PolarGap 2015/16

Filling the GOCE polar gap in Antarctica
(and ASIRAS radar flight for CryoSat support)

DATA ACQUISITION REPORT V5

Tom Jordan, Carl Robinson, BAS
Arne V Olesen, Rene Forsberg, DTU-Space
Kenichi Matsuoka, NPI
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Abreviations/acronyms

Above ground level .... AGL
Airborne SAR/Interferometric Radar System .... ASIRAS
Antarctic Specially Managed Area .... ASMA
Alfred Wegener Institute .... AWI
Antarctic Logistics & Expeditions .... ALE
Antarctic Logistics Centre International .... ALCI
British Antarctic Survey .... BAS
CryoSat Validation Experiment .... CryoVEx
Dronning Maud Land Air Network Project .... DROMLAN
Technical University of Denmark .... DTU
European Space Agency .... ESA
Gravity field and steady-state Ocean Circulation Explorer .... GOCE
Inertial-measurement unit .... IMU
Lacoste & Romberg .... LCR
Lamont-Doherty Earth Observatory .... LDEO
Norwegian Polar Institute .... NPI
National Science Foundation .... NSF
Quality control .... QC
Uninterruptible Power Supply .... UPS
Zero-Length Spring Corporation .... ZLS

1. INTRODUCTION

The ESA PolarGAP gravity field campaign was successfully carried out in the period between DEC 7, 2015 and JAN 19, 2016 using a BAS Twin-Otter aircraft. The last and most challenging data gap in Antarctica is now covered with reconnaissance airborne geophysical data, and the last remaining data void on the planet filled with medium-resolution gravity data.

The primary objective of the PolarGAP campaign was to do an airborne gravity survey over the southern polar gap in the ESA gravity field mission GOCE, beyond the coverage of the GOCE orbit (south of 83.5°S). An additional aim was to collect ASIRAS Ku-band radar data over an interior Antarctic region around 85°S, 135°E, in order to provide data to investigate anomalous patterns seen in CryoSat ice sheet elevation changes. The flight operations were supported by ESA, with additional significant in-kind and manpower contributions from project partners BAS, DTU-Space, and the Norwegian Polar Institute (NPI).

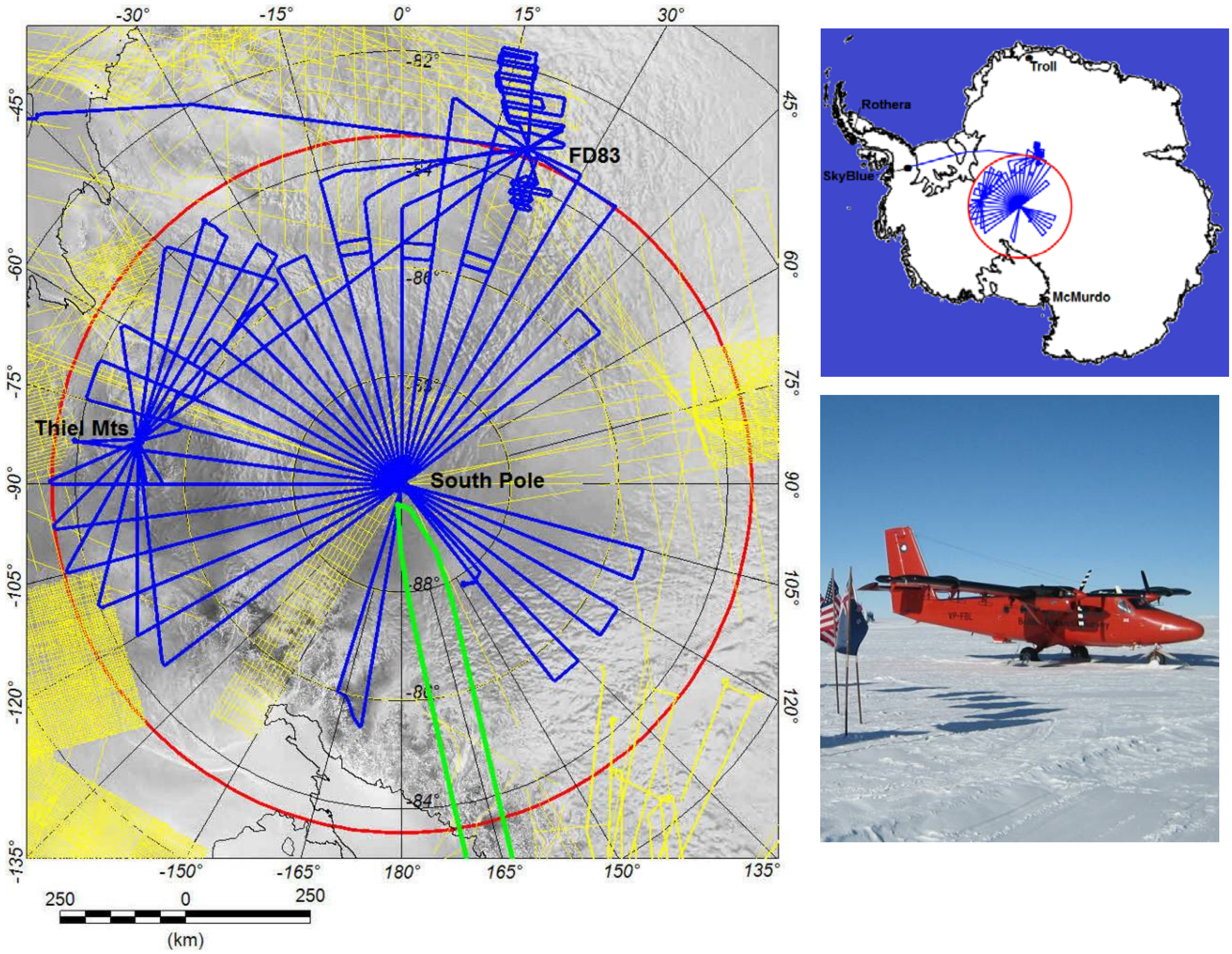


Fig.1. PolarGAP flight coverage across central Antarctica (blue). The yellow lines show existing gravity data, and green radial lines mark gravity profiles flown by LDEO/Columbia University, as part of the NSF-supported ROSETTA project in Nov 2015. BAS Twin-Otter at South Pole lower right.

Given the costly and complex nature of logistic operations in the interior of Antarctica, a whole suite of airborne geophysics instruments were flown together with the gravity systems to maximise the scientific benefit of the PolarGAP project. This new data together reflects a significant advance in geophysical and glaciological knowledge of a virtually unknown region of Antarctica. The data types collected include:

- Gravity data (with Lacoste&Romberg and IMU gravity sensors)
- Magnetic total field data (sub-ice geological fabric)
- Ice penetrating 150 MHz radar data (ice thickness, stratigraphy, and bed conditions)
- Lidar data (swath high-resolution laser scanning of snow surface)
- ASIRAS Ku-band coherent radar data (CryoSat proxy) –one flight only.

