacles. Enhanced collision avoidance is essential for safe operations.
    - *Specific recommendation:* Develop and validate platforms and operational controls to allow operation in extreme environments (specifically extremes of temperature)
- **Sustainability:** UAS use is being proposed as a mechanism by which the carbon footprint of airborne research activities can be reduced. UAS activities in themselves are not carbon neutral and there is an opportunity here for innovation to reduce it. UASs need to be powered, be that through the use of batteries, solar power or liquid fuel. The method used depends on the operational application but across the board, this is an area where focused development is needed for example developing light, safe, high-capacity batteries and automatic recharging capability. UAS platforms are made from a range of materials chosen for their engineering properties and once obsolete or damaged beyond further use tend to be discarded.
    - *Specific recommendation:* Develop UAS platforms that are recyclable with components, including power train, that are environmentally sustainable, extending to the development of platforms that are biodegradable (lessening environmental impact if lost in the field)
- **Relationships:** To develop, or have access to a UAS that is fit for purpose, action needs to be taken to build strong relationships with UAS developers and providers. Building lasting relationships with established providers and developing fruitful links with relevant engineering groups requires being proactive and committing resources.
    - *Specific recommendation:* The science community to engage with technology providers to communicate their current and future needs

5.2.2 Data

Data is a broad term and as used in this context encompasses many areas of interest; not only its stewardship or compliance to FAIR principles, but also software, volumes and how data can be fused. UAS missions are a rich source of data with great research potential, but for this to be realised there needs to be greater consideration of data stewardship. Data stewardship involves the formalisation of roles and responsibilities and their application, to ensure that research objects are managed for long-term reuse and in accordance with the FAIR data principles. The FAIR principles emphasise machine-actionability (the capacity of computational systems to find, access, interoperate and reuse data with no or minimal human intervention) because humans increasingly rely on computational support to deal with data as a result of the increase in volume, complexity and creation speed of data. Across the spectrum of providers, there is a lack of understanding and appreciation of what this means, entails and how they will benefit. The community needs to understand data management principles to be able to apply them.

The need for the adoption of a data standard and the benefits this brings have been introduced in the previous section in overview form.

Drilling down into the details has revealed several specific areas of challenge.

- **Standards:** The need for the adoption of a data standard across UAS activities and the need for this to be aligned with those in use internationally has already been discussed. This does have wider implications as there would have to be sharing across many scientific areas, including operational procedures, calibration techniques and data processing. A main recommendation is that walls between groups need to be broken down and a culture of collaboration and sharing be encouraged.
    - *Specific recommendation:* Develop and adopt data standards to facilitate the development of generic open tools
- **Metadata:** This is the information about the platform and sensor package, calibration history, mode of operation and so on. This information needs to be available for both platform and sensor, as sensor packages can be carried by different platforms. A subset of metadata is the concept of PIDINST (Persistent Identifier for Instruments; much like a DOI for papers). These provide long-term traceability for instruments and can be referenced in the main metadata in a file.
    - *Specific recommendation:* Adopt metadata standards (such as the UK Gemini ISO 19139 data standard used by the EDS) and develop controlled vocabularies

There are many benefits around the development of generic software tools that come with the adoption of standards, but there are also many issues and challenges faced by providers in this sphere. A significant proportion of the instrumentation used relies on manufacturer-proprietary software, which is often expensive with licences that limit the amount of data that can be processed, the number of users at any one time or the number of systems it can be installed on. Reliance on the manufacturer's software also introduces challenges around obsolescence, software updates and support. Increased usage will see the production of increased volumes of data and processing challenges from a licence perspective. A solution in this area is the use of open-source software. Such software does exist and has been tested, but there are challenges around reliability and ongoing support. However, in some areas, such solutions are lacking, including for fusing data feeds from the platform (telemetry) with those from the sensors. The development and ongoing support of open-access software requires software engineering skills not commonly available within the science community - the lifecycle of software products is as important as that of hardware. The required skills are in great demand commercially and hence there are difficulties in recruitment and retention.

Greater use of UASs and enforcement of the NERC data policy should see an increase in the volume of data (raw, intermediary and post-processed archivable products) and will have an associated carbon footprint and cost. There is a need for discussion on what data to keep, for how long and where, particularly concerning raw and intermediary data (as when new processing techniques are developed, they can only be applied if the raw or intermediary data files are available). With processed data currently stored in multiple file formats across the EDS there is a high risk of duplication and replication in addition to poor visibility. The adoption of standards and the development of a Discovery Data Portal would go a long way in decreasing data-related risks.

Table 5.3 below summarises the key conclusions and recommendations for both the community and NERC that are specific to the topic area.

Table 5.3: *Sector-specific key conclusions and recommendations for the aerial autonomy community and for NERC*

Report section	Key Conclusions (KC)	Key Recommendations for the Community (KRC)	Key Recommendations for NERC (KRN)
4.1 Regulation	4.1. KC.1: The regulatory framework can be complex and can change quickly both within the UK and internationally 4.1.KC.2: It is essential for the research community to keep up-to-date with any regulatory changes 4.1.KC.3: Certain regulatory restrictions exclude some areas of research, including flying beyond visual line of sight (BVLOS) and heavy UASs 4.1.KC.4: Maintaining the currency of UAS pilot flight hours within research groups can be difficult due to time constraints and staff turnover	4.1.KRC.1: Develop future regulation through the research community working with the CAA, to allow for environmental science applications 4.1.KRC.2: Explore mechanisms by which the UK can affiliate with EASA (EU Aviation Safety Agency) to allow UK pilots to fly in all EU countries and vice versa	4.1.KRN.1: Provide a NERC-funded point of contact for the environmental research community who can assist with any regulatory or training questions for UK and international UAS usage
4.2 Platforms	4.2.KC.1: The landscape of available platforms is rapidly developing, opening up potential new opportunities for carbon savings and science applications 4.2.KC.2: Making use of these requires flexible approaches, for example leasing (with existing certifications and pilot) rather than owning 4.2.KC.3: Smaller platforms (<10kg) struggle for time in the air/range 4.2.KC.4: Opportunities for UAS and sensor reuse or recycling are very limited. This affects sustainability as platforms and sensors become obsolete very fast	4.2.KRC.1: Review current methods and processes to establish where UASs are an effective replacement for existing higher-carbon methods of data collection 4.2.KRC.2: Provide requirements and use case examples to industrial and engineering R&D collaborators to encourage the development of more suitable future platforms for science sensors (for example alternative power sources, range, endurance and so on) 4.2.KRC.3: Develop alternative sources of power for example hydrogen fuel cells; encourage collaboration with Engineering R&D for platform development 4.2.KRC.4: Ensure that UAS capability is in line with UKRI's Trusted Research and Innovation and encourage UK development of future-proof	4.2.KRN.1: Carry out further assessment to identify whether NERC should own, buy in service, or develop a centralised or distributed facility with a wider remit than the current UAS-offer of the NERC Field Spectroscopy Facility (FSF), particularly to include larger UASs, BVLOS capabilities and training and test sites 4.2.KRN.2: Create shared UAS (and sensor) registers to enable all NERC organisations using UASs to share their knowledge and indicate what UAS can be loaned or provided as a collaborative service to others (in addition to the spectroscopy-focused offer of FSF) 4.2.KRN.3: Encourage the use of partially or completely recyclable platform-sensor setups; provide focused calls for the development of partially or fully recyclable platforms and sensors; share any opportunities for re-use or recycling

		platforms for science, incl copters (through EPSRC, Innovate UK and industry activity)	4.2.KRN.4: Engage with the government for UK-based green technology development and to drive sustainability through a full-cycle pathway from source materials to recycling UASs
4.3 Sensor Integration	4.3.KC.1: Integration of sensors with platforms in a way that neither impinges on data acquisition nor on certification is an essential step in building UAS capability for science and needs to be adequately resourced 4.3.KC.1: Gaps currently exist in the integration of sensors onto platforms and access to platforms for proof of concept testing	4.3.KRC.1: Develop a capability to model airflow around airframes and easy-to-use tools that break down the need for expert knowledge 4.3.KRC.2: Develop plug-and-play systems for easier integration of platforms with sensors	4.3.KRN.1: Maintain and expand expertise and knowledge within facilities managed by NERC Centres and Collaborating Institutes on platform certification for novel sensors
4.4.1 Sensors - Atmospheric	4.4.1.KC.1: Many commercial suppliers provide UAS atmospheric observational services - not all are rigorous or transparent in their data processing and calibration	4.4.1.KRC.1: Develop capability in the following areas: 4.4.1.KRC.1.1: PM (Particulate Matter) size-resolved mass loading, carbon mass loading 4.4.1.KRC.1.2: Precipitation, cloud, droplet and aerosol size distribution 4.4.1.KRC.1.3: Aerosol composition and optical properties 4.4.1.KRC.1.4: Cloud particle and precipitation imagery 4.4.1.KRC.1.5: Cloud, condensation and ice nuclei concentration 4.4.1.KRC.1.6: In-cloud temperature 4.4.1.KRC.1.7: Total water content 4.4.1.KRC.1.8: Whole Air Sampling (WAS) 4.4.1.KRC.1.9: Remote sensing: LiDAR (multi-wavelength and doppler), Radar (W, S, Ka and X band, insect), DOAS (Differential Optical Absorption Spectroscopy) 4.4.1.KRC.1.10: Spectral radiometer 4.4.1.KRC.1.11: Infra-Red thermometer for surface temperature 4.4.1.KRC.1.12: Trace gases: Air Quality (O_3, SO_2, NO_x), Greenhouse Gases (CH_4, CO_2, CO, NH_4), Volatile Organic Compounds, Halo-carbons	4.4.1.KRN.1: Develop calibration capability for sensors both in the laboratory and in-field 4.4.1.KRN.2: Launch funding opportunities to resource development of medium TRL (Technology Readiness Level) capability towards an operational fleet of integrated sensor/aircraft 4.4.1.KRN.3: Fund a programme to identify the FAAM (Facility of Airborne Atmospheric Measurement) capability that can be miniaturised for UAS use and make it happen

		4.4.1.KRC.1.13: TKE (Turbulent Kinetic Energy), diffusivity, eddy covariance (EC) of winds (i.e. momentum transfer) 4.4.1.KRC.1.14: EC of sensible heat 4.4.1.KRC.1.15: EC of trace gases 4.4.1.KRC.1.16: Radiation divergence (solar and terrestrial) 4.4.1.KRC.1.17: Temperature structure (Temperature Structure Function Coefficient CT^2)	
4.4.2 Sensors - Ecology and Biodiversity	4.4.2.KC.1: We require lighter multi- and hyper-spectral sensors covering the full spectrum of 300nm - 2500nm for vegetation traits, stress and physiology studies, water quality studies, plastic and gas pollution 4.4.2.KC.2: Retrieving surface temperature from thermal sensors can be challenging with more affordable systems 4.4.2.KC.3: For LiDAR: processing raw data into usable (standard) formats is not transparent	4.4.2.KRC.1: Improve simultaneous recording of (downward) solar irradiance and (upward) surface reflected radiance across narrow spectral bands	4.4.2.KRN.1: Launch focused opportunities for development and innovation of UAS sensors: with emphasis on multi- and hyper-spectral reflectance retrieval including SWIR
4.4.3 Sensors - Geosciences	4.4.3.KC.1: We require lighter multi- and hyper-spectral sensors covering the full spectrum VNIR, SWIR and TIR for geoscience mineral identification 4.4.3.KC.2: We require lighter more stable-tethered geophysical sensors to measure specific geophysical parameters for the subsurface, such as time-domain EM (TDEM)	4.4.3.KRC.1: Develop a hyperspectral TIR sensor for UAS deployment to be applied for geosciences, with a testing and calibration facility to enable trust in measurement quality and accuracy 4.4.3.KRC.2: Develop TDEM capability for UAS deployment to enhance geophysical subsurface measurement, with testing and calibration facility to enable trust in measurement quality and accuracy	4.4.3.KRN.1: Open funding opportunities to develop, build and test (i) a hyperspectral TIR sensor suitable for use on UASs for geological application and (ii) new geophysical sensors to extend geophysical measurement capability from UASs
4.4.4 Sensors - Glaciology	4.4.4.KC.1: Radar is the key technology for glaciological observation 4.4.4.KC.2: Researchers are likely to require large UASs to conduct required regional surveys with expected power and frequency requirements 4.4.4.KC.3: Radar of the correct size/frequency is not currently available but is now feasible to develop	4.4.4.KRC.1: Develop a 150 MHz ice-penetrating radar to allow regional surveys of thick ice to be carried out	4.4.4.KRN.1: Fund the development of a 150 MHz ice-penetrating radar 4.4.4.KRN.2: Test new radar systems over the thick ice of Svalbard, Greenland or Antarctica

4.4.5 Sensors - Hydrology	4.4.5.KC.1: The following are needed: 4.4.5.KC.1.1: GPR for bathymetry of turbid waters 4.4.5.KC.1.2: Doppler radar to measure water speed and height 4.4.5.KC.1.3: Hyperspectral instruments in the VNIR and SWIR with in-flight capabilities to collect downwelling radiance and convert to reflectance for the monitoring of water quality for human health	4.4.5.KRC.1: Develop more robust procedures for using UASs for water quality monitoring when converting to reflectance using sensors to measure downwelling radiance and inter-calibration of instruments instead of modelisation 4.4.5.KRC.2: Develop procedures and use cases for obtaining and validating bathymetric monitoring of rivers using UAS-mounted green LiDAR	4.4.5.KRN.1: Launch funding opportunities to advance the use of optical reflectance sensors for water quality monitoring. 4.4.5.KRN.2: Fund research into mapping of UK rivers and floodplains with bathymetric LiDAR, with potentially significant benefits to flood observations
4.4.6 Sensors – Oceano-graphy	4.4.6.KC.1: Similar to hydrology, lighter and smaller hyperspectral instruments that can be mounted on multirotors are needed to measure ocean optical properties in the VNIR and SWIR; this will make it possible to safely take off and land from ships to monitor specific areas at risk or further develop and validate satellite products such as Primary Production 4.4.6.KC.2: Other than at the surface, observing oceanic properties (using for example optical instruments) within the water column is generally not possible with electromagnetic wavelengths 4.4.6.KC.3: Some physical aspects of the seabed can be detected but only in shallow waters (allowing shallow-water feature detection bathymetric detection using photogrammetry); green LiDAR solutions can provide the necessary data for shallow waters for blue carbon projects 4.4.6.KC.4: UAS-mounted sensors are likely to be of greatest value in filling the 'White Ribbon' (shallow coastal waters, where ships and even day boats have difficulty in navigation and acoustic mapping is inefficient) 4.4.7.KC.5: UAS-based surveys are effective tools for population monitoring of certain marine animals (for example seals, whales, seabirds) and certain marine phenomena (for example temperature or turbidity plumes)	4.4.6.KRC.1: Develop novel optical sensors (specifically green LiDAR and Shortwave Infrared (SWIR)); this technology stands to revolutionise the collection of environmental information (seabed habitats, shallow-water bathymetry) in the 'White Ribbon' (shallow coastal waters, where ships and even day boats have difficulty in navigation and acoustic mapping is inefficient) 4.4.6.KRC.2: Develop appropriate ground-truthing methods for the validation of UAS-derived data products 4.4.6.KRC.3: Engage with the wider surveying community and especially the MCA (Maritime and Coastguard Agency) and UKHO (UK Hydrographic Office), to ensure alignment with existing hydrographic standards: this will ensure that the greatest number of data users will benefit from the data 4.4.6.KRC.4: Communicate directly with the MCA to understand the value of cost-effective, bathymetric LiDAR collection for the Civil Hydrography Programme 4.4.6.KRC.5: Share methodologies for census surveys and the development of best practices	4.4.6.KRN.1: Fund a prototype 'White Ribbon' aerial mapping platform 4.4.6.KRN.2: Commission trial projects to validate: (i) the platform/sensor unit, (ii) applicability across various environmental conditions (for example differing turbidity regimes, shore exposure, seabed types and so on) and (iii) calibration and validation sites and protocols