Data sets were complemented by supporting GPS and IMU data for aircraft positioning and attitude determination. Ground reference stations for GPS and magnetic measurements were also operated. The absolute gravity reference level for the survey was established by links to the absolute gravity site at McMurdo base in the Ross Sea, and the well surveyed gravity point at Rothera Research Station on the Antarctic Peninsula. All data were quality controlled in the field, confirming collection of high-quality data, with nearly 100% of planned flight lines resulting in useful data across all data streams.

2. SUMMARY OF OPERATIONS

A BAS Twin-Otter aircraft VP-FBL was used to collect the airborne data, operating from two remote tented field camps (FD83, front page picture, and Thiel Mountains, cf. Fig. 2), as well as the US Amundsen-Scott South Pole Station. The field camps were necessary in order to cover the outer regions of the polar gap, beyond the range of the Twin-Otter aircraft. Fuel at these two camps was positioned by commercial operators ALCI by Iluyshin-76 air drop at FD83, and by ALE by tractor train from the Union Glacier blue ice runway to Thiel Mountains.

The FD83 camp (front page figure) was established by NPI, with support flights made by ALCI (DC3 Basler camp put-in and pull-out from Troll) using the DROMLAN network. NPI’s Center for Ice, Climate and Ecosystems (ICE) sponsored, as part of the FD83 operations, dedicated flights over the Recovery Lakes (the second-largest subglacial lake system in Antarctica; following up on 2013 cooperative DTU-BAS-NPI surveys in the same region). The Thiel Mountains camp was staged by BAS, using a separate support BAS Twin-Otter.

Fig. 2. ALCI Basler and BAS support Twin-Otter at FD83. Fuel drum depot between aircraft.

The central part of the survey was carried out from the US Scott-Amundsen South Pole base, thanks to a special agreement with NSF. Several flights around South Pole crossed the normally restricted Antarctic Specially Managed Area (ASMA #5), and were negotiated through the BAS environment office and NSF (see Appendix 5).

Fig. 3. Top: Thiel mountain PolarGAP camp. Lower: Fueling at SkyBlue.

The overall timeline for the PolarGAP airborne survey operations were as follows:

Dec 3-12: Mobilization to BAS base Rothera and installing equipment.
Mobilization of NPI staff from Troll to FD83 field camp.
Dec 13-21: Transit to FD83 via BAS blue ice runway "Sky Blue".
PolarGAP survey and NPI lake flights from FD83.
Dec 22-27: Weather delay, *Christmas*, and transit to Thiel Mts base camp.
Demob of FD83 NPI staff to Troll with ALCI Basler.
Dec 26-Jan 6: Survey flights from Thiel Mts camp, some weather delays.
Jan 6-7: Transit to South Pole station, one day lost in crossing date line.
Jan 8-16: Aerogravity survey flights from South Pole.
Jan 17-18: ASIRAS installation and survey flight.
Jan 19-22: Demob, Twin-Otter to Rothera, 2 pax to NZ via McMurdo.

A total of 38 survey flights were carried out numbered P1-P38. These flights included the NPI recovery lakes flights, the ASIRAS flight and a requested local photographic flight over the South Pole station. The total number of flight hours by the survey aircraft, including transit flights to/from Rothera, was 145 hrs, for a total of 38600 km of flights, of which 26000 km survey lines.

A detailed summary of operations can be seen in Appendix 1 (Gantt chart), and a detailed summary of the flights given in Appendix 2.

Fig. 4. Amundsen-Scott South Pole Station, luxurious base for PolarGAP and ASIRAS flights

The following personnel participated directly in the PolarGAP field activities:

Tom Jordan – BAS (field leader)
Carl Robinson – BAS (Survey instrument engineer)
Kenichi Matsuoka - NPI (institute PI, FD83 lake flights)
Harvey Goodwin – NPI (logistics support)
Arne V Olesen – DTU (gravity specialist, FD83 and Thiel flights)
Rene Forsberg – DTU (co-PI, South Pole last part – weather delay)
Ben Tibbetts – BAS logistics support (Thiel Mts)
Ian Potten, Andy Vidamour, Mike Bertrand – BAS pilots and mechanic

BAS head of logistics *Mike Dinn* and NPI logistics officer *Sven Lidström* were instrumental in setting up logistics and permissions.

3. SURVEY HARDWARE AND INSTALLATION

The survey instruments were installed in the BAS Twin-Otter as outlined in Fig. 5 and shown in Fig. 6. The installation took place in the hangar at the British Rothera Station, except for ASIRAS, which was installed outdoors at South Pole (-30 C), after removal of LCR gravimeter and the ice penetrating radar (due to weight and space limitations).

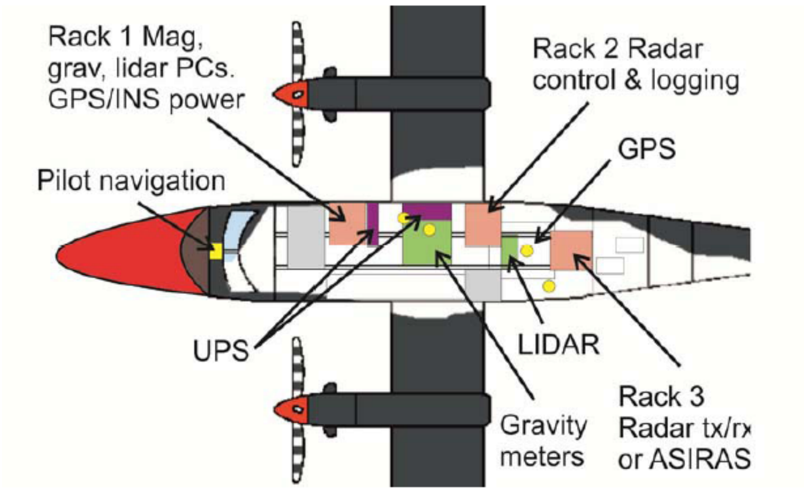


Fig. 5. Installation of instruments in Twin Otter. IMU's located on floor forward of gravimeter

Gravity was measured with a ZLS-modified Lacoste and Romberg (LCR) gravimeter S-83, belonging to BAS. The LCR gravimeters have very low and stable drift, and are a well proven aerogravity system. In addition we flew a high-end inertial navigation system (iMAR RQH-1003, provided by TU Darmstadt), which has been proven to give high resolution gravity at the mGal level in recent DTU-Space surveys in Chile and Malaysia. The LCR and IMU gravity systems combine long-term stability and short term dynamic linearity, and thus together may produce optimal broad-band high-accuracy gravity measurements. An additional lower-grade BAS IMU (iMAR FSAS), flown primarily to provide roll and pitch for the laser scanner, turned out also to be a potential useful aid in gravity processing.

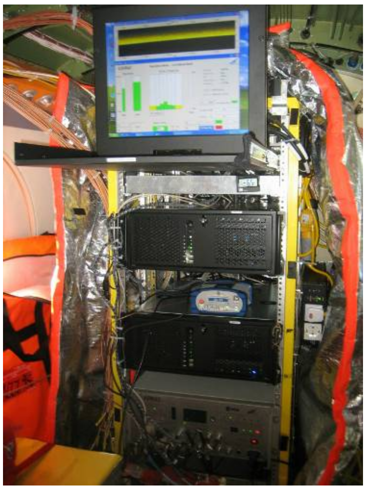


Fig. 6. Left: Forward look in cabin, with LCR gravimeter sensor and magnetometer and power conditioner rack unit; right: ASIRAS installation in back of aircraft cabin.

Magnetic total field was measured with two wing tip-mounted Scintrex CS-3 Cesium vapour magnetometers. A cesium vapour magnitomiter from DTU and a proton procession magnetometer from BAS were used for reference at FD83 and Thiel Mountains respectively. At South Pole the Lucent Technologies fluxgate magnetometer from the Polar Experiment Network for Geospace Upper atmosphere Investigations (PENGUIn) project was used as a geomagnetic reference station. On two instances the magnetometer software system froze leading to data gaps of 158-195 km.

Ice penetrating radar measurements were carried out using the BAS 150 MHz in house developed radar system. The system uses under-wing mounted dipole antennas, and can give reliable ice thickness measurements for ice over 4km thick. Certain ice sheet conditions, such as enhanced flow, lead to warming and/or fracturing of the ice and may mask the bed. An uncontrolled shutdown of the radar system at the end of flight P22 resulted in damage to amplifiers in the radar receiver. This problem was repaired in the field using redundant amplifier channels, and the radar system recovery of bed elevation for flight P24 and subsequent missions appeared as before in the in-flight QC monitor.

Lidar ice sheet elevation data were measured with a Riegl Q240i laser scanner (the same type used in the ESA CryoVEx campaigns). These measurements have an accuracy of a few cm, with the overall system accuracy limited by the kinematic GPS positioning, typically at the 10 cm rms level. To estimate angular offsets of the laser scanner data, calibration flights were made over runway at Rothera, as well over GPS-surveyed buildings at Rothera and South Pole station.

Multiple geodetic GPS systems were used for precise aircraft positioning. On the survey aircraft Javad, Novatel, and Leica receivers were used. Coincident base station data was collected using a variety of GPS receivers; Javad at all locations, NPI operated Trimble at FD83, BAS operated Leica at Thiel Mountains, and UNAVCO operated Trimble at South Pole. All data from the airborne and base measurements were copied to two separate backup discs on a daily basis.

Reference gravity ties were carried out between the survey aircraft field tie down positions and gravity stations at Rothera, South Pole and McMurdo with LCR land gravimeters BAS G-784 and DTU G-867. These ties are important as they precisely link the PolarGAP survey to the global gravity base network. In addition they provide a link to earlier measurements made during the IceGrav (2011-13) and ESA Dome-C (2013) campaigns, and will be used to help re-calibrate older gravity measurements in the polar GOCE gap.

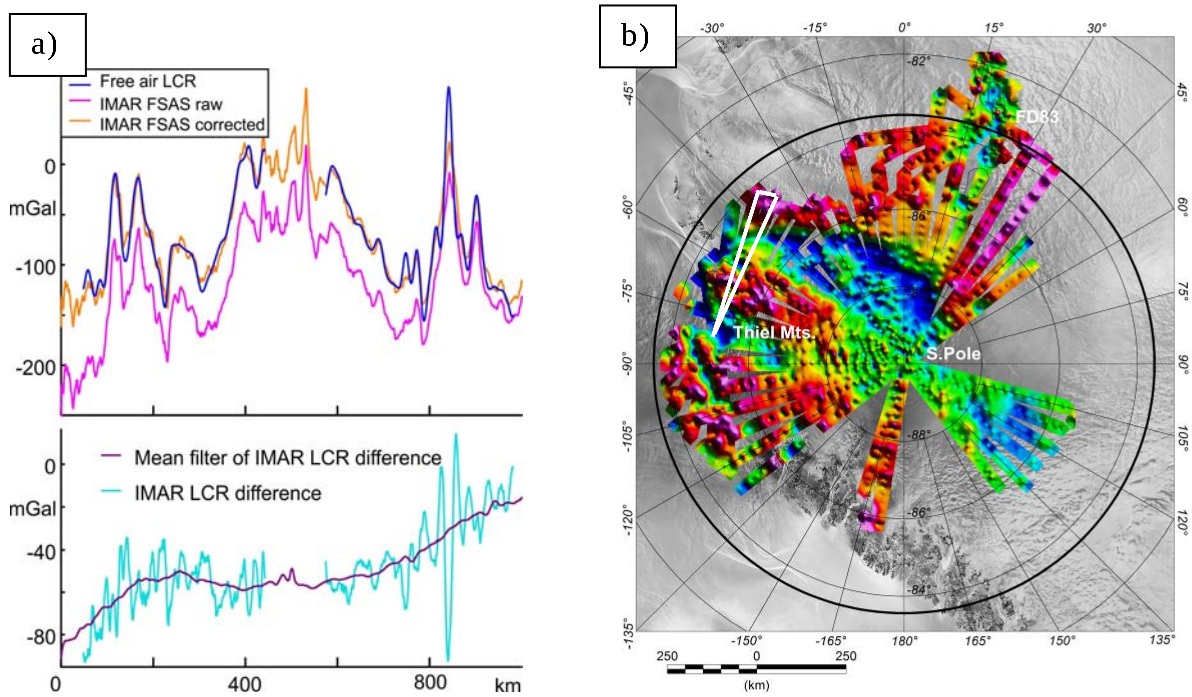
Fig.7. Gravity reference stations at South Pole. a) Official reference gravity point in service tunnel (-50 ℃). b) New temporary reference at base of stairs up to South Pole station entrance

4. PRELIMINARY EXAMPLES OF DATA

Preliminary QC of the LCR free air gravity data (Fig 8) reveals good line to line correlation, with no obvious biases between lines (Fig. 8b). Noise in this data set is apparent, likely due to horizontal and vertical accelerations, which will be removed during post processing. Comparison between the LCR free air data and gravity estimates from the FSAS IMU system show a long wavelength non-linear trend in the FSAS data, likely reflecting temperature variations across the flight (Fig. 8a). After smoothing, this non-linear trend was removed from the FSAS data, providing an anomaly pattern comparable to the LCR system (Fig. 8c). The de-trended FSAS free air anomaly data has less noise associated with aircraft horizontal and vertical accelerations, and extends closer to the ends of the survey lines.

The free air anomaly pattern observed by both systems is indicative of the sub-ice topography. As the ice thickness data from the radar system has not yet processed the gravity data provides the first glimpse of the sub-ice topography across the poorly explored region around South Pole (Fig. 8). Most obviously a broad newly mapped basin is evident grid north of South Pole separating the highlands towards FD83, from the inboard part of the Transantarctic Mountains.