4.4.7 Sensors - Earth Observation	4.4.7.KC.1: NCEO is the NERC Centre with the most expertise in EO sensors and in remote sensing data quality, calibration and validation; they have unique experience with UASs - for example flying large and unique EO sensors on large and unique UASs (for example GHOST GHG spectrometer on the NASA Global Hawk) 4.4.7.KC.2: Through NERC FSF, NCEO already provides a UAS-based capability accessible to the community via a NERC facility and a capability far in advance of what most universities possess; this could be built on in terms of wider community provision and certainly used to determine “lessons learned” 4.4.7.KC.3: UAS-based sensors for RGB imaging and basic LiDAR are high quality and fairly mature; everything else is relatively immature and currently all UAS-based sensors provide less capability and quality than can be provided by (the substantially larger and higher specification; but manually operated) crewed-aircraft-based sensors - apart from in a few cases potentially those UAS sensors carriable by the largest, most sophisticated UASs (which are often military related) 4.4.7.KC.4: The restriction of data collection capabilities to VLOS operations only, UK-registered UASs and operators being unable to easily operate overseas and difficulties in working in areas away from mains power, all combine to severely limit the usefulness of UASs in many areas of environmental science where a UAS EO capability would be in theory very useful; for example if we wanted to observe a deforestation pattern or actively burning fires in a forest we could fly our crewed sensors over the location to collect the data; it is very likely not legal to fly a UAS to the location *unless* you can make your way very close to it and be within line of site – something that is obviously quite difficult indeed in many forest environments which might be tens of km from any road or track	4.4.7.KRC.1: Develop science-grade, properly calibrated EO sensors able to be operated from UAS platforms in a useful manner and with measurement characteristics informed by scientific need - this includes EO for probing the atmosphere (for example GHG column amounts via NIR/SWIR spectroscopy) as well as imaging the surface - and coupled with platforms (and ideally policies) providing the capabilities needed to usefully deploy them 4.4.7.KRC.2: Consider the additional data which could usefully be collected together with the EO data - for example, one or more of dGPS’ed ground-control points, downwelling light intensity at different wavelengths, aerosol optical depth, atmospheric profiles of temperature pressure and water vapour and so on. 4.4.7.KRC.3: Develop UAS platform hardware to carry science-quality EO sensors; give consideration to non-standard alternatives to current platforms - for example HAPS (High Altitude Platforms), swarms, tethered, aircraft that make the transition from vertical take-off to horizontal flight smoothly 4.4.7.KRC.4: Clarify the insurance situation and work for UASs carrying high worth equipment	4.4.7.KRN.1: national EO infrastructure to ensure access for research community to cutting-edge technology, including in terms of UASs both novel types of platform (long duration, HAPS, high lift capacity and so on) and science-grade EO sensors compatible with UAS operations 4.4.7.KRN.1.2: the skills and provision or development of data processing tools and equipment that are needed to ensure UAS-derived EO data is well calibrated, correctly interpreted and utilised effectivity to the necessary standards 4.4.7.KRN.1.3: technologies including access to computing, AI, machine learning and digital twins to support the handling and analysis of large EO data 4.4.7.KRN.2: Consult with other national and international organisations to learn lessons from their UAS-focused EO programmes and initiatives – ESA and NASA are key examples

	4.4.7.KC.5: Current commercial sensors beyond simple RGB imagers are often not that easy to operate, not that well calibrated and overall provide data that is far less quality controlled and sophisticated than that which can be collected from sensors able to be carried from crewed aircraft (like the NCEO NAEO capability) 4.4.7.KC.6: Platforms that are complementary to crewed aircraft and provide different operating characteristics could provide additional and very useful capabilities for NERC science - such as high altitude platforms (HAPS)		
4.5 Data	4.5.KC.1: Everybody is doing their own thing 4.5.KC.2: No agreed ways yet of dealing with data collection and processing - there is a lack of guidance, standardisation and metadata standards 4.5.KC.3: Data are often not accessible to the wider community, existing UK repositories are not set up to receive and curate large volumes of UAS data 4.5.KC.4: Opportunities for assimilation of UAS data into both operations of research models are being lost 4.5.KC.5: Uptake of UAS data requires high levels of expertise and proprietary knowledge, access is currently often neither inclusive nor equitable 4.5.KC.7: Avionics data fusion needs to become shared learning 4.5.KC.8: There are few software tools for users or providers	4.5.KRC.1: Develop and deliver data management and stewardship training 4.5.KRC.2: Develop a Discovery Data Portal 4.5.KRC.3: Develop software to aid metadata collection, fuse telemetry and sensor data and enable near-real-time data visualisation 4.5.KRC.4: Engage as a community to make sure the data acquired from different airborne platforms is findable and accessible, promoting collaboration across different centres and institutes and facilitating the creation of time series or multidisciplinary research	4.5.KRN.1: Increase communication about NERC data policy and enforce it 4.5.KRN.2: Enable a broad user base for UAS-derived data and make its use inclusive: lower the need for expert knowledge to both provide a supported data product and to access it. To achieve this requires the development of cross-centre pools of software engineers and data scientists: 4.5.KRN.2.1: Software Engineering pool: supporting tool development and help desk activities not just for UAS activities, but enable effective use of digital infrastructure 4.5.KRN.2.2: Data Scientist pool: Environmental Data Service) "group" working with the provider and end-user communities enabling an effective workflow chain that is sensitive to the uniqueness of the individual communities; as with software engineers, this would not just be for UAS activities but to enable the effective use of digital infrastructure 4.5.KRN.3: Develop and implement data carbon footprint metrics that can be applied and submitted alongside the required data management plan – this would illustrate the carbon footprint of data post processing and storage and could be used in the long term to help illustrate the balance between science benefit and carbon cost; it would be beneficial for this to be part of a suit of metrics that could be applied to all aspects of UAS-based science

In conclusion: UASs are part of a portfolio of actions that, when implemented well, offer a tremendous opportunity both to reduce the carbon footprint of environmental research and thereby contribute to UKRI's Net Zero goal for 2040 and to provide substantial scientific benefit. The community of NERC Centres and Collaborating Institutes is enthusiastic to explore these opportunities, to ensure validated UASs can address appropriate science questions with the lowest possible environmental impact, following best regulatory practice and leading to trusted, FAIR and well-managed data. The authors of this report are keen to continue working with NERC Head Office to build on the recommendations of this scoping study and to turn potential into realised benefit.

6. Appendix - Existing Use Cases

During the community engagement described in chapter 3, stakeholders were invited to provide use case studies based on existing UAS research. Below are the collated entries of the submitted existing use cases, grouped in alphabetical order by submitting NERC institute.

Large-Scale Wildlife Surveys Using Fixed-Wing Remotely Piloted Aerial Systems

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Science Objective

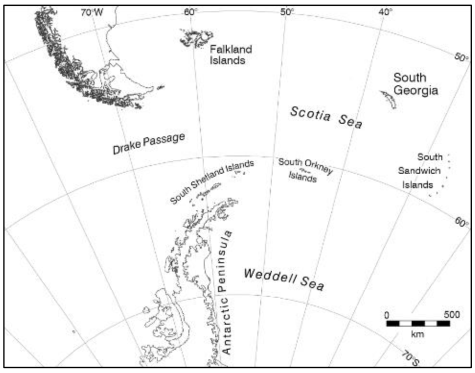
The Darwin Plus 109 project *Initiating Monitoring Support for the SGSSI-MPA Research and Monitoring Plan* (ongoing) is looking to leverage remotely piloted aerial systems to undertake a large-scale baseline reference survey of the key indicator species across South Georgia. The project has two main objectives:

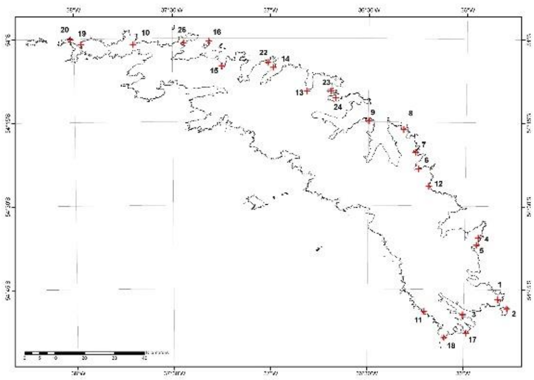
1) To acquire photogrammetric standard, vertical aerial photography of key indicator species at target sites across South Georgia.

2) To test and develop field-based workflows to enable the successful use of the fixed-wing eBeeX UAS as a data collection platform within the environmental constraints experienced on South Georgia, including operation beyond visual line of site (BVLOS).

Environmental Setting

The fieldwork took place in South Georgia over two summer seasons (21/22 and 22/23), with a total of 26 target sites. The timing of the surveys was determined by the breeding cycle of the different species.





UAS Specification	Timing of Deployment
Platform: AgEagle eBeeX Sensors: Aeria X (RGB) / Duet T (thermal / RGB)	Deployments: December 2021 - January 2022 and October - November 2022.

Methodology

The project was built around the AgEagle eBeeX platform, an autonomous, fixed-wing UAS with an endurance of 90 minutes and a maximum range of 60km. Permission to operate

BVLOS out to 8km from the pilot was granted by Air Safety Support International (ASSI) who are responsible for regulating South Georgia air space. The fieldwork was conducted in two halves with roughly half of the time in the field based at King Edward Point (KEP) and the other half of the time on the FPV Pharos SG, allowing the team to access the more remote sites. All flights were conducted using the eBeeX flight management software eMotion, while the specifications for each flight were determined by the requirements for the species in question.

Processing

Post-processed kinematic (PPK) processing is undertaken using the onboard GNSS data within eMotion, before Agisoft MetaShape is used to undertake the photogrammetry and orthorectification. The individual animals are then counted using a variety of methods depending on the species in question.

Results

The combination of extended range and endurance that the platform offered, along with its autonomous operation made it ideal for surveying the large wildlife colonies found around South Georgia. In total, 44 flights were conducted across the two seasons with the eBeeX platforms covering a combined distance of 629.6km. Of the 44 flights, 38 were conducted BVLOS from the pilot. The ‘field deployable’ nature of the eBeeX proved critical, allowing the field team to access sites overland when alternative logistics were not possible, operating away from the station / support for several days at a time. Please note, the core science outputs from this project are still ongoing.

during fur seal survey at Hound Bay (21/22 season).

Example of imagery collected during elephant seals survey at St Andrews Bay (22/23 season).

Flight path of the St Andrews Bay survey. Total distance was 42.6km, reaching a maximum distance from the pilot of 3km. Imagery: Microsoft.

Challenges

- The BVLOS limit of 8km was due to the limitations of the radio modem used by the eBeeX, a more powerful radio modem would allow extended BVLOS operation.
- To operate from a ship (and avoid landing on the island) the ship would require dynamic positioning (DP). Unfortunately, FPV Pharos SG does not have DP, however, operating from alternative ships such as the RRS Sir David Attenborough would open up this possibility.

Project Team

Nathan Fenney, Phil Hollyman, Adrian Fox, Phil Trathan, Martin Collins and Jamie Coleman

Collaboration:

DARWIN PLUS

Sea Ice Observations for Ship Navigation

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Science Objective

Sea ice and icebergs are a significant and dynamic navigation hazard for ships operating in the polar regions. Up to date information about the current sea ice and iceberg conditions is required by the ship's crew to ensure safe and efficient routing decisions. In addition to information from remote systems such as satellite imagery and automated route planning tools, local observations provide highly valuable information to support decision making. UAS systems deployed from the ship provide rapid, up to date local observations which are invaluable in this context and reinforce information from other sources.

Environmental Setting

For BAS, all areas of ship operations in the Southern Ocean which are potentially affected by sea ice, fast ice and icebergs. This includes approaches to Rothera and Halley stations, but also scientific cruise routes and other coastal offload sites.

UAS Specification	Timing of Deployment
Platform: DJI Mavic Sensors: Optical camera	Austral spring to autumn All day operation depending on weather

Methodology

UAS flights for sea ice and iceberg observations are planned based on the ship's operational requirement and any available satellite imagery. Flights either (a) follow a route based on observed sea ice conditions (using live video feedback to guide area of investigation) or (b) putting UAS platform at maximum altitude above the ship and capturing 360º panoramic footage. Video footage is either reviewed onboard immediately after the flight or a VR headset is used to provide the ship's officer with a live view during the flight.

Processing

Minimal processing of the video and stills footage is performed using either DJI or other editing software.

Results

Examples of images from RRS Ernest Shackleton (previous BAS resupply vessel) during a cruise to the Ronne Ice Shelf in the Weddell Sea. These images demonstrate the over-horizon and 360º view achievable with a UAS. The field of view is illustrated in the table below.

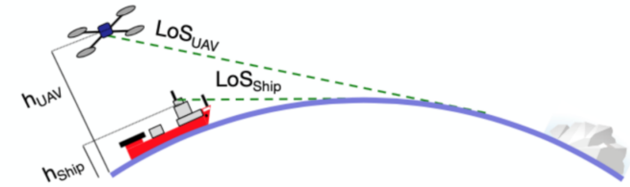


Fig 5: Line of Sight from ship vs. UAV

Platform	Height above sea level	Line of Sight (LoS)
Ship - bridge	12m	7nm
Ship - conning tower	20m	9nm
UAV	150m	26nm
UAV	300m	37nm

Challenges

Weather conditions (especially strong winds and reduced visibility from snow) can limit UAS operations and limit usefulness of results.

Multicopter UAS platforms currently have limited range from ship and lack stability to perform systematic survey flights to obtain sea ice observations over larger areas.

Proposed solution(s) to challenges

Range limitations currently being addressed by investigating operations of a fixed-wing UAS platform (for example eBeeX) from the BAS ship RRS Sir David Attenborough.

Walrus from Space – UAS Images to Validate Walrus Satellite Count

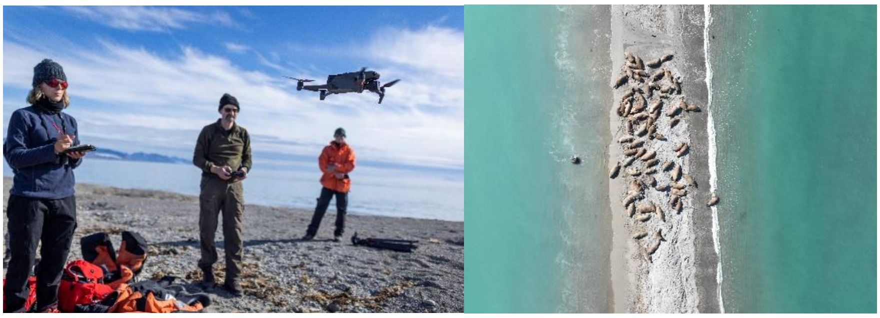
British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Science Objective

Regular counts of walruses (*Odobenus rosmarus*) across their pan-Arctic range are necessary to determine accurate population trends and in turn understand how current rapid changes in their habitat, such as sea ice loss, are impacting them. However, surveying a region as vast and remote as the Arctic with vessels or aircraft is a formidable logistical challenge, limiting the frequency and spatial coverage of field surveys. An alternative methodology involving very high-resolution (VHR) satellite imagery has proven to be a useful tool to detect walruses, but the feasibility of accurately counting individuals has not been addressed. Here, we compare walrus counts obtained from a VHR WorldView-3 satellite image, with a simultaneous ground count obtained using a remotely piloted aircraft system (UAS). We estimated the accuracy of the walrus counts depending on 1) the spatial resolution of the VHR satellite imagery, providing the same WorldView-3 image to assessors at three different spatial resolutions (*i.e.,* 50cm, 30cm and 15cm per pixel) and 2) the level of expertise of the assessors (experts vs a mixed level of experience - representative of citizen scientists). This latter aspect of the study is important to the efficiency and outcomes of the global assessment programme because there are citizen science campaigns inviting the public to count walruses in VHR satellite imagery.