Our preliminary QC of the gravity data confirms that the data set is of good quality. Subsequent processing, including differential GPS processing with precise ephemeris, horizontal acceleration corrections, and robust independent ties to gravity bases at McMurdo and Rothera stations will provide a data set with mGal accuracy. This new gravity data set represents an important advance in both geodetic and geophysical knowledge of the poorly explored South Pole region.



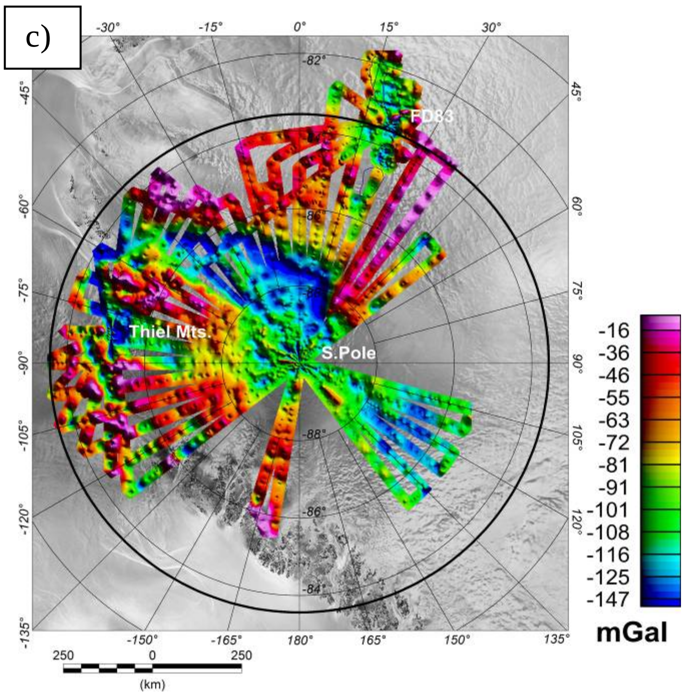


Fig. 8 Preliminary QC gravity anomalies. a) Example profile view showing initial gravity anomalies from LCR and IMAR-FSAS systems (upper panel) and difference between LCR and IMAR-FSAS system showing non-linear drift (lower panel). Gap in LCR data at ~500 km reflects turn at end of line.
b) Gridded Free air anomaly from LCR meter S83. White line locates profile in a.
c) Free air anomaly from FSAS IMU system corrected for long wavelength drift using LCR meter.

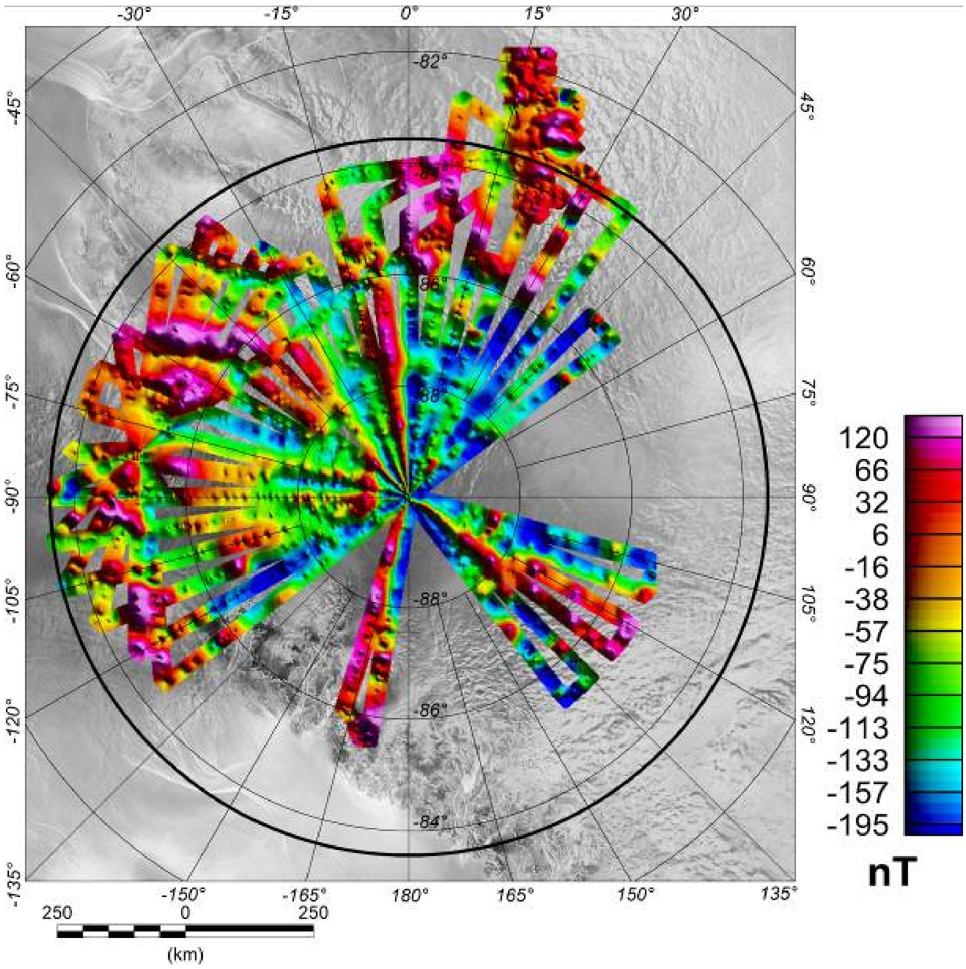


Fig. 9. Preliminary QC aeromagnetic data across the PolarGAP region.

The aeromagnetic data collected during the PolarGAP survey suggests that there are a number of distinct magnetic provinces and previously un-recognised structures across the region (Fig. 9). However significant further processing is required before a detailed geological analysis can be made from this data set.

Quality control of the airborne radar data was primarily carried out by the operator during the survey flights by observing a scrolling display of the stacked radar traces. Figure 10 shows an example flown across South Pole station. The ice sheet bed in this region is known to be ~2.8 km below the ice surface, and is clearly imaged. Distinctive artefacts result from off-axis reflectors from the station buildings, seen here as diagonal lines. In addition englacial structures are observed within the ice below the region of South Pole station, likely reflecting the ICECUBE neutrino detector, a 1 km^3 of ice which has been drilled and instrumented with over 5000 light detectors.