Environmental Setting

We flew the UAS at an altitude of 55 m, based on findings from Palomino-González *et al.* (2021) who tested the level of disturbance in response to UAS flights undertaken above walruses in Svalbard and observed no disturbance when UAS were flown at altitudes above 50m. We added a precautionary 5m and flew at 55m above the walruses in our study. We observed no disturbance (for example no head lifting) during our UAS flights within view of the remote pilot and observers on the ground. We piloted the UAS to take-off and land downwind, at distances greater than 300m from the walruses.



Fieldwork team, © Emmanuel Rondeau / WWF-UK (left) and walruses hauled out at Sarstangen, Norway (right), UAS image © 2023 BAS Hannah Cubaynes and Peter Fretwell

UAS Specification	Timing of Deployment
Platform: DJI Mavic 3 Sensors: Hasselblad camera sensor: 4/3 CMOS, effective pixels: 20 MP, focal length: 12mm, image width: 5280 pixels, image height: 3956 pixels; for further detailed specifications, see: https://www.dji.com/uk/mavic-3/specs	15 July 2022 • UAS: 13:10 UTC • Satellite: 13:25 UTC

Methodology

On 15 July 2022, we visited a walrus haul out at Sarstangen, Svalbard, Norway and flew a DJI Mavic 3 under Permit No. 22/00507-2 from the Governor of Svalbard (RiS number 11906), at the precautionary altitude of 55 m. We piloted the UAS to take-off and land downwind, at distances greater than 300m from the walruses.

Walruses were counted in the UAS and satellite VHR imagery (50cm, 30cm, 15cm) by walrus experts and citizen scientists. Statistical analyses were conducted to assess the effect of the spatial resolution and level of experience.

We used a semi-automated method to determine the herd density of walruses in the UAS image using ESRI ArcMap 10.8 (ESRI, 2023). First, the UAS image was georeferenced to the satellite image (Georeferencing tool in ArcMap). One expert placed points in the middle of each individual walrus present in the UAS image. Then, we constructed a convex hull around each point to draw an outline around the group of walruses (Minimum Bounding Geometry tool with the option of Convex Hull in ArcMap). As this outline included only half of the body of some walruses, we then used the Buffer tool to ensure that all walruses were included in the outline, using a buffer of 1.5m, as the average size of an adult walrus is 3m.

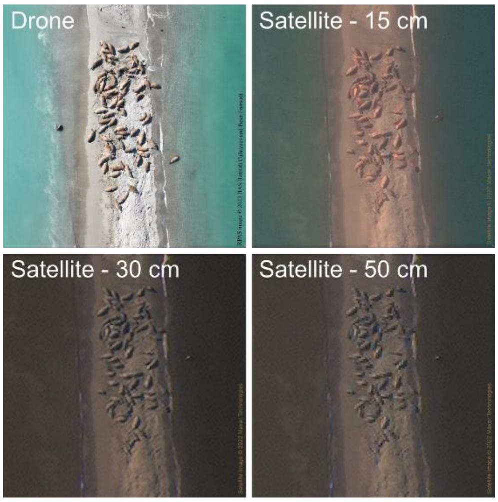
Processing

UAS image was readily available for counting, the satellite imagery were pansharpened.

Results

There were 73 walruses in our UAS “control” image with a density of 0.09 walrus/m^2. We acquire concurrent VHR satellite imagery with the UAS imagery, 15 minutes apart. On the ground monitoring showed that the number of walrus did not change in this time window. Our results show that walruses were under-counted in VHR satellite imagery at all spatial resolutions and across all levels of assessor expertise. Counts from the VHR satellite imagery with 30cm spatial resolution were the most accurate and least variable across levels of expertise.

This was a successful first attempt at validating VHR counts with near-simultaneous, *in situ,* data but further assessments are required for walrus aggregations with different densities and configurations, on different substrates.



Challenges

Timing the collection of the UAS image with the Satellite image.

Proposed solution(s) to challenges

Contact the satellite imagery provider to know the time pass.

Collaboration:

Snow Hill Emperor Penguins: Using UASs and Citizen Science to Monitor Emperor Penguin Numbers	British Antarctic Survey NATURAL ENVIRONMENT RESEARCH COUNCIL

Science Objective

Emperor penguin numbers are at risk through anthropogenically induced climate change mainly due to reduction in Antarctic sea-ice. The species is reliant on stable, long lasting land-fast sea-ice as a breeding platform, on which the adults raise their chicks. With rising ocean temperatures recent years have seen early sea ice break up, which leads to chick mortality and over time population decline. Current models, based on IPPC climate scenarios at current emission rates predict that the species will be quasi extinct (<99% of population remaining) by the end of the century. The most northerly colonies are being affected first, but as yet no science has been done on the sites already under pressure from warming temperatures. Our motive was to assess overall population, breeding success and environmental drivers at Snow Hill emperor penguin colony, the most northerly breeding site of the species using counts from UASs. The aim was also to compare accurate UAS counts with concurrent estimates of colony size from VHR satellite imagery, which is routinely used to estimate populations at unvisited sites.

Environmental Setting

The field site was the emperor penguin colony that is located on the sea ice adjacent to the southeast coast of Snow Hill Island. The colony is thought to consist of 3-6000 individual birds. We accessed the colony for two days in mid-November by helicopter via the cruise ship ultramarine, landing 2km for the nearest penguins and crossing the stable sea ice on foot. At this time the colony consisted of 8-12 sub-colonies or suburbs, each holding several hundred adults and chicks, which stretch over several square kilometres.

UAS Specification	Timing of Deployment
Platform: DJI MAVIC2	November 17th 2023

Methodology

Sea ice travel was conducted on foot using an experience ice guide and sledge-borne ice penetrating radar. Vertical UAS photography was taken of 7 of the 11 sub-colonies. Due to time constraints and the extensive and random positioning of sub colonies UAS operation was conducted manually. At each sub-colony a base was set up with observer (Norman Ratcliffe) and operator (Peter Fretwell). Each base was 30m from the sub-colony and flights were conducted at an altitude of 70m to minimise disturbance (none was noted during the operation). Flights were conducted in a box transit with 60% overlap. VHR Satellite imagery was tasked from MAXAR over the same period to compare satellite estimates with UAS counts.

MAVIC 2 UAS operation at Snow Hill Island emperor penguin colony

Processing

The imagery was post processed to create ortho mosaics using SOCET GXP software. This was assessed and counted in two ways; firstly one trained expert counted the number of chicks and adults at each sub-colony, secondly a bespoke citizen science app was created in Zooinverse to test the ability of crowd counting for future UAS surveys; the “Polar Observatory” https://www.zooniverse.org/projects/polinasevastyanova/polar-observatory . For this application, the orthophotos from the seven sub-colonies were split into 350 10m x 10m tiles, adults and chicks were counted on each tile by a minimum of 15 citizen scientists and a median value of each tile was used to compare with the expert observer.

Results

UAS imagery was taken of the majority of the colony and clearly shows chicks and adult emperor penguins which were counted to assess population, adult to chick ratios (which infer breeding success) and can be used as a calibration with satellite imagery. Four satellite images were taken, but the one nearest in time (19th Nov) had thick haze and was not suitable. An earlier image from 11th Nov at 50cm resolution and a 30cm resolution imagery from 23rd November will be assessed to compare with the counts from the UAS imagery.

UAS imagery showed that the chick to adult ratio was very low, suggesting high chick mortality at this site. This was backed up by ground observation where many scores of chicks were observed dead in melt pools – these melt pools around the colony only happen at the warmest breeding sites. Further statistical analysis on the comparative accuracy of expert to crowd counts and UAS vs satellite counts is ongoing.

The citizen science app proved very successfully with the 350 images all counted at least 15 times within two days of publishing the app.

Thumbnail of one of the ortho mosaic images of a sub-colony at Snow Hill Island

An example of one of the 10mx10m ortho rectified UAS images used in the Polar Observatory citizen science crowd counting app.

<table>
<tr><th colspan="2">Challenges</th></tr>
<tr><td colspan="2">At present the only way to access the colony is from cruise ship, although safe and efficient it meant that only limited time could be spent doing the survey and therefore not all sub-colonies could be covered. Cloud cover at the time of UAS survey mean that concurrent satellite/UAS survey was several days apart, compromising the effectiveness of the comparison.</td></tr>
<tr><th colspan="2">Proposed solution(s) to challenges</th></tr>
<tr><td colspan="2">In future surveys we propose BAS based field logistics using twin otters and field camps over several weeks to give ample time for survey work and to take multiple surveys to maximise the chances of concurrent satellite/UAS survey and to better understand variability in the colony. This cannot be done at Snow Hill, so other breeding sites will have to be assessed that facilitate safe field operation.</td></tr>
<tr><td>Collaboration:</td><td>WWF FOR YOUR WORLD</td></tr>
</table>

SWARM – Windracers Ultra for Environmental Science Data Collection

Science Objective

Multiple Antarctic science areas utilise data from airborne surveys. The Future Flight 3 Innovate UK funded project aimed to test the capability of the Windracers Ultra large (10m wingspan) UAS to collect environmental science data for several disciplines. A call for areas of data collection was put out to all BAS scientists and the following areas for survey were identified: Environmental monitoring of Antarctic Specially Protected Areas (ASPAs), krill ecology/distribution, collecting atmospheric turbulence data to support meteorological studies, collection of airborne gravity and magnetic data underpinning investigation of the tectonic evolution of the Antarctic Peninsula and radar imaging of ice thickness and internal structure.

Environmental Setting

For this study the Windracers Ultra was operated from the gravel runway at Rothera Research Station. Survey missions extended up to 90km from the station, with individual survey missions being up to 260km long. All science missions were operated Beyond Visual Line of Sight (BVLOS). Surveys were flown at between 450 and 500m above ground level. Local temperatures were between +/-5°C. Operations were limited to periods when the risk of icing associated with cloud at survey altitude was deemed low. Extensive cloud cover also limited the ability to collect some of the science data streams.

Windracers Ultra and survey team with view from onboard camera used for post flight operational assessment and learning.

UAS Specification	Timing of Deployment
Platform: Windracers Ultra TD-2 Sensors: PhaseOne 50MP optical Camera Headwall Nano VNIR Hyperspectral camera GoPro cameras (x3) iMAR iCORUS gravity sensor GEMSys K-magnetometer Aeroprobe 5 hole atmospheric turbulence probe CReSIS 600-900 MHz ice penetrating radar	January to March 2024 – Antarctic summer into autumn.

Methodology

Sensors were grouped into different scientific configurations and flown together. Each sensor configuration was mounted on their own dedicated removable floor, replacing the standard cargo floor in the Ultra UAS. Configurations included camera systems (visual and hyperspectral), potential field geophysics (gravity and magnetics) and radar. In addition, the atmospheric turbulence probe was fitted to a wing tip and remained installed for all missions. Environmental science (camera) missions flew out to the target ASPAs then tight line spacing (180 m) survey lines were flown over the islands in question. For the tectonic missions a 2km line spacing survey block 90x20km was flown.

Processing

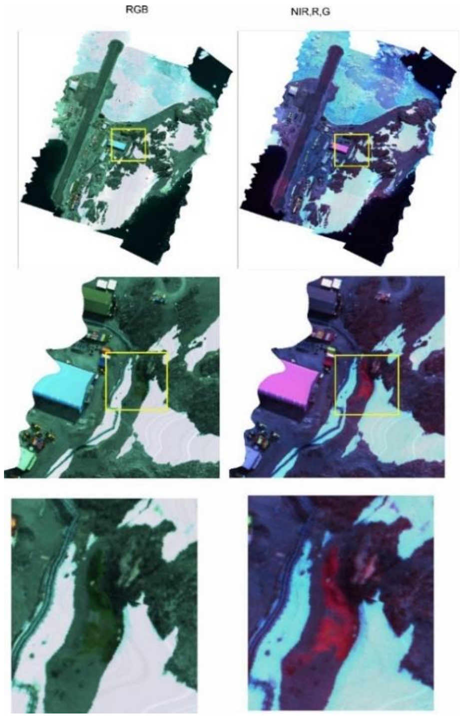
Each survey data set required its own processing flow and calibration. This includes pre-mission calibration by overflight of known targets for the hyperspectral system and calculation of compensation coefficients for the aeromagnetic survey flights.

Results

The Windracers Ultra successfully flew ~3000km over 25 missions. It successfully collected visual imagery, hyperspectral, gravity, magnetic and atmospheric turbulence data. In addition, we were able to demonstrate integrated flying with Antarctic crewed aviation, being airborne on a simulated science mission at the same time as the BAS Dash 7 aircraft.

Here we show an example of the hyperspectral data over Rothera Research station. Left panels show traditional RGB view. Right panels shows hyperspectral enhancement of vegetation highlighting a local moss bank. This enhancement can be used to monitor vegetation cover on all the surveyed ASPAs and forms a base line for future study.

Further data processing will lead to science outputs across all targeted science areas where data was collected.



Challenges

Risk of icing limited the operational window of the platform.

Interference between radar and a prototype radio communication system on the Ultra meant the radar system could not be flown.

Proposed solution(s) to challenges

In the short-term implementation of icing detection will expand the operational envelope, while a longer-term aspiration is active icing mitigation from on board systems and modifying aircrafts flight path to mitigate icing occurring.

The cause of the radar interference was identified and a solution demonstrated on the ground. This will be implemented in the next generation of the Ultra platform.

Collaboration: WINDRACERS, DISTRIBUTED AVIONICS

UAS for Abandoned Mine Activity: Monitoring Contaminated Land

British Geological Survey

Science Objective

Assessment of mine hazards and seepage points from UAS to inform decision making on long term management of metal mine sites. Quantification of mine water run-off contamination from abandoned mine activity on integration with auxiliary geological and hydrological data.

Environmental Setting

Abandoned lead mine at Cwmystwyth, ESE of Aberystwyth, Mid-Wales (UK). Site lies at the base of a steep-sided NNE-SSW trending ‘U’ shaped glaciated valley where the Afon Ystwyth flows. Mine workings have progressed high up valley sides with large amounts of mine waste covering the valley.

UAS Specification	Timing of Deployment
Platform: Matrice 210-RTK Sensors: Zenmuse X5S (RGB) & XT (LWIR)	Winter (pre-vegetation growth) Diurnal (pre and post solar heating max)

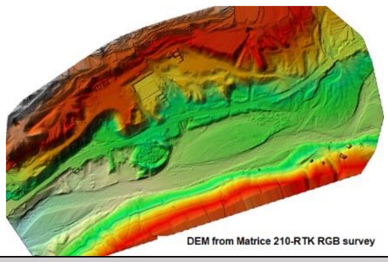
Methodology

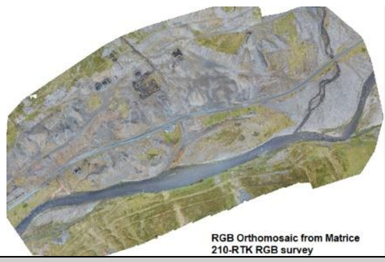
UAS flights were defined in Pix4D as pre-programmed single-grid surveys. Both RGB and thermal surveys were performed with sensor view angle set at NADIR and flight paths set to enable front-back and side-side overlap of 70% for RGB and 90% for LWIR Thermal. Altitude was set @80m to provide output pixel resolution of 2cm (RGB) and 15cm (LWIR Thermal). Imagery was recorded in JPG (RGB) and RJPG (LWIR Thermal) formats with ground targets set out across study site providing accurate dGPS geopositioning and temperature calibration using FLIR T650sc. Flights were repeated pre and post solar heating maximum to enable assessment of temperature amplitude indicative of volumetric variation in ground surface.

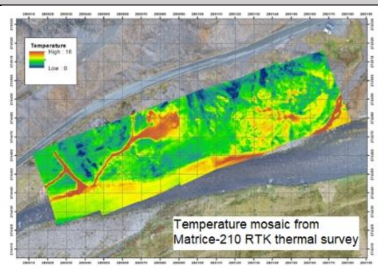
Processing

Use of Pix4D to generate orthophoto mosaic and output DEM through photogrammetric processing of RGB. Use of FLIR Tools® v6.3 with coincident meteorological and ground parameters to calibrate LWIR Thermal images to ground temperature before co-registration and generation of thermal mosaic.

Results







Challenges

Strong valley winds limited battery life and caused challenges with UAS landing.
Required proprietary software for conversion from RJPG to temperature images.
Low thermal contrast in thermal images prevented photogrammetric orthomosaic output.

Collaboration:

Llywodraeth Cymru Welsh Government; Cyfoeth Naturiol Cymru Natural Resources Wales; Environment Agency; defra

Kilbourne Hole Volcano

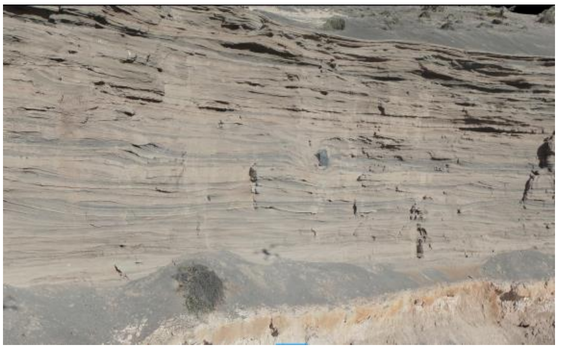
Science Objective

The BGS were invited by NASA Goddard Instrument flight team to join their field excursion to Kilbourne Hole Volcano (KBH) in New Mexico. The core objectives of this trip were to:

1) To learn more about the history of phreatomagmatic eruptions at KBH maar volcano.
2) To compare terrestrial and aerial LiDAR measurements of surge-bed cross-bedding foresets from within the tuff rings.
3) To contribute the RISE EVA exercises.

Environmental Setting

Kilbourne Hole is a maar volcanic crater that is between 24,000 and 100,000 years old and forms part of the Potrillo volcanic field. This area is part of the Rio Grande Rift, where rising magma interacts with groundwater saturated sediments. The elliptical crater is approximately 3.2km long x 2.2km wide.



(Images © BGS, 2021)

UAS Specification	Timing of Deployment
Platform: DJI Matrice 300RTK Sensors: Zenmuse L1	Easter 2021 All day

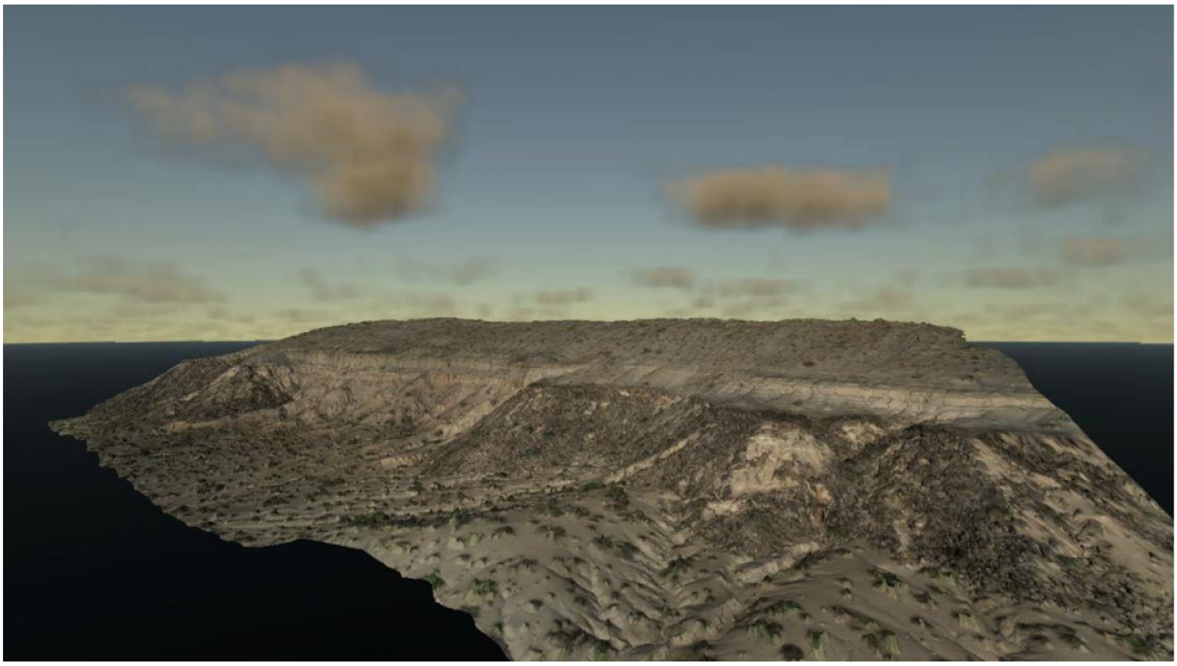
Methodology

UAS flights were defined in DJI Pilot as pre-programmed surveys. Altitude was set at c.50m, with sensor view angles set at NADIR to collect both RGB and LiDAR surveys with flight paths set to enable front-back and side-side overlap. Output pixel resolution of <1.5cm. OBLIQUE surveys were flown free hand, capturing multiple RGB images that overlapped, to allow for photogrammetry of the crater walls. Output pixel resolution was <1cm. Flights took approximately 40 minutes each to perform and there were eight in total. Since the UK RTK service did not work in the USA it was necessary to provide external GNSS data during the processing, this was sourced from a base station that was running at the same time as some flights and data from the UNAVCO service.

Processing

LiDAR data were processed in the DJI Terra software package to produce a point cloud georegistered to NAD-83 UTM zone 13. The standard settings were applied, with point cloud (las format) and model (obj format) selected as outputs. RGB imagery acquired by the L1 sensor was also processed in DJI terra to create a 3D model, this was also referenced to NAD-83 UTM zone 13 with the base station GNSS data to improve its positional accuracy.

Results



Photogrammetry results from the SE Rim of Kilbourne Hole © BGS, 2021

Challenges

Strong winds in the afternoons caused challenges with UAS flights and landing.

Flights were limited by the fact that we were unable to travel with the M300 batteries and therefore needed to hire batteries when we reached the US. Therefore, we only had 4, limiting the number of flights we could make per day.

Collaboration:

MONITORING SOCOTEC

Canal & River Trust
Making life better by water

Geoenergy Monitoring for Energy Security

Science Objective

Decarbonisation of heat in our homes and businesses is an essential step towards meeting net zero targets. In the UK, historic coal mining has left a legacy of flooded, abandoned mines throughout the country. The water in these mines presents an opportunity for clean heat energy to contribute towards a sustainable future. The UKGEOS Glasgow Observatory is a research facility designed for investigating this shallow, low-temperature, mine-water heat energy and potential heat storage resources. The observatory site is typical of towns and cities with a post-industrial urban and coalfield legacy. Towns and cities are where the greatest demand for decarbonising heat lies. Mine-water heat abstraction is a technology that is proven but not widely realised. The observatory enables research into the questions that remain about this heat source, from size and sustainability to environmental impacts (https://www.ukgeos.ac.uk/glasgow-observatory).

UAS were used to provide a baseline DEM and ortho image, with repeat for monitoring ground motion as a potential consequence of mine-water heat abstraction, as well as assessing the potential for LWIR imagery to monitor resulting warm gas release.

Environmental Setting

The UKGEOS Glasgow Observatory is situated near the Cuningar Loop Park and Gardens in Rutherglen, Glasgow, near the site of the 2014 Commonwealth Games village. The site is slightly undulating with a mound in the centre that enables good visibility of all sections of the survey area. The area is bounded by trees on the East and West, a public car park to the South and the River Clyde looping round to the North. The area is open to the public with numerous paths and picnic tables crossing the site. The geoenergy equipment compounds are situated in the West and South of the survey area.

Image © B. McIntyre, BGS (2023)

UAS Specification	Timing of Deployment
Platform: DJI Inspire-1 RAW Sensors: Zenmuse X5S (RGB) & XT (LWIR)	Summer (with planned seasonal repeat) RGB: Daytime (uniform sky) LWIR: pre-and post-solar noon

Methodology

UAS flights were defined in Pix4D as pre-programmed double-grid surveys. The RGB and thermal surveys were performed with sensor view angle set at 80° and NADIR respectively and with flight paths set to enable front-back and side-side overlap of 70% for RGB and 90% for LWIR. Altitude was set at 100m (RGB) and 80m (LWIR) to provide output pixel resolution of 2.5cm (RGB) and 15cm (LWIR Thermal). Imagery was recorded in JPG (RGB) and RJPG.

(LWIR) formats but ground control targets NOT set out across the study site, but post-processing performed using accurate geopositioning from control heights at known positions.

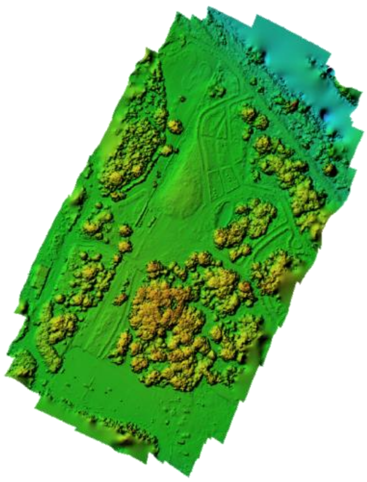
Repeat surveys for monitoring ground motion at times post-injection will use ground control target deployment and accurate geopositioning from dGPS, as well as future temperature calibration using FLIR T650sc temperature measurements on the deployed targets. Flights will be repeated pre and post solar heating maximum to enable assessment of temperature amplitude indicative of volumetric variation in ground surface with respect to the injection.

Processing

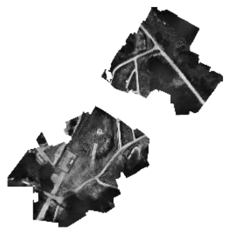
Use of AgiSoft PhotoScanPro to generate orthophoto mosaic and output DEM through photogrammetric processing of RGB. Use of FLIR Tools® v6.3 with coincident meteorological and ground parameters to calibrate LWIR Thermal images to ground temperature before co-registration and generation of thermal mosaic.

Results

OrthoRGB



DEM



OrthoLWIR

Challenges

Thermal shadowing from wind-blown vegetation.
Area frequented by the public, including dog walking area and picnic site.
As it is an exposed site, high gusting wind was encountered.

Proposed solution(s) to challenges

Thermal acquisition during quieter wind conditions.
Additional spotters required, consider times with reduced public – no lunchtime flying.
Retain more battery power for control to compensate for windy landing conditions.

Geological Conservation at Croft Quarry

British Geological Survey

Science Objective

Following on from Planning Permission granted to Aggregate Industries UK Limited for: Proposed lateral extension to the mineral extraction area within Croft Quarry, retention of access and ancillary development and reclamation via importation of restoration material, Heaton Planning requested the BGS to carry out a terrestrial and UAS LiDAR survey for the conservation and recording of geological conservation features exposed in the current quarry and future extension which fall into a Site of Special Scientific Interest (SSSI) designated by Natural England.

Environmental Setting

Croft Quarry SSSI forms part of a group of igneous rock bodies that are exposed at, or near surface, often as upstanding hills in south Leicestershire, known as the South Leicestershire Diorite Suite. Protruding above surrounded by the red Triassic strata, the quartz-diorite and tonalite rocks at Croft have been exploited since Roman times; the current quarry has a depth of -136m OD, representing one of the deepest quarries in Europe.

UAS Specification	Timing of Deployment
Platform: DJI Matrice 300RTK Sensors: Zenmuse L1	Summer 2022 During daylight hours, over 3 days

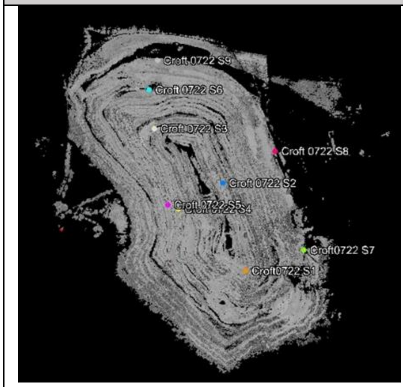
Methodology

The quarry was surveyed using both Terrestrial LiDAR Scanning (TLS) and UAS, from 9 TLS positions including the upper quarry edge and from within the quarry (10 scans in total). UAS flights were defined in Pilot and manually as a nadir and at 45° and 90° using the Zenmuse L1 to perform LiDAR and matching RGB imagery. The nadir altitude was set at 50m to provide a point cloud density of 283 points/m^2 and a photo output pixel resolution of ~1.5cm, with a side overlap of 70%, the scanning mode set to repetitive, a flight speed of 10 m/s, the number of returns set to three and calibration enabled. The UAS was flown from 5 positions, both on the upper edge and from within the quarry (10 flights in total, 162 minutes flight time); the data was used to create both a 2D and 3D ortho-rectified photogrammetric image and a 3D RGB coloured point cloud.

Processing

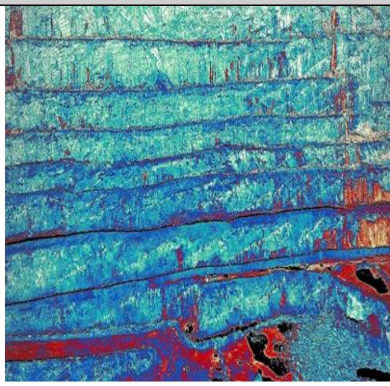
Use of DJI Terra to generate 3D point clouds and 2D & 3D orthophoto mosaics. Outputs were DEM from LiDAR and orthophoto images and models from RGB.

Results



Location of TLS positions

UAS image looking ENE showing buried topography



TLS image enhanced with multi-spectral filters looking East

Challenges

Unpredictable wind conditions due to eddying currents over quarry walls.

Loss of RTK positioning as UAS moves lower into the quarry.

Difficulty in sighting UAS precisely due to flying below launch position and manual flying close to quarry faces.

Proposed solution(s) to challenges

Enhanced stabilisation of UAS.