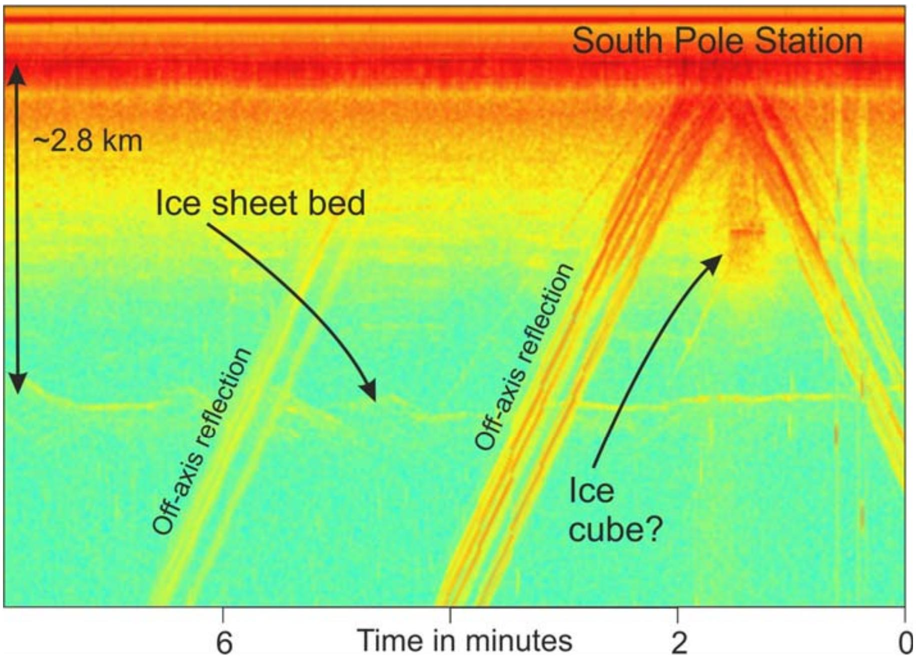


Fig. 10. Example of in-flight QC radar display crossing the South Pole.

A preliminary example of lidar data over the South Pole base area is shown in Fig 11. This image is based on initial GPS solutions and aircraft attitude from the lower grade iMAR FSAS IMU, without proper calibration of offset angles (errors in roll and pitch can be seen as some weak striping across the scans). The displayed flights over the South Pole area was done on two days (P26 and P36), and at different flight elevations above ground level (ca. 400 m and ca. 600 m). Laser scanning over the pole itself showed apparent anomalies related to software singularity bugs, which will be corrected by later post processing. Otherwise there is good agreement between the four different passes, and many surface features can be seen.

It is evident that the Riegl Q240i lidar works well around 400 m AGL, but loses some signal at 600 m. The majority of flying was carried out below 420 m AGL, and ~73% was carried out below 600m AGL. However, due to the need for constant elevation along lines parts of some flights were flown at significantly greater height AGL, and Lidar data may not be recovered, additionally low cloud on some flights obscured the Lidar. For the ASIRAS flight a constant elevation (AGL) of ca. 450 m was maintained throughout the flight.

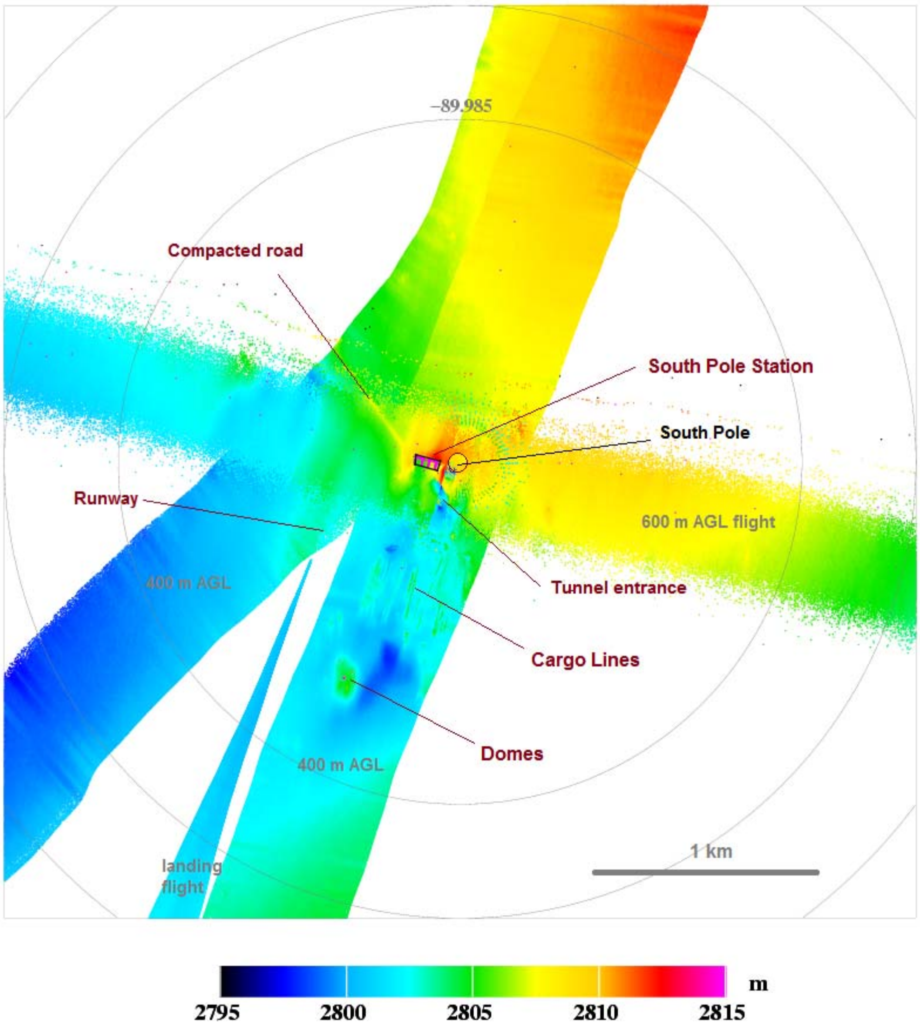


Fig. 11 Lidar data over South Pole station area, from two different days and different flight height above ground level. The South Pole station itself shows up as pink structure (building height saturate scale); the black square around the building is GPS-measured building corners.

Fig. 12 Aerial view of South Pole Station from the grid north. Selected features in Lidar scan are highlighted.

The ASIRAS radar was installed on flight P37. ASIRAS data was collected in 3 roughly 1-hr segments, with each subfile at 5 min interval, cf. log file info in Table 1. The data were collected in LAM (Low Altitude) mode, following the CryoVEx campaign principles, with a nominal elevation AGL of 1500 ft. A pattern over one of the CryoSat "necklace" anomalies was flown with multiple different headings, spaced ~10° apart, cf. Fig 13. The ASIRAS data will be processed by AWI at a later stage; no field calibration corner reflectors were in place, but the South Pole station and runway was overflown, giving a potential calibration site (the roof of the station was measured with static GPS, and is quite flat and large, cf. Fig. 12).

Table 1. ASIRAS file sequence timing, from flight P37, 18 JAN 2016.