Enhanced RTK capability with potential connection to base station within confined areas.

Enhanced visibility features on UAS for visual aid.

Potential for auto vertical face terrain tracking set at a fixed distance from a vertical structure to prevent collision.

Collaborations:	Heatons Planning Environment Design

Geological Fault Mapping

British Geological Survey

Science Objective

Mapping the three-dimensional orientation of geological structures. The structures (faults) are well exposed in the wave cut platform and also the cliff at the back of the beach. Having exposures in two planes (horizontal platform and vertical cliff) allows for the full orientation of the structures to be mapped. The objective was to assess the integration of nadir photography and vertical (cliff) photography into a single model using geolocation through RTK enabled UAS.

Environmental Setting

Selwicks Bay at Flamborough Head on the East Yorkshire coast of England has a well exposed Chalk wave cut platform. Behind the gravel beach are chalk cliffs.

Image © BGS (2022)

UAS Specification	Timing of Deployment
Platform: DJI M300 RTK Sensors: L1 RGB camera	July 2022 Low tide and low wind speeds.

Methodology

The DJI M300 was used due to the high quality RGB imagery acquired by the L1 sensor and the RTK GNSS positioning meaning that no external ground control data was required.

The M300 UAS was carried down to the beach at approximately 4pm, once the beach was empty of the public. Take off was completed from the shingle beach.

A nadir survey of the bay was programmed in DJI pilot software with a 50m elevation and 70% forward and 50% side overlap. This survey was flown, once completed the pilot took manual control of the M300 and the camera adjusted to be side looking.

The pilot then flew the UAS at approximately 10m elevation and 30m distance from the cliffs. RGB imagery were manually acquired, the UAS was flown slowly and frequency of photography was such to ensure sufficient overlap. This required the pilot to keep a careful eye on both the controller screen and UAS, it was therefore essential to have a spotter to ensure safety.

Processing

DJI's Terra software was used to process the RGB images acquired by the L1 sensor to produce a 3D model. The nadir and vertical photos were processed at the same time. The M300 RTK GNSS positioning was used as the spatial reference.

Results

3D model showing structure in platform and cliff

3D model showing structure in the cliff face

Challenges

Integration of nadir and vertical photography

Care required when flying vertical images due to need to be close to cliff

Public on the beach

Need for low tide

Proposed solution(s) to challenges

Luck meant that low tide on our visit coincided with late afternoon when the beach was empty so the public were not a concern.

We selected a time of year with low wind speeds and were lucky that they were low when we arrived, it would not be safe to fly close to the cliff in higher winds.

Geothermal Energy Research in Mexico

Science Objective

Assessing the relationship between thermal UAS data and tectonic structures, surface geothermal manifestations and soil gas monitoring to better understand the tectonic, sedimentary and geochronological evolution of a geothermal system at Los Humeros caldera, Mexico, where geothermal features occur both with and without surface expression.

Environmental Setting

Los Humeros is a 5-8km wide oval caldera situated 200km East of Mexico City (Mexico) at an elevation of approx. 2800±50m. The caldera is bounded by rim faults with steep cliffs and has an active geothermal system that is exploited for energy production. The topography within the caldera is gently sloping, with in-caldera fault escarpments evident in the central and southern areas. The caldera contains evidence of mineral alteration, high temperature anomalies and fault structures indicative of an active geothermal system.

Image © C. Jordan, BGS (2018)

UAS Specification	Timing of Deployment
Platform: DJI Inspire-1 RAW Sensors: Zenmuse X5S (RGB) & XT (LWIR)	RGB: daytime LWIR: pre-dawn and post-solar noon

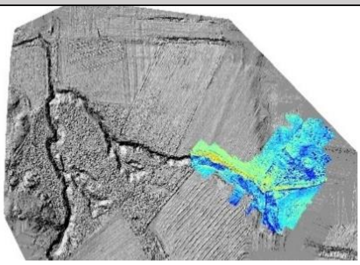
Methodology

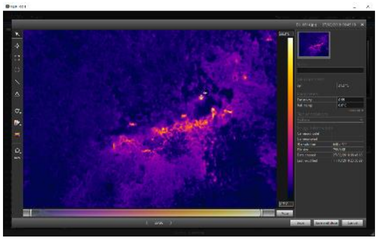
UAS flights were defined in Pix4D as pre-programmed single-grid surveys. Both RGB and thermal surveys were performed with sensor view angle set at NADIR and flight paths set to enable front-back and side-side overlap of 70% for RGB and 90% for LWIR Thermal. Altitude was set at 80m to provide output pixel resolution of 2cm (RGB) and 15cm (LWIR Thermal). Imagery was recorded in JPG (RGB) and RJPG (LWIR Thermal) formats with ground control targets set out across the study site providing both accurate geopositioning using GPS and temperature calibration using FLIR T650sc. Flights were repeated pre-dawn and post solar heating maximum to enable assessment of temperature amplitude indicative of volumetric variation in ground surface.

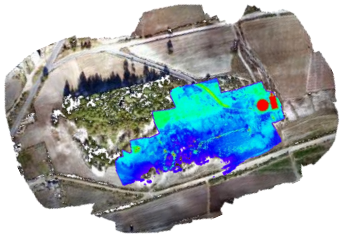
Processing

Use of Pix4D to generate orthophoto mosaic and output DEM through photogrammetric processing of RGB. Use of FLIR Tools® v6.3 with coincident meteorological and ground parameters to calibrate LWIR Thermal images to ground temperature before co-registration and generation of thermal mosaic.

Results


OrthoLWIR in DEM


LWIR in FLIR Tools ®


OrthoLWIR on OrthoRGB

Challenges

Low battery temperature pre-dawn at high altitude - reduced flight time.
High battery temperature during high altitude sunshine - reduced flight time (overheating).
Required proprietary software for conversion from RJPG to temperature images.
Low thermal contrast in thermal images hindered photogrammetric orthomosaic output.

Proposed solution(s) to challenges

UAS that can maintain battery at a constant temperature.
Thermal camera that does not require specific software to extract absolute temperature.
Ability to extract time-stamped meteorological conditions from UAS control for calibration.
Use of moderate (not too low) emissivity targets for image matching in vegetated areas
Photogrammetric software that uses temperature images rather than unconverted (R)JPG

Collaborations:

GEMex

The GEMex project was a cooperation in Geothermal energy research between Europe-Mexico for development of Enhanced Geothermal Systems and Superhot Geothermal Systems. It was supported by the European Union’s Horizon 2020 programme for Research and Innovation under grant agreement No 727550

Infrastructure Assessment at Slaithwaite Reservoir

Science Objective

The Canal and River Trust had commissioned SOCOTEC Monitoring LTD to implement geophysical monitoring in collaboration with the BGS to investigate suspected leakage issues of the core, embankment dam and tunnel using a combination of geophysical monitoring, terrestrial LiDAR and UAS surveys.

Environmental Setting

Slaithwaite Reservoir was constructed in 1797 to supply the Huddersfield Canal and impounds the waters of Merry Dale Clough, a tributary of the River Colne. The reservoir has a surface area of 46,000m^2 and an estimated volume of 175,000m^3. The dam is oriented roughly north south and is built at the east end of the reservoir. It is a 17m high earth fill dam with a reported puddle clay core.

Image © BGS (2021)

UAS Specification

Platform: DJI Matrice 210RTK
Sensors: Zenmuse X5S

Timing of Deployment

Autumn 2021
During daylight hours

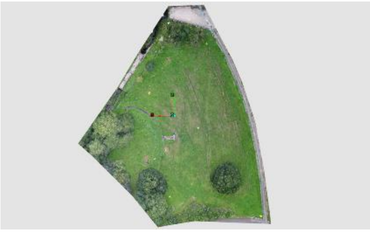
Methodology

UAS flights were defined in Pix4D as pre-programmed single-grid surveys. The RGB survey was performed with sensor view angle set at NADIR and flight paths set to enable front-back and side-side overlap of 70 %. Altitude was set at 50m to provide output pixel resolution of <1.5cm. Imagery was recorded in JPG format with ground control targets set out across the study site providing accurate geopositioning using Network RTK GNSS. Flights took approximately 20 minutes each to perform and there were four in total. Terrestrial LiDAR surveys and geophysical surveys were also carried out during this time.

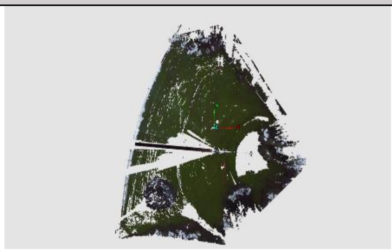
Processing

Use of Pix4D to generate orthophoto mosaic and output DEM through photogrammetric processing of RGB.

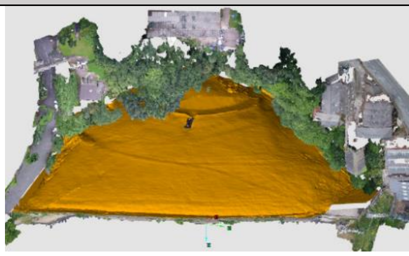
Results



Point cloud of Dam (Matrice 210)



Point cloud of tunnel (Faro X-330)



DEM of Slaithwaite Dam & tunnel

Challenges

Strong winds caused challenges with UAS flights and landing.

Major changes in topographic height caused issues with take-off positioning.

Proposed solution(s) to challenges

Enhanced stabilisation of UAS to counteract strong winds.

Enhanced capability of UAS to terrain track with accurate take-off geopositioning.

Collaboration:

SOCOTEC Monitoring; Canal & River Trust – Making life better by water

Landslide Monitoring at Hollin Hill, Yorkshire

Science Objective

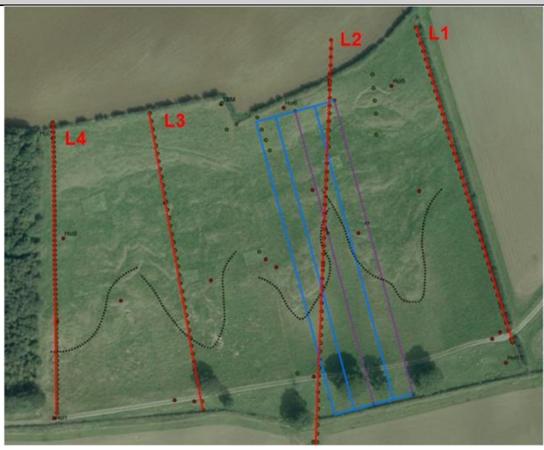
The BGS has operated a field observatory site at Hollin Hill, in North Yorkshire, since 2004. It brings together a combination of field surveying, geomorphological, geophysical, engineering and hydrogeological expertise for monitoring of landslide development.

The landslide lies to the north of York, is several hundred metres wide and extends some 200m down slope. It is located on the south facing side of a degraded Devensian ice-margin drainage channel; the slope has an angle of approximately 12º. This landslide is National Landslide Database ID 15659/1.

Repeat RGB, LiDAR and LWIR surveys have been used to assess the potential of UAS to monitor ground motion with interpretation on comparison with geoscience field monitoring data.

Environmental Setting

Hollin Hill is situated on an undulating south-facing steep slope in open pasture near Terrington, on the south of the Howardian Hills AONB. The slope consists of Redcar Mudstone (Lower Lias) at the base, with an outcrop of the Staithes Sandstone Formation (Middle Lias) running across the middle section of the slope. The Whitby Mudstone Formation (Upper Lias) overlies this, with the upper part of the slope composed of the Dogger Formation. Both the Redcar Mudstone and the Whitby Mudstone are highly susceptible to landsliding and movement across the entire slope is due to these two Formations.



GoogleEarth image from December 2002 © Infoterra Ltd & Bluesky

UAS Specification

Platform: DJI Matrice 210RTK & 300RTK
DJI Inspire-1 RAW
Sensors: Zenmuse X5S & L1
Zenmuse XT1

Timing of Deployment

Various seasons from 2020 – 2023
During daylight hours

Methodology

The field and landslides at Hollin Hill were surveyed using a Riegl VZ-1000 Terrestrial LiDAR Scanner, a Leica GS18T Global Navigation Satellite System and a DJI Matrice 210RTK & 300RTK and a DJI Inspire-1 RAW UAS.

Six Ground Control Points (GCP) were placed across the top of the cliffs along with the landing pad and positioned using the Leica GS18T Network RTK GNSS.

Two photogrammetric surveys (North-South & East-West) were defined in Pix4D and carried out using the DJI Matrice 210RTK. The RGB survey was performed with sensor view angle set at nadir and flight paths set to enable front-back and side-side overlap of 70%. Altitude was set at 50m to provide output pixel resolution of <1.5cm.

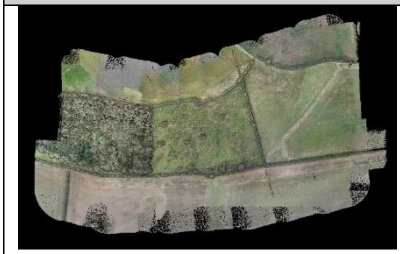
A series of one nadir and four matching oblique (45°) flights were carried out using the DJI Matrice 300RTK. The LiDAR and the matching RGB imagery were acquired using the Zenmuse L1 sensor with a side overlap of 70%, the scanning mode set to repetitive, a flight speed of 10m/s, the number of returns set to three and calibration enabled. The altitude was set at 50m to keep within regulations and to provide a point cloud density of 283 points/m^2 and a photo output pixel resolution of ~1.5cm.

A thermal imaging survey was carried out using the DJI Inspire-1 RAW. The survey was defined in Pix4D with sensor set at nadir with front-back and side-side overlap of 70% for RGB and 90% for LWIR. Altitude was set at 80m to provide output pixel resolution of 2cm (RGB) and 15cm (LWIR Thermal).

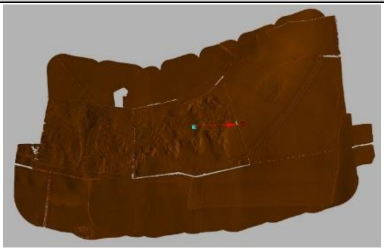
Processing

Use of Pix4D to generate orthophoto mosaic and output DEM through photogrammetric processing of RGB. Use of FLIR Tools® v6.3 with coincident meteorological and ground parameters to calibrate LWIR Thermal images to ground temperature before co-registration and generation of thermal mosaic in image processing software. Use of DJI Terra to generate 3D point clouds and 2D & 3D orthophoto mosaics. Outputs were DEM from LiDAR and orthophoto images and models from RGB.

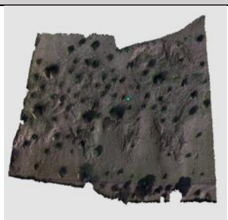
Results



Photogrammetric orthomosaic generated from Matrice 300RTK



DTM generated from Matrice 300RTK showing landslide area beneath trees



DEM generated from Matrice 30RTK

Challenges

At certain times of the year strong gusting winds and very cold weather caused challenges with UAS flights (especially batteries) and landing.

At certain times of the year conditions underfoot were extremely muddy. Vegetation was high and wet causing issues with take-off positioning and ground observation.

Required proprietary software for conversion from RJPG to temperature images.

Proposed solution(s) to challenges

UAS with enhanced stabilisation to minimise wind effects.

UAS with RTK to minimise need for additional ground control.

Require sensors that output at-sensor temperature without need for proprietary software

Methane Plume Detection Using CH_4 Sensor	British Geological Survey
Science Objective	
Test flight of fixed-wing methane detection platform developed in collaboration with Quest UAS	
Environmental Setting	
Agricultural land approx. 5 miles from Amble Northumberland. The land is elevated and has very clear fields of view all round. Depending on the time of year, crops such as oilseed rape are grown, providing suitable landing surface for fixed wing UASs.	
UAS Specification	**Timing of Deployment**
Platform: Q200 Surveyor with modified pod Sensors: Boreal CH4 sensor (prototype)	[season] Winter [daytime] All day, light permitting

Methodology

Flight tests comprised of one 'walk over' test and three flights with controlled gas release. The UAS was carried across the site at 'zero altitude' while methane was released at 80cm above ground level at a rate of 100 L sec^{-1}. A temporary display panel was connected to the sensor to provide real-time readings to the operator. The ground test showed that a gas plume could be identified approximately 100m from the release point.

Subsequently a 10m mast was used to release known rates of methane at that height over a series of three unprogrammed, autopilot-assisted flights:

i) Gas release at approximately 200 L sec^{-1} for 6 minutes.
ii) Gas release at approximately 750 L sec^{-1} for 2 minutes, 90 second gap to change cylinders, followed by another approximately 750 L sec^{-1} for 2 minutes (i.e. two cylinders used)
iii) Gas release starting at approximately 14:45 GMT. Approximately 750 L sec^{-1} for 2 minutes, 90 second gap to change cylinders, approximately 750 L sec^{-1} for a further 2 minutes, another 90 second gap to change cylinders, approximately 750 L sec^{-1} for 20 seconds, trailing off to zero after a further 40 seconds (i.e. two and a quarter cylinders used).

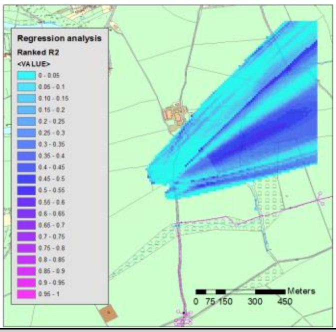
Processing

RTK and Gas concentration data were imported into GIS and Google Earth and used to map flight path and concentration levels. A single point gas plume model was written in C++, which included observed wind and temperature data to model the plume shape and dispersion characteristics. An ensemble of possible plume locations is run covering a large area and each modelled plume compared to the UAS collected data. The 'goodness of fit' between the modelled and observed data are then mapped to show likely source.

Results

Google Earth model

Vertical Terrain map



Ranked regression analysis identifying the source of the gas release.

The star indicates the real location of the release point.

Challenges

Flight and landing conditions on the day were not ideal; cold, with occasional snow flurries, wind gusts and muddy conditions underfoot. Additionally, the gas regulator froze during release so flow rates are estimates at best.

The fixed-wing UAS requires a 2-person crew (pilot and commander) to operate and a complex and time-consuming bungee launch system. Due to the relative fragility and significant cost of the Boreal gas sensor, particular care must be paid during take off and landing to prevent damage to the vulnerable system components. This further limits the operational arenas the system can be deployed in, if there are no suitable soft landing areas such as crops or heavy grass growth

Proposed solution(s) to challenges

Ability to warm sensors (potentially from UAS battery heat output, but not drawing down the power)

Collaborations:	QUESTUAV

Mineral Exploration and Field Skills Training

Science Objective

This NERC ATSC course: *Multidisciplinary fieldwork training in a professional geoscience environment* provides practical fieldwork training in a professional geoscience environment by focusing on an application for the mining industry. It emphasises the development of field observation skills relevant to mineral exploration and for applied earth science research into volcanic and magmatic processes. It includes field deployment of several instrument technologies: UAS photography, spectroscopy, portable XRF, portable XRD and ground LiDAR. The concept behind the course is to enable doctoral and early career researchers to experience the workflow used in the planning, capture and interpretation of field data. It will also utilise statistically based analysis of spatial data to define mineral deposit targets.

Environmental Setting

The Island of Milos, Greece, is renowned as a natural laboratory for examining volcanism and mineralisation, with several different styles and variations of each are well exposed and easily accessible. As a Mediterranean Island in spring/summer the weather is dry, warm and mostly sunny.

Image © BGS (2023)

UAS Specification	Timing of Deployment
Platform: DJI Phantom 3 pro and Mini Pro 3 Sensors: RGB cameras integral to above	May 2023 During daylight hours

Methodology

During the course, PhD students and early career researchers (32 in total) are split into four groups of eight. They are each given an area in which to work up a mineral deposit and quantify the resource and environmental and social considerations to its extraction. Field tools are available upon request.

One request was to create a 3D model to identify the paleo water tables present within a Native Sulphur deposit, such information is critical to understand the formation of the sulphur and therefore if it might indicate part of a larger more valuable (gold bearing) deposit. This deposit is within a steep sided valley:

1. Both the Phantom and Mini were used to acquire data for photogrammetric processing
2. Flight plans for the Phantom were created to acquire RGB imagery from a height of 80m, front overlap was specified at 90% and side overlap at 70%.
3. Since the valley was steep sided the Phantom was then free flown to gather side looking photos of the valley sides.
4. The DJI Mini Pro was then used to acquire close up imagery of key outcrops. The Mini was used in these locations due to its collision sensors and increased controllability compared to the Phantom.

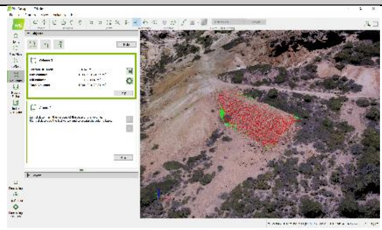
A second request was to extract the volume of mine waste, such waste is now economically viable so represents a resource:

1. DJI Phantom used in survey mode
2. 50m elevation, front overlap was specified at 90% and side overlap at 70%.
3.

Processing

Use of Pix4D to generate orthophoto mosaic, output DEM and 3D model through photogrammetric processing of RGB. GCPs were not used, since this was a training exercise it was more valuable to expose a greater number of students to the deployment of UAVs than accuracy of the resulting data.

Results

 3D model for the Sulphur deposit generated from the RGB imagery. Green surfaces are interpreted paleo water table.	 3D model of mine waste	 Estimating volume of mine waste from the 3D model

Challenges

Interference from power lines, there was a set to the north and a set to the south, these caused the Phantom 3 Pro to lose connection to the controller. Steep topography.

Proposed solution(s) to challenges

Avoid flying in between the power lines, this was difficult at this location, a possible solution is to fly higher or lower and see if that minimises the interference. Steep topography is mitigated via careful route creation and flying.

Monitoring Coastal Landslides at Aldbrough Coastal Landslide Observatory

British Geological Survey

Science Objective

The east Yorkshire coastline is some of the most rapidly eroding coast in Europe, as such BGS have been monitoring the cliffs at Aldbrough for 20+years with Terrestrial Laser Scanning (TLS). UAS offer the opportunity to monitor greater lengths of coastline. The science questions are:

1. What is the accuracy of the UAS LiDAR and photogrammetry vs the TLS?
2. How do we integrate the UAS and TLS data to form the most efficient and accurate monitoring strategy?
3. What the rates of coastal erosion?
4. What are the processes of coastal erosion?

Environmental Setting

Aldbrough is located approximately midway on the extensive Holderness coast in South Yorkshire [NGR525770 439605], about 10km southeast of Hornsea. The ~300m stretch (extended to ~2km) is centred on the road accessing the Caravan Park. The cliff faces northeast, is low (17m) and of consistent height. It consists of till and is actively receding, both by toppling and rotational mechanisms.

Image © BGS (2023)

UAS Specification	Timing of Deployment
Platform: DJI Matrice 210RTK & 300RTK Sensors: Zenmuse X5S & L1	All Seasons from 2021–2023 During daylight hours

Methodology

The cliffs at the Aldbrough Coastal Landslide Observatory were surveyed using a combination of Riegl VZ-1000 Terrestrial LiDAR Scanner, a Leica GS14 & GS18T Global Navigation Satellite System, a Leica Pegasus Backpack Mobile Mapping System and a DJI Matrice 210RTK & 300RTK Uncrewed Aerial System, with an X5S Camera, XT2 Thermal Camera & L1 LiDAR module.

The following gives a brief outline of the survey set-up and survey:

- The Leica GS14 was set-up as a base station, for post-processing of the Leica Pegasus Backpack data
- Six Ground Control Points (GCP) were placed across the top of the cliffs, along with the landing pad and positioned using the Leica GS18T Network RTK GNSS
- A walk-over survey of top of the cliffs (~ 1km North & ~1km South) was carried out using the Leia Pegasus Backpack MMS
- Eleven high-resolution scans were taken across the top of the cliffs (500m North & 500m South) using the Riegl VZ-1000 TLS, positioned using the Leica GS18T Network RTK GNSS

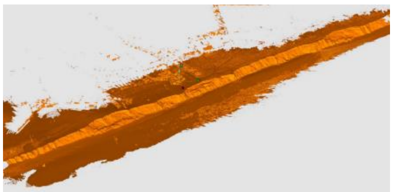
- Four photogrammetric surveys (North-South & East-West) (2 x 500m North & 2 x 500m South) and one high-density oblique photogrammetric survey (200m centred on the road) were carried out using the DJI Matrice 210RTK UAS
- Two high-density thermal surveys (200m North & 200m South) were carried out using the DJI Matrice 210RTK UAS
- Three aerial LiDAR surveys (1km North & 1km South) were carried out using the DJI Matrice 300RTK UAS
-

Processing

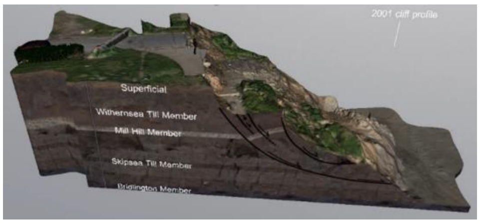
Use of Pix4D to generate orthophoto mosaic and output DEM through photogrammetric processing of RGB. Use of FLIR Tools® v6.3 with coincident meteorological and ground parameters to calibrate LWIR Thermal images to ground temperature before co-registration and generation of thermal mosaic in image processing software. Use of DJI Terra to generate 3D point clouds and 2D & 3D orthophoto mosaics. Outputs were DEM from LiDAR and orthophoto mosaic images and 3D models from RGB.

Results

Point cloud generated from Matrice 210RTK (orthophoto mosaic)



DEM created from combined TLS and UAS LiDAR



3D model of Aldbrough

Challenges

Gusting winds and cold weather caused challenges with UAS flights, take-off and landing.

Conditions underfoot could be unstable.

Vegetation can often be high and wet causing issues with take-off positioning.

Proposed solution(s) to challenges

Enhanced stability of UAS against gusting winds.

Enhanced RTK for more precise UAS geopositioning for accurate landing.

Pond Identification Through Vegetation at Gresham Marshes, Notts

Science Objective

The Environment Agency, working closely with the Wildlife Trust, are currently undertaking eco-surveys, footpath clearance and hedge laying activities at Gresham Marshes. The EA contacted the BGS to provide an aerial survey of the pond locations within the site, the science question was: Can the L1 LiDAR data enable ponds hidden by vegetation to be identified?

Environmental Setting

Gresham Marshes is an Environment Agency owned small area of land. It is a local wildlife site and wildlife reserve located off Gresham Park Road and Wilford Lane in West Bridgford, Nottingham.

The ponds were dug in December 2018 by EMEC. There wasn't a report or official design for the ponds, they were created by workers at the site and there are no maps showing where they are.

Image © BGS (2021)

UAS Specification

Platform: DJI Matrice 300RTK
Sensors: Zenmuse L1

Timing of Deployment

Winter 2021
Morning

Methodology

UAS flights were defined in DJI Pilot as a series of one nadir and four matching oblique (45°) flights. The LiDAR and the matching RGB imagery was performed using the Zenmuse L1 sensor with a side overlap of 70%, the scanning mode set to repetitive, a flight speed of 10m/s, the number of returns set to three and calibration enabled. The altitude was set at 50m to keep within regulations and to provide a point cloud density of 283 points/m2 and a photo output pixel resolution of ~1.5cm. Imagery was recorded in JPG format with ground control targets set out across the study site providing accurate geopositioning using Network RTK GNSS. The five flights took a total of 60 minutes.

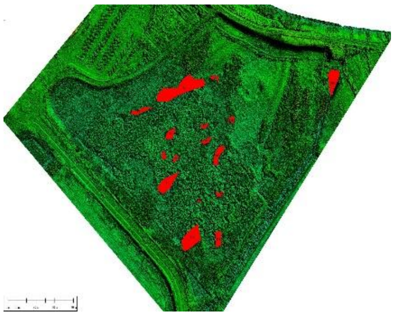
Processing

Use of DJI Terra to generate point cloud and 2D & 3D orthophoto mosaics. Outputs were DEM from LiDAR and orthophoto images and models from RGB.

Results

Gresham Marshes

(aerial photo)



DEM of marsh area with ponds highlighted in red

Coloured point cloud of marsh area with ponds highlighted

Challenges

Gusting winds and cold weather caused challenges with UAS flights and landing. Conditions underfoot were muddy. Vegetation was high and wet causing issues with take-off positioning. Landing issues caused breaking of rotor blade.

Close proximity of school meant flights were restricted to area of marshes, with minimal extension on flight-lines.

Proposed solution(s) to challenges

Enhanced stabilisation of UAS to counteract gusting winds.

Use of UAS with RTK for better geopositioning without need for additional ground control.

Stronger rotor blades to minimise breakage on landing when coming into contact with vegetation.

Easier arrangement of flight permissions to enable acquisition over full survey area.

Collaborations:	The Wildlife Trusts; Environment Agency

UAS Quantification of Greenhouse Gas Emission Fluxes

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Science Objective

Quantification of CH_4 and CO_2 net emission fluxes from point (and local area) sources (and sinks) to reconcile national and regulatory emission inventories and to identify and mitigate GHG sources. Scientific objectives to arrive at quantification included sensor development, UAS integration, telemetry and sampling strategies and emission flux modelling suited to point sources (or diffuse sources over a surveyed area).

Environmental Setting

Areas and sources surveyed include:

Active and historic landfill sites in Manchester and Ipswich (~ $1km^2$)

North Sea Oil and gas platforms

Onshore hydraulic fracturing sites – UK

Dairy Farm - UK

Biochar-treated soils - UK

UAS Specification

Platforms: Bormatec Explorer (fixed wing), DJI-S1000, DJI Matrice-600 (rotary)
Sensors: *In situ* Infrared spectrometers: LGR UGGA, LGR MGGA, ABB Hoverguard (CH_4 and CO_2), Edinburgh Gascard II (CO_2)

Remote sensing: Tokyo Instruments open-path IR TDL (CH_4 column-weighted mean)

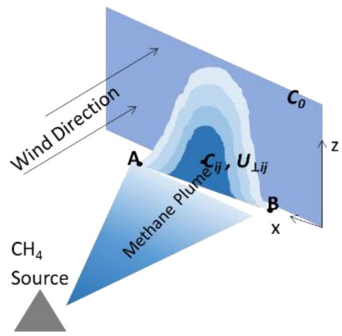
Timing of Deployment

Spring, Summer and Autumn (2015-2023)
All measurements made in daylight hours with winds 2-8ms^{-1} with no precipitation

Methodology

We quantify GHG flux using a mass balance method based on our published FAAM aircraft work studying Arctic and African wetlands and urban and North Sea GHG sources. We have applied this to UAVs to quantify emissions from landfill, fracking and dairy sites in the UK as described in Shaw et al., 2021 (and references therein).