Start time UTC	ASIRAS time start	ASIRAS time stop	PC1 file time, first sequence	Comments
20:00, reboot	20:57:17	21:51:07	21:02	Take off 19:49 UTC
20:55	21:51:50	23:18:35	21:56	"Necklace" pattern
22:20	23:18:37	23:57:30	23:23 Stop 00:24	Overflight SP station 23:19, landing 23:25

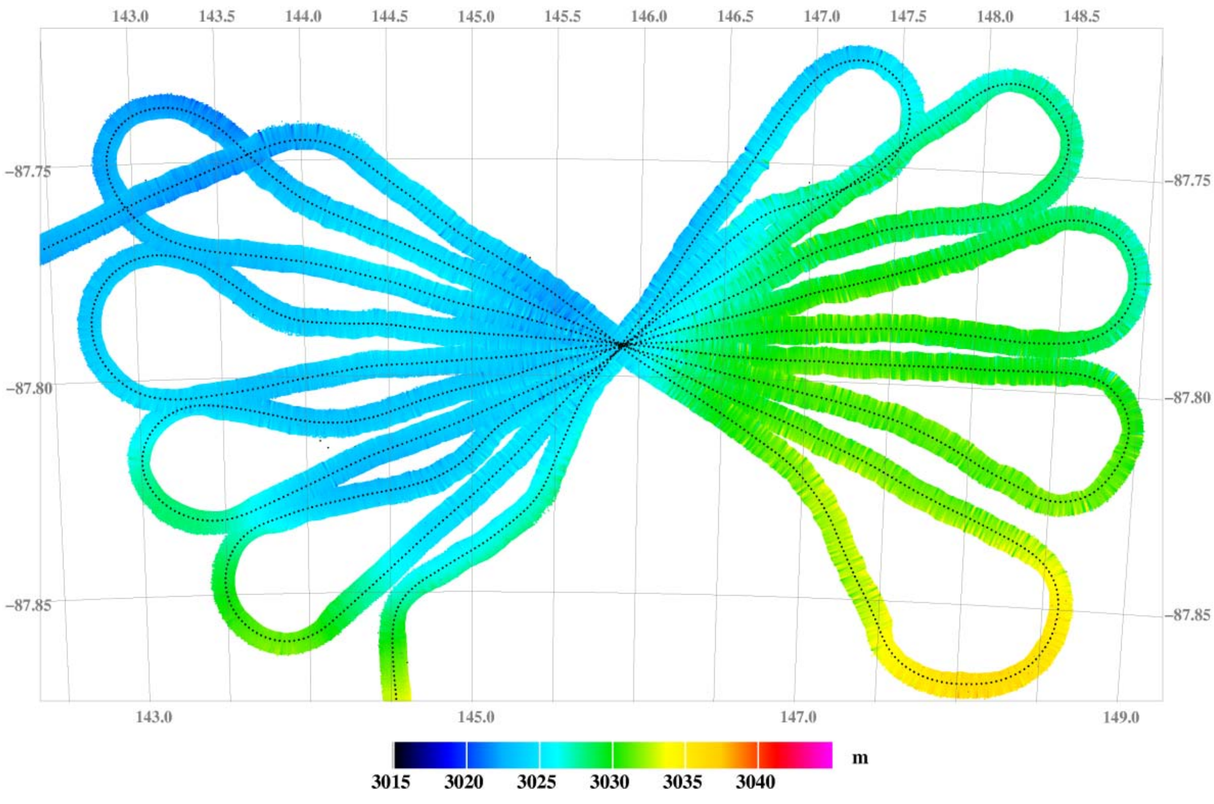


Fig. 13. Lidar data over the flown CryoSat "necklace" anomaly at 87.8°S, 146°E. The preliminary lidar data shown are based on the lower grade IMU, some roll/pitch noise is seen.

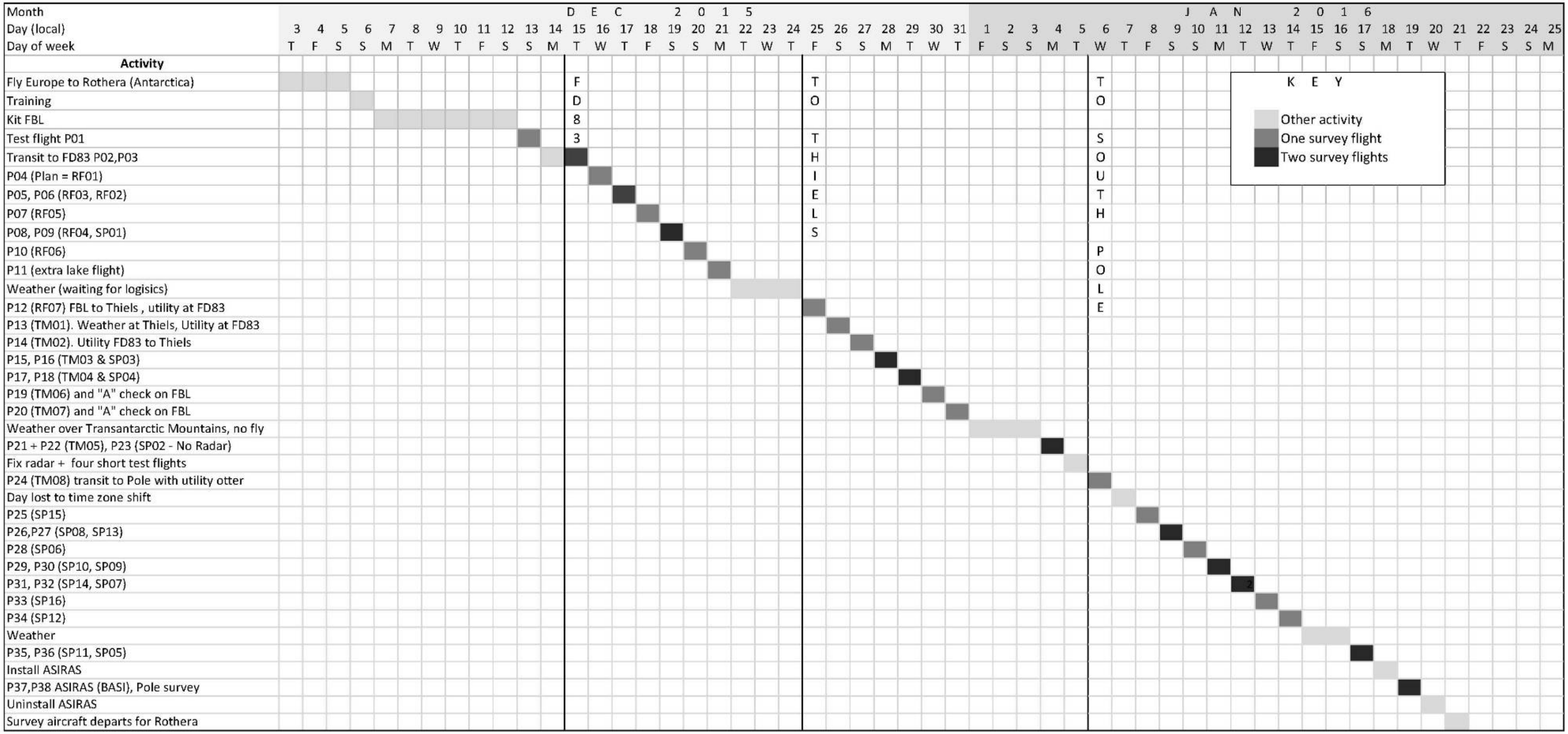
ACKNOWLEDGEMENTS

The PolarGap team thank NSF for access to South Pole Station, fuel support, and transit from/to South Pole to Christchurch, New Zealand for two participants; we thank all the staff at South Pole station for kind and efficient support. We specifically thank NOAA for their cooperation with our flights through the clean air sector adjacent to South Pole, UNAVCO for provision of GPS base station data at South Pole and the Polar Experiment Network for Geospace Upper atmosphere Investigations (PENGUIn) project for provision of South Pole magnetic base station data. Norsk Polarinstitut and the staff at Troll are thanked for their logistic support for the project, ALE for permission to use fuel at the Thiel Mts depot, and ALCI for timely provision of logistics services. We thank professor M. Becker, TU Darmstadt, for providing the iMAR RQH-1003 for the project. We thank Kevin Hughes from the BAS environmental office and Polly Penhale from NSF for helping arrange flights through the South Pole ASMA.