Quantification involves sampling *in situ* GHG concentrations and wind vectors upwind and downwind of (a) source(s) and applying conservation of mass principles to quantify source net inputs. Spatial sampling (flight design) is key to constrain plume morphology (see Figure).

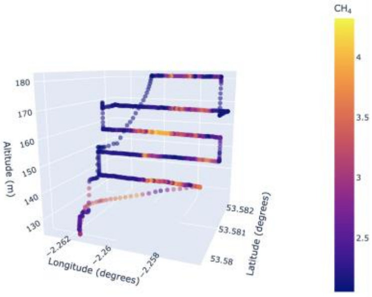


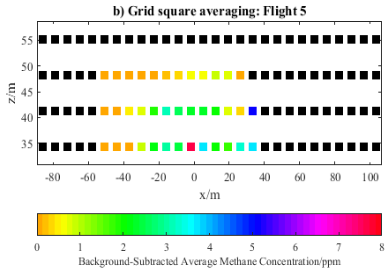
Processing

While the mass balance method is elegantly and conceptually simple, conditioning data for flux calculation requires extensive expertise and complex algorithms to account for (and quantify) sources of uncertainty, which include wind variability, upwind background variability and instrumental error. Processing also includes spatial interpolation of data and confidence assessment in the adequate sampling of an emission plume (for example if the top or the sides of a plume may have been missed).

Results

Example results (right) show sampled CH_4 concentrations along a 3D flight track and spatially interpolated plume data over a landfill site. These data are then used as inputs to the mass balance algorithm.





Challenges

Wind measurement on rotary UASs remain a significant source of uncertainty for this method – sonic anemometers suffer from systematic error associated with air flow around rotary UASs.

Realtime telemetry of concentration data can be difficult over long ranges.

There is a trade-off between the duration and speed of sampling by fixed wing platforms versus rotary UASs (with pros and cons of each when considering the type of sampling required for GHG flux quantification).

BVLOS flights would be preferable for hard-to-reach sources, but permissions are hard.

Maintenance of platforms and obsolescence of some commercial models represents risk to continuity of work.

High precision sensors are often very expensive (>£50k) representing risk when flown in challenging environments.

Proposed solution(s) to challenges

Wind profiles measured by LiDAR or on towers can be an acceptable mitigation for rotary UAS wind measurement. Wind measurement by miniaturised turbulence probes on fixed-wing UASs shows excellent promise.

High power RF telemetry (or 4G networks) can help with real-time telemetry to aid dynamic in-flight sampling.

A combination of rotary and fixed-wing UASs in swarm configuration could be synergistic.

BVLOS permissions are impractical to obtain for responsive science flying (for example for volcanic sampling) – streamlining this could open up new and more responsive science.

A dedicated commercial supplier of bespoke UASs could mitigate risk of removal of commercial UASs from the market.

Moderate precision (cheaper and lightweight) sensors tailored to UASs could mitigate risk and reduce costs – scope for developer collaboration. Complementary sensors (for example for GHG tracers and proxies like N_2O, NH_3, C_2H) would add additional analytical potential.

A UKRI facility could expand access and mitigate project risk if a pool of platforms could be maintained (and potentially flown) for science. This would also avoid problems with maintaining critical mass of pilots/experience within individual groups which are at the mercy of ongoing fixed-term project funding.

Through the GEMMA programme NCAS now have an AERIS GHG *in situ* analyser suited to UAS use.

Collaborations

MANCHESTER 1824 The University of Manchester · SURVEYAR Remote Environmental Survey · Environment Agency · ABB

Upscaling Vegetation Structure and Function

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

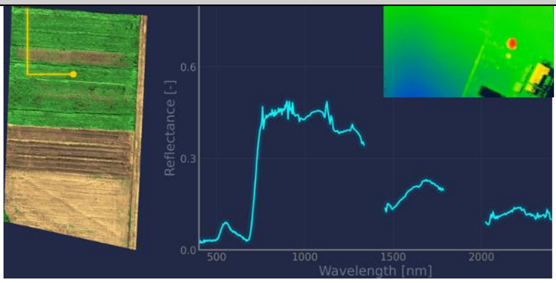
Science Objective

LiDAR: for estimating canopy structure and aboveground biomass (AGB) at fine (m) scale, to help validate EO estimates (GEDI, BIOMASS), assess uncertainty of larger-scale estimates and test/develop new EO retrieval tools.

Hyperspectral: for validating surface reflectance retrievals from EO data (particularly S2 data processed with the SIAC atmospheric correction algorithm); testing biophysical parameter retrievals.

Environmental Setting

Forests, trees and crops. All types, but tropical and temporal forest, urban forest and open-grown trees, crops.



Example figure of crop measurements made at Rothamsted as part of AgZero+ using Headwall sensor; spectral profile of marked pixel; upper right panel LiDAR measurement over surface.

UAS Specification	Timing of Deployment
Platform: Matrice M600; DJI Mavic Mini 2 Sensors: Riegl minivux LiDAR; Headwall hyperspectral camera; RGB camera	LiDAR: Summer/winter Day: for hyperspectral, requires clear skies, stable illumination and 1-2 hours either side of solar noon.

Methodology

LiDAR: collecting top-down forest canopy height and crown properties. Individual tree height and crown size for estimating biomass and carbon of individual trees stocks; vertical profiles of vegetation structure to estimate LAI and canopy cover and state; leaf on / leaf off LIDAR to get gap fraction and wood/leaf fraction.

Hyperspectral: coverage over vegetation at multiple sun angles, states of growth, leaf on/leaf off.

RGB camera: use for cover mapping, qualitative assessment and SfM for DSMs.

Processing

Various

Results

See above for hyperspectral + LiDAR. Early stages of deployment of all.

Challenges
Technically challenging to operate LiDAR and hyperspectral sensors. Hyperspectral in particular requires stable illumination conditions; all require relatively low wind speeds; challenges of geolocation for example with GNSS base station. Flight duration for Headwall sensor is only 15 mins. Challenge of permissions and legislation when working abroad, as well as institutional insurance for instruments and indemnity insurance for people / public. We operate within UK legislation and with GVC (General Visual Line of Sight Certificate) & A2 Certificate of Competency certification & with institutional insurance (via UCL). But the requirements (and responsibility) for certification and insurance vary with institution, platform and location.

Proposed solution(s) to challenges
Working within limited wind and sun conditions, at sites close to take-off point. Establishment of a semi-permanent monitoring site at Rothamsted to allow rapid deployment of UAS from KCL (Kings College London) facility and time-series data collection. Pooling of expertise within NCEO (and more widely NERC FSF and so on) to make use of UAS much more routine - development of data collection protocols, processing tools and processing pipelines is needed (standardise & speed up data collection & processing).

UAS for Wildfire Observations

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

Science Objective

Measurements of fires burning in the natural environment are difficult to obtain and possibly dangerous as well. Using UAS allows us to get certain of these measurements more easily and safely and allows us to sample smoke lofted upwards from a fire (rather than staying near the ground) - which is actually the most significant in terms of the total fraction of smoke produced. Fires can be measured in this way from manned aircraft – but the expense, CO_2 emissions and inability to fly close to the ground all hinder this type of measurement and limit it to very large fires. Placing appropriately equipped UASs into the smoke plumes coming from wildfires or agricultural burning allows us to measure emission ratios and emissions factors of the various smoke aerosols and trace gases in fires of a wide range of types and sizes, as well as to assess things like the fire spread rate and fire intensity. Onboard the UAS, we have a gas sampling data logger and a customized aerosol counter, which help measure the concentrations of gases and aerosols in the plumes. Additionally, on a separate platform, RGB/Thermal cameras – and imagers adapted to measure in the NIR, are utilized to measure the spread rates of the fire and the fire intensity. All these measurements are informative for assessing the impact of landscape fires on the environment and for calibrating and validating models that represent this type of phenomena.

Environmental Setting

Rural areas in Southern Africa, SE Asia, Canada and UK.

UAS Specification

Platform: DJI Phantom 3 Pro, DJI Matrice
Sensors: Gaslab pro cm-1000, customized aerosol counter, RGB/thermal cameras, digital camera adjusted to measure in the NIR, customized smoke collection system

Timing of Deployment

Dry seasons in these countries. Typically 8am to 6am, each fight around 10-15 mins for smoke sampling or up to 30 mins for fire spread rate assessment.

Methodology

For fire rate of spread and intensity measurements, the UAS is hovered over the burning area for up to 30 mins whilst the fire goes underneath.

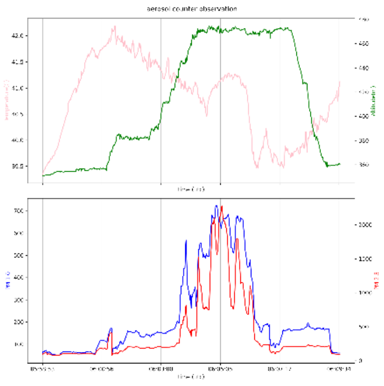
For plume assessment the UAS carries *in situ* sampling equipment. It is hovered in clean air for 2 to 5 minutes to assess the level of gases and aerosols present in the ambient environment. Subsequently, it is flown into the plume for 3 to 5 minutes to obtain measurements of the smoke. Once the required data was collected, the UAS returned to a clean air location and hovered for an additional 2 minutes to once again measure clean area. We repeated this method several times until the UAS's batteries were depleted. During these flights, we used the Gaslab Pro CM-1000 to measure CO/CO_2 concentrations and a customized aerosol counter to determine aerosol mass concentrations, specifically PM1, PM2.5 and PM10.

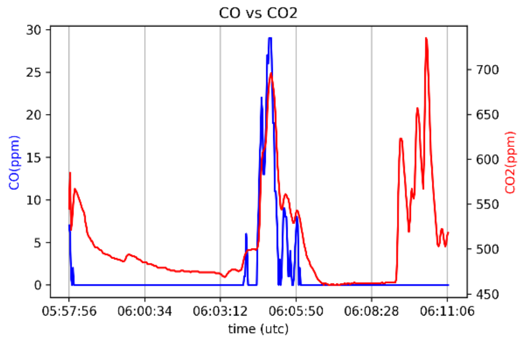
Processing

Co-registering of the RGB, thermal and NIR imagery and thresholding to identify the fire front allows the spread rate and the intensity of the fire to be derived.

Data of the smoke coming from Gaslab and aerosol counter are processed using python code, deriving emissions ratios between the different measured species and then emissions factors.

Results





Challenges

One significant challenge we faced during these observations was the environmental temperature. In Laos for example, especially during the dry season, the ambient air temperature often exceeds 38 degrees Celsius. Unfortunately, the working temperature limit of the Phantom 3 UAS is up to 40 degrees Celsius. As a result, both the batteries and engines of the UAS constantly overheated during our operations – though the UAS proved fantastically robust to this issue given the challenging circumstances.

The overheating issue had several negative consequences. Firstly, the battery life was significantly reduced due to the high temperatures, limiting the flight time and data collection duration. Secondly, the overall performance of the UAS was adversely affected, leading to suboptimal results compared to its standard performance under ideal temperature conditions.

A second challenge is payload capacity and flight duration. We have to use sub-optimal *in situ* sensors because higher performing ones are too heavy to carry with the UAS, plus the battery life is limited and we cannot stay hovering above the fire or in the plume very long.

Proposed solution(s) to challenges

Maybe find a proper UAS which designed for working in higher temperatures. Also one that can fly for longer (ideally 45 mins or more) and carry more sophisticated instrumentation (that is, a heavier payload – say 2 or 3kg rather than <1kg).

UAS for Evapotranspiration

Science Objective	
The UAS was employed to derive crop height, growth rate, land surface temperature (LST) and evapotranspiration (ET). Data was collected from a DJI M200 to provide a comparison with the airborne ET retrievals through a multi-sensor upscaling approach.	
Environmental Setting	
Rothamsted UK, Grosseto Italy	
UAS Specification	**Timing of Deployment**
Platform: DJI Matrice 200 Sensors: FLIR Vue Pro thermal camera, Parrot SEQUOIA+ Multispectral Sensor Adapted digital camera for SfM processing	Growing season of the crop Once per week generally but occasionally for LST and ET three or four times in the daytime typically

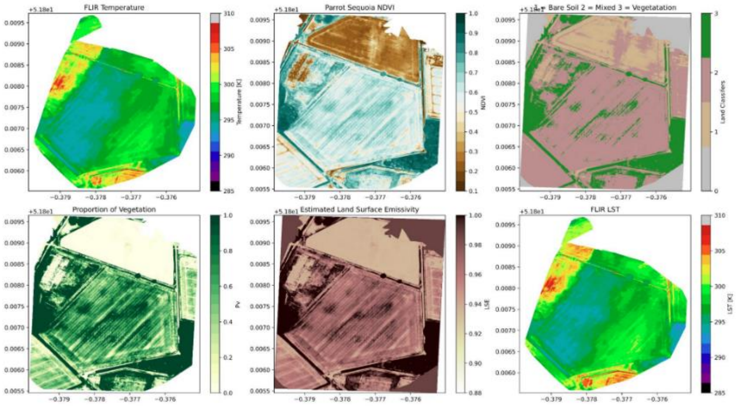
Methodology

For LST and ET, the UAS was flown in two modes: (i) a 'hovering' mode in which the UAS was maintained in position at 100m to view both wheat and barley fields simultaneously to monitor change in surface brightness temperatures; and (ii) a 'mapping' mode in which one field was flown at 80m (to enable higher spatial resolution) with overlap between the lines. The hovering mode was only flown to coincide with airborne overpasses and was timed to coincide with the LSTM pattern (although note that due to battery constraints the UAS had to land to change batteries and relaunch during the full pattern). Flights in mapping mode were repeated at different times in the day and on multiple days during the campaign period to consider diurnal and long-term variability of evapotranspiration, which can be retrieved from radiometric surface temperatures and vegetation maps using methods such as the Two Source Energy Balance (TSEB) model.

For crop height determination, the UAS was flown in mapping mode.

Processing

Data are processed by Pix4Dmapper and dedicated python code.

Results	
Crop height can be determined to 5cm precision and from this crop growth rate can be determined. For the LST and ET mapping, we find that these can be estimated with reasonable accuracy over an entire field.	

Challenges
The potential loss of geoinformation is a concern with both the FLIR thermal camera and Parrot sensors – with them losing geocoded information. The FLIR camera's temperature determination performance is not stable and it requires approximately 15 minutes of warm-up time before take-off. A more precise thermal imager would be beneficial – ideally one with 3 to 5 LWIR bands ideally. Additionally, the limited battery life of the UAS restricts the observation area that can be covered in a single flight.

Proposed solution(s) to challenges
Develop or purchase a better thermal camera. Use an eVTOL fixed wing UAS with a long battery life in the future.

HyperDrone: SWIR Multispectral Proxies for Plastic Debris on Shorelines

PML | Plymouth Marine Laboratory — SAMS Scottish Association for Marine Science

Science Objective

Development of instruments and algorithms for remote sensing of plastics need standardised global *in situ* observations. Compared to aquatic environments, dry shores are more accessible to frequent *in situ* observations. As part of the HyperDrone project, (funded by the Discovery Element of the European Space Agency's Basic Activities) we aimed to develop a standardised indicator for *in situ* radiometric detection of plastic debris with the view to be deployed globally on different platforms.

Plymouth Marine Laboratory (PML), with the support of the NERC Field Spectroscopy Facility and the Scottish Association for Marine Science (SAMS), undertook field campaigns collecting radiometric data using handheld spectrometer and hyperspectral images from sensors mounted on UASs. To make a robust dataset, data were collected along the shoreline in real environmental conditions and uncertainty estimates were tailored by NERC-FSF for those acquisitions. This will in turn ensure best results for designing bespoke theoretical instruments for the remote sensing of plastics that rely on data collected by these campaigns.

Environmental Setting

Two field campaigns were carried out including the cases of rocky shore and sandy beach. An initial campaign took place at Tyninghame beach and a second field campaign at Oban airport's shore.

In both cases, the data was collected around midday during summer for the best illumination conditions. Fieldwork was also performed during low tides to maximise space available.

UAS Specification

Platform: DJI M600
Sensors: Headwall hyperspectral co-aligned VNIR and SWIR (on loan from NERC-FSF)

Timing of Deployment

Summer around midday for best illumination and at low tide.

Methodology

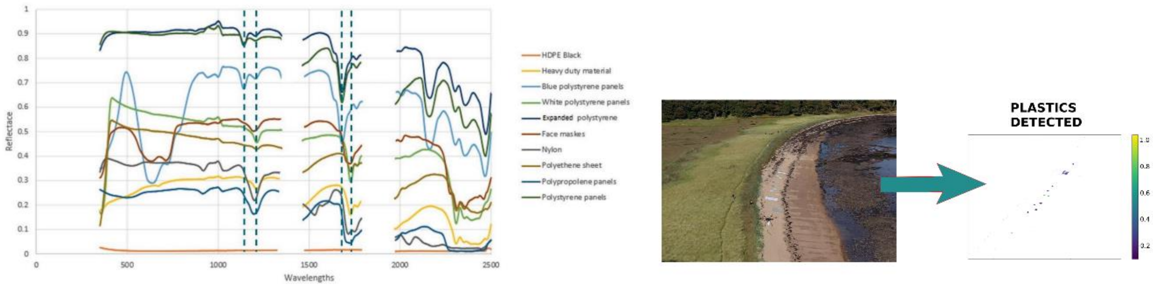
The reflectance of a variety of virgin plastic targets that were deployed on the shoreline was collected using a field spectrometer in reflectance mode and the Headwall hyperspectral pushbroom imager mounted on a DJI M600 UAS. UAS hyperspectral data was collected at the different altitudes of 30, 60, 90 and 120m resulting in GSD (Ground Sampling Distance) of 2 - 7.5cm with each plastic target being at least 1 x 1m at least. An additional Headwall calibration target of 2 x 3m was also deployed to allow conversion from radiance to reflectance.

Processing

UAS hyperspectral images were geocorrected using the LiDAR data collected simultaneously with the Headwall instrument via direct geocorrection using the manufacturer software. Geocorrection was further corrected on QGIS via an iterative method that used each target corner as a manually defined tie-point. To extract the Headwall radiometric data of each target, Regions Of Interest were defined for each pixel to avoid edge effects. The at-sensor radiance was converted to reflectance thanks to the use of the Headwall calibrated reference panels and an empirical correction.

Data is available to encourage other researchers to develop their own algorithms for plastic detection and data from flights [20200929]() and [20210722]() can be downloaded for free from the CEDA archive.

Results



SWIR plastic features were found across plastic targets that shared composition. An algorithm for plastic detection was developed using those wavelengths.

Challenges

The HyperDrone project is now complete and the authors are working on publishing their results. This case of study has been suggested as it captures the best procedures for collecting the best quality of radiometric data while ensuring the data meets FAIR requirements to be made available to other researchers.

The challenge is that hyperspectral sensors are very expensive and therefore a low-cost UAS multispectral sensor will be a better solution towards its deployment for a global program to monitor plastic pollution.

Proposed solution(s) to challenges

A follow up project to build a low-cost multispectral sensor for the remote sensing of plastics using the findings of HyperDrone project.

Hydrogen-Fuelled Survey Platform

SAMS
Scottish Association for Marine Science

Science Objective

Assess the capability of using solid-state hydrogen fuel for long-range UASs.

Environmental Setting

Electric BVLOS Operations as a viable platform for *in situ* atmospheric measurements.

UAS Specification	**Timing of Deployment**
Platform: Bespoke ultra-efficient airframe carrying an H_2-based power delivery system. Sensors: UAS EKF (Extended Kalman Filter) data from the avionics. Hydrogen generator logger. No specific environment sensors.	North Scotland in February 2016. Daytime.

Methodology

SAMS's partner, Cella Energy Ltd, was a ~12 person SME based on the Rutherford Appleton Labs (RAL) campus. They had developed a hydride capsule that would dissolve into H_2 gas (and a small residue) when triggered by a pulse of heat. Their system was at TRL 6 and they wished to make a power unit suitable for a <7kg UAS, using the H_2 delivery to drive a miniature commercial fuel cell. The whole system, plus filters and safety monitors, would fit into a SAMS-designed bespoke aircraft.

Cella teamed up with SAMS because the latter had experience with building novel fixed wing aircraft and had a history (2 staff, via BAS) of BVLOS operations. Not least, SAMS had a robotics test facility (the S-MRF Building) on their campus which was physically unconnected with any other infrastructure, making the safety case for strap-down bench testing the aircraft with the H_2 generation simpler. SAMS also had a track record of working on the local Oban Airport and we were able to borrow their emergency fire practice site (see image) for the final flight tests.

Processing
The final (successful) aircraft was the third version built because the Cella fuel-cell system proved very sensitive to contamination from the hydride residue products. Unforeseen and heavy (for UAS terms) filters were needed during the project, forcing repeated design modifications of the airframe.
Results
The final flight was a success (see right) but resulted in a unplanned landing when the electric current-flow failed. A postmortem showed that the fuel cell delivery telemetry (how much power was being generated) did not match the current draw demanded of the aircraft during excessive flight manoeuvres, but these data were being monitored by two separate telemetry systems (and two different flight crew). Better on-ground communication during pre-cruise would resolve this. 
Challenges
Initial funding for the project came from Innovate UK. Despite promising results, further funding bids were curtailed when Cella energy was bought out by a US venture capital group, who wish to acquire the hydride patent. Cella Energy was then closed.
Proposed solution(s) to challenges
Hydrogen fuel cell technology is a young but viable BVLOS option for <7kg aircraft but has a very different power density - energy density performance than the more familiar LiPo battery. LiPo can deliver high power for short duration (e,g, for copters), whilst H_2 delivers moderate power but for much longer duration (for its weight). See more information and watch a video in an article in the Press and Journal.

NERC UAS School (PhD-Level Course)

Science Objective

Equip PhD-level students with comprehensive UAS training covering safe operation, capabilities and practical hands-on experience, enabling them to leverage UASs as efficient sensor platforms for environmental data collection.

Environmental Setting

Comprehensive 5-day course to provide hands-on practical skills to undertake a UAS campaign safely and successfully for NERC oriented science.

UAS Specification	Timing of Deployment
Platform: DJI phantom, Parrot AR Sensors: Custom data loggers, Temperature loggers, IR camera	West Scotland August 2015 - 2017 Daytime

Methodology

Practical use of mini- and micro-UASs for the Environmental Sciences.

SAMS collaborated with Birmingham, Reading, Southampton and Exeter Universities to host a comprehensive 5-day training course for PhD students, focusing on the practical use of mini- and micro-UASs in the field of Environmental Sciences.

The primary objective of this course was to equip PhD students involved in Environmental Sciences with hands-on skills and experience in utilizing UASs for their research.

The practical sessions involved simulated missions, wherein course participants had the opportunity to select "off the shelf" sensors and integrate them into mini/micro-UAS airframes. They also learned how to plan and execute scientific flights efficiently, followed by processing the data collected during these missions.

In addition to the practical sessions, students attended lectures conducted by experts in the field. The topics covered included regulatory and air traffic legislation, flight planning and checks, as well as the integration of instruments into UAS designs, exploring the fascinating realm of miniaturization.

Processing

During the comprehensive 5-day UAS training course, PhD students were trained in data processing for utilizing mini- and micro-UASs in Environmental Sciences. The workflow covered data collection, pre-processing, georeferencing, data fusion, analysis and visualization. Students learned to efficiently extract valuable information from collected data, enabling them to advance their research objectives.

Results
The UAS training course equipped PhD students with UAS operation skills, sensor integration expertise and efficient flight planning capabilities. Graduates demonstrated proficiency in data processing, applying environmental insights to enhance their research projects. The training led to increased adoption of UASs in research, interdisciplinary collaboration and an expanded research scope.
Challenges
Adhering to ever-changing regulations and air traffic legislation governing UAS operations demanded careful planning to ensure compliance during scientific flights. Secondly, selecting and integrating appropriate sensors into UAS airframes posed technical hurdles, necessitating consideration of payload capacity and data synchronization.
Proposed solution(s) to challenges
Dedicated courses and a training and test facility that can deliver research specific training. Integration between science and engineering to better adapt sensors in UAS platforms, dedicated test facility to ensure integration and efficient accurate data collection. SAMS Robotics Academy is a good example of how this integration can happen.

NERC NEXUSS Grand Challenge

Science Objective

The NEXUSS Grand Challenge is the keystone element in the first-year training of each NEXUS PhD cohort. Students work in teams to address a scientific or industry-relevant environmental challenge. The primary purpose is to give hands-on experience working as a team to use autonomous equipment in a semi-directed environment.

Environmental Setting

Above ocean operation located in Ardmucknish bay utilising SAMS Robotics Facility and vessels as a Main base.

UAS Specification	Timing of Deployment
DJI MAVIC, DJI SPARK	September 2017

Methodology

The Grand Challenge offers NEXUSS PhD students a practical opportunity to apply their education and training while developing teamwork and communication skills. This involves hands-on experience with various autonomous systems, including Uncrewed Aerial Systems (UASs), to understand their limitations and drive research in their studies.

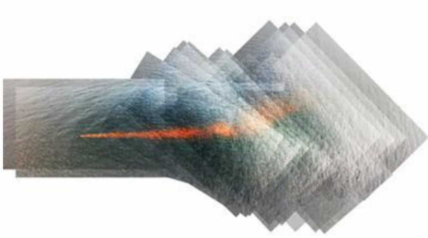
The students face a dynamic challenge through evolving scenarios (2017, a leaking undersea pipe scenario was utilised using rhodamine dye), receiving new information regularly and are supported by a UAS pilot who assist them in planning UAS missions and collecting data for the challenge. This approach cultivates a comprehensive understanding of autonomous systems, fosters problem-solving abilities and prepares students for real-world deployments of reliable and robust solutions.

Processing

The teams employed UASs to conduct aerial surveys aimed at identifying the region of the simulated spill. The students were not provided with the precise location of the spill and were tasked with using UASs to locate it within the bay. To facilitate this process, the data collected through UASs was processed using PIX4D, enabling the creation of detailed maps. These maps were then shared with other teams to expedite the process of locating the simulated leak. A Hyball ROV was then used to look more closely at the “pipe” and identify the source. Data were combined to make estimates of the extent of the spill. Back on land, the teams used a numerical model for the region to track forwards and backwards in time, to pinpoint the source and estimate its spread.

Results

The NEXUSS Grand Challenge saw significant progress in addressing the environmental challenge of locating a simulated undersea pipe leak using autonomous equipment. Teams effectively utilized UASs for aerial surveys, identifying the spill region within the bay. Collaboration and data integration resulted in accurate estimation of the spill's extent, despite the dynamic nature of the scenarios and technical complexities of autonomous systems.



Data collected through UASs and processed using PIX4D facilitated the creation of detailed maps, accelerating the search process. The collaboration among teams in sharing maps exemplified effective communication and teamwork skills. Integration of Hyball ROV for a closer examination of the "pipe" successfully identified the source of the leak. Combined data from UAS and Hyball ROV allowed accurate estimation of the spill's extent. Back on land, a numerical model tracked forwards and backwards in time, pinpointing the source and estimating its spread. The challenge highlighted the unpredictable nature of real-world environmental scenarios and technical complexities associated with autonomous systems.

Challenges

Teams having to utilise trained UAS pilots and potential issues of getting flight permission at short notice. Flying from moving vessels in open water. Data standards among sensors, Sensor connectivity to UAS.

Proposed solution(s) to challenges

Pre-UAS training is essential for the "pilot" team, enabling them to fly under the guidance of an experienced pilot. This necessitates a suitable training and test facility.

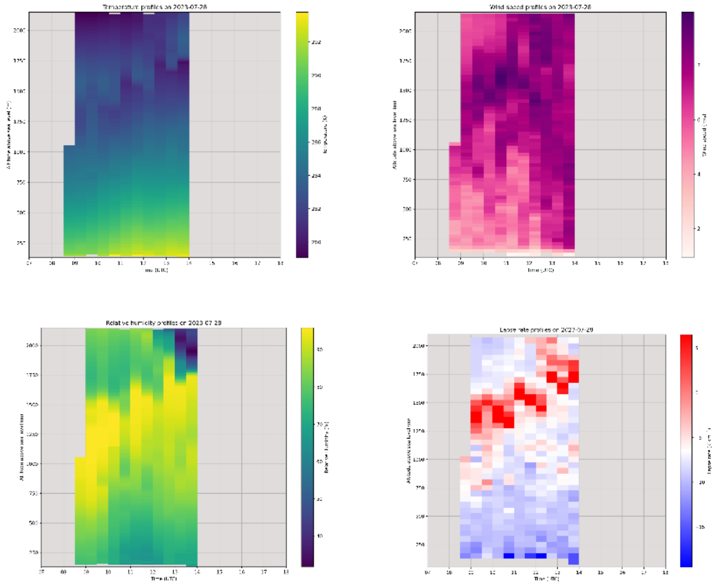
Create a methodology of best practices for flying from a vessel or utilizing BVLOS operations from a land base.

Develop DATA standards to streamline the integration of UAS sensors into other data sets and models. Additionally, work on Connection/Communication standards to enhance sensor-to-platform interconnectivity and communication.

WesCon–WOEST Field Campaign Summer 2023	National Centre for Atmospheric Science NATURAL ENVIRONMENT RESEARCH COUNCIL Menapia
Science Objective	
Measure the evolution of turbulence in the convective boundary layer.	
Environmental Setting	
British Summer	
UAS Specification	**Timing of Deployment**
Platform: Menapia MetSprite Sensors: Temperature (T), Pressure (P), Relative Humidity (RH or U) (10 Hz), 3D winds (40 Hz)	Summer 2023, 0800–1600
Methodology	
Four wxUASs (those which repeatedly measure atmospheric profiles in a routine manner) deployed to both Chilbolton for 120m profile and hover (constant presence by replacing one wxUAS with another) and to SPTA which allows for 2km profiling.	
Processing	
Winds are corrected for UAS motion and rotation. Multiple T/RH sensors with different response times and accuracies are processed into one. NetCDFs are produced following the WMO standard recently created for wxUAS. Hover data are processed with the eddy covariance method for turbulent fluxes.	

Results

The campaign is ongoing but has demonstrated the capability and value in these types of frequent measurements. Some sample data are attached. These show part of the diurnal cycle of a capping inversion at the top of a convective boundary layer. The humidity is high inside cloud and rapidly drops in the free troposphere. An inversion in temperature is visible and as very high values of lapse rate.



Challenges

1. Airspace access and cooperation with key stakeholders of those airspace.
2. Personnel fatigue.

Proposed solution(s) to challenges

1. A centralised facility which maintains good relations with stakeholders of key and strategic airspace in the UK.
2. More automation of flights, multiple wxUASs managed by one human operator.