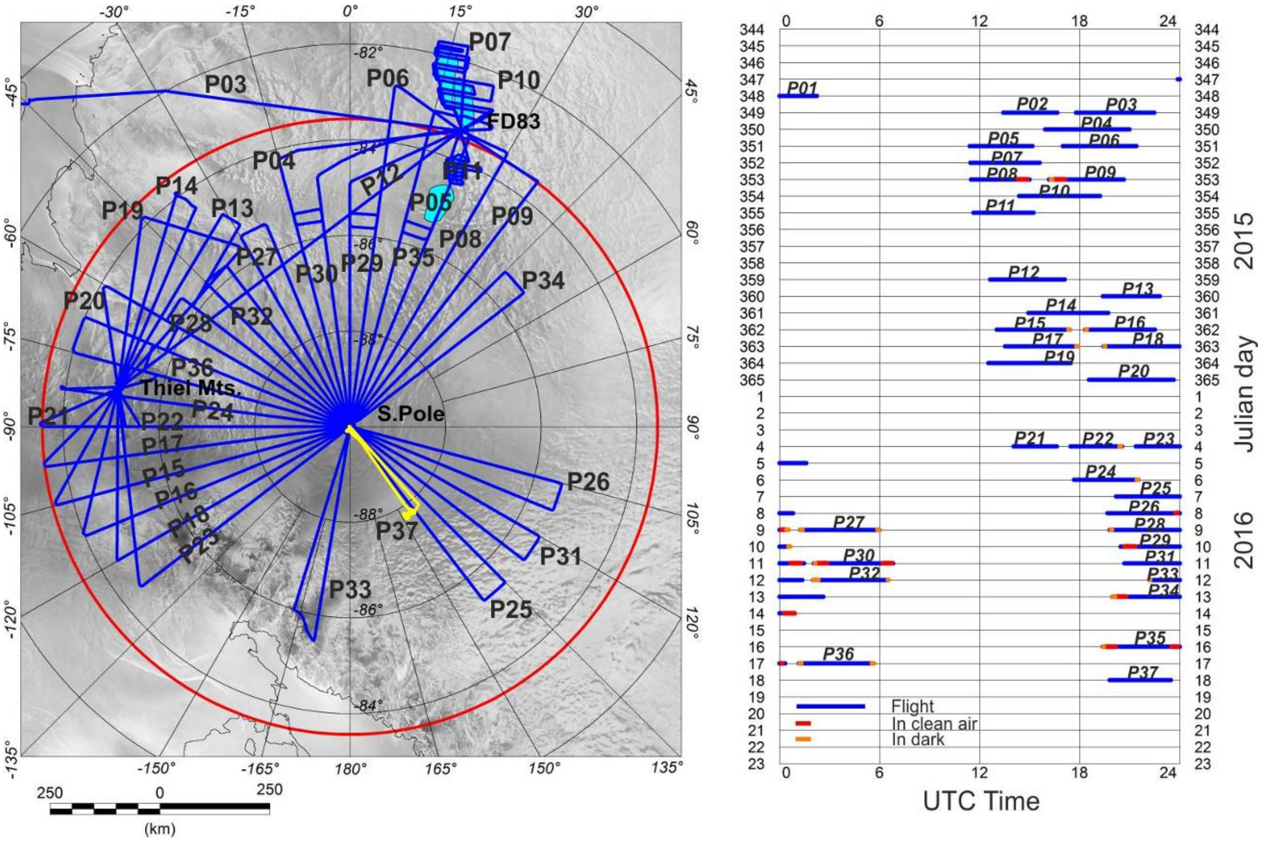
The PolarGap campaign was supported by ESA, with additional financial or in-kind support from BAS, DTU-Space and NPI's Centre for Ice, Climate and ecosystems (ICE).

Fig. 13. The survey team at the South Pole, after the last PolarGAP flight on JAN 19, 2016. From left: Ian Potten, Rene Forsberg, Andy Vidamour, Carl Robinson, Tom Jordan and Mike Bertrand. Arne Olesen (FD83+Thiel), Kenichi Matsuoka and Harvey Goodwin (FD83) and Ben Tibbetts (Thiel) not in picture.

APPENDIX 1. GANTT CHART OF ACTIVITY DURING THE POLARGAP SURVEY



APPENDIX 2. DETAILED FLIGHT AND DATA OVERVIEW



PolarGAP flight overview. a) Map of PolarGAP gravity flights (blue) numbered in the order flown (P03 to P36). Yellow line marks ASIRAS flight (P37), with detail over CryoSat anomaly. b) Graphic showing survey progress in time. Note red and orange sections show time of flights through normally restricted Clean Air, and Dark sectors of the South Pole Specially Managed Area (ASMA #5). See Appendix 5 for full report on activity within the ASMA.

Table showing flight start and end times and significant technical issues.

Flight	Start		End		Distance	Location	Comment
ID	Date	time	Date	Time	Km		
P01	13/12/2015	23:53:07	14/12/2015	02:14:26	509	Rothera	Test
P02	15/12/2015	13:25:15	15/12/2015	16:39:20	787	Transit	No Laser
P03	15/12/2015	17:47:21	15/12/2015	22:28:34	1012	Transit	No Laser
P04	16/12/2015	15:55:44	16/12/2015	20:59:07	1098	PolarGAP (FD83)	
P05	17/12/2015	11:24:59	17/12/2015	15:09:42	853	PolarGAP (FD83)	
P06	17/12/2015	16:59:33	17/12/2015	21:23:33	977	PolarGAP (FD83)	195 km no mag
P07	18/12/2015	11:27:27	18/12/2015	15:36:13	986	Lakes (FD83)	
P08	19/12/2015	11:29:11	19/12/2015	15:00:04	858	PolarGAP (FD83/Pole)	No RQH /Laser
P09	19/12/2015	16:10:07	19/12/2015	20:38:47	955	PolarGAP (FD83/Pole)	No RQH/Laser
P10	20/12/2015	14:22:42	20/12/2015	19:13:19	1040	Lakes (FD83)	
P11	21/12/2015	11:38:08	21/12/2015	15:13:32	785	Lakes (FD83)	
P12	25/12/2015	12:38:28	25/12/2015	17:06:09	1016	PolarGAP Transit	
P13	26/12/2015	19:23:46	26/12/2015	22:48:04	739	PolarGAP (Th)	
P14	27/12/2015	14:55:25	27/12/2015	19:42:42	1009	PolarGAP (Th)	
P15	28/12/2015	13:01:58	28/12/2015	17:24:10	1017	PolarGAP (Th/Pole)	
P16	28/12/2015	18:19:32	28/12/2015	22:30:39	1012	PolarGAP (Pole/Th)	
P17	29/12/2015	13:31:42	29/12/2015	17:52:58	957	PolarGAP (Th/Pole)	
P18	29/12/2015	19:25:43	29/12/2015	23:58:42	1020	PolarGAP (Pole/Th)	
P19	30/12/2015	12:32:04	30/12/2015	17:27:12	1080	PolarGAP (Th)	
P20	31/12/2015	18:33:38	31/12/2015	23:38:09	1076	PolarGAP (Th)	
P21	04/01/2016	14:02:28	04/01/2016	16:37:31	549	PolarGAP (Th)	
P22	04/01/2016	17:27:22	04/01/2016	20:32:17	604	PolarGAP (Th/Pole)	
P23	07/01/2016	21:22:08	07/01/2016	01:36:08	1052	PolarGAP (Pole/Th)	No radar
P24	06/01/2016	17:40:03	06/01/2016	21:31:39	814	PolarGAP Transit	
P25	07/01/2016	20:10:55	08/01/2016	00:48:36	1050	PolarGAP (SP)	
P26	08/01/2016	19:40:34	09/01/2016	00:32:41	1098	PolarGAP (SP)	
P27	09/01/2016	01:14:59	09/01/2016	05:59:56	1079	PolarGAP (SP)	
P28	09/01/2016	19:48:20	10/01/2016	00:37:51	1021	PolarGAP (SP)	
P29	10/01/2016	20:27:24	11/01/2016	01:28:08	1096	PolarGAP (SP)	
P30	11/01/2016	02:03:46	11/01/2016	06:48:32	1083	PolarGAP (SP)	
P31	11/01/2016	20:40:59	12/01/2016	01:21:52	1068	PolarGAP (SP)	
P32	12/01/2016	02:00:57	12/01/2016	06:31:48	1014	PolarGAP (SP)	158 km no mag
P33	12/01/2016	22:11:51	13/01/2016	02:37:14	1020	PolarGAP (SP)	
P34	13/01/2016	19:57:26	14/01/2016	00:54:49	1081	PolarGAP (SP)	
P35	17/01/2016	19:22:32	18/01/2016	00:20:14	1083	PolarGAP (SP)	
P36	18/01/2016	01:09:30	18/01/2016	05:39:10	1046	PolarGAP (SP)	
P37	18/01/2016	19:48:00	18/01/2016	23:27:38	794	ASIRAS (SP)	No L&R or radar
P38	19/01/2016	00:55:40	19/01/2016	01:46:00		Photographic survey	Lidar & GPS only

APPENDIX 3. LCR GRAVITY METER BASE TIES AND STILL READING VALUES

Precise gravity reference values are essential for the absolute level of the airborne gravity data to be correct. Two LCR gravimeters – G-784 from BAS and G-867 from DTU – were used to make ties to FD83 and Thiel Mountains from Rothera, and South Pole Station from McMurdo, respectively. The readings of the two gravimeters was adjusted for drift and tares, and fitted to absolute gravity values at McMurdo and Rothera (the value at Rothera derived from ties during the 2009-13 ICEGRAV surveys, based on absolute values in Punta Arenas, Ushuaia and Troll), as well as absolute gravity values at McMurdo (Thiel-1 reference station, Rogister et al, 2011).

Unfortunately a gravimeter tie from McMurdo to South Pole was not possible, as the cargo with G-867 ended up at South Pole by mistake. However, a gravity tie from Novo to Dome-C via South Pole station (ESA Dome-C campaign, 2013, AWI and DTU), as well as a BAS tie from AGAP 2008, was used to confirm the single tie from South Pole to McMurdo, as outlined below.

The FD83 gravity value from the 2015 gravity tie alone, compared to an adjusted value jointly using the 2015 tie, and ICEGRAV 2013 ties from Troll, agree to 0.1 mgal, in spite of the 2013 and 2015 locations being some hundreds of meter apart. As the FD83 camp is extremely flat, this therefore confirms the rather long-duration, somewhat uncertain G-784 PolarGap tie loop Rothera-FD83-Thiel Mts-Rothera (duration 35 days). The airborne still readings, shown below also, may further provide an independent check of the reference gravity ties.

Preliminary investigations of this still value shows there are indeed some possible residual problems in the ties, with an approximately 1.5 mGal offset still to be identified (see Figure below). It is currently being investigated, and could either come from Rothera or South Pole gravity values, or from errors in the LCR airborne base readings. Since Rothera base value is tied to South America, this could be a likely source, as could be erroneous ties to South Pole in combination with the 19 cm/yr estimate of dh/dt at South Pole being wrong (this is currently being checked with permanent GPS data)..

LCR gravity reference values for the PolarGap Survey (mGal)

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Gravity values at South Pole reference point in utilities tunnel
----------------------------------------------------------------
982315.24   T Diehl value IGSN71+abs corr (Dome-C report)
982314.44   T Diehl 2008 original (IGSN ref)
982316.47   DTU tie 2016
982316.26   Dome-C project value 2013, AWI tie from Novo abs (DTU processing)
982316.44   Dome-C value 2016, assuming 19 cm/yr downward movement
982316.23   Tom J tie 2009 (8 day tie, LCR scale factor)
982316.64   Tom J estimated value 2016

Network gravity reference values, underscored g-values PolarGap
----------------------------------------------------------------
982970.543  McMurdo Thiel-1 Absolute value 2011
982970.532  McMurdo Thiel-1 Absolute value 2009
982970.3    McMurdo AGAP reference value (Tom Jordan)
982969.23   McMurdo IGSN71 gravity value (T Diehl 2008)

982468.05   Rothera Hangar, ICEGRAV 2010-13 adjustment
982467.43   Rothera Hangar, BAS value (Jones, Ferris 1999)
```

```
PolarGap adjusted values of aircraft parking ground gravity values
-------------------------------------------------------------------
pno      g     error est.
40   982468.05   ±0.1    Rothera, hangar
71   982272.43   ±0.2    FD83 aircraft parking
80   982691.25   ±0.2    Thiel Mountain camp
301  982313.63   ±0.1    South Pole, Twin Otter apron
303  982313.06   ±0.1    South Pole, main apron at fuel tanks
------------------------------------------------------------------
```

LCR airborne gravimeter still values

Flight	Location	Date	Time	ST	Tcor	Still
Test	Rothera lab	09/12/2015	19:00	12776.8	0.3	12777.1
Test	Rothera lab	10/12/2015	11:55:00	12777	0	12777
Test	Rothera hang	11/12/2015	16:00:00	12775	1	12776
Test	Rothera hang	12/12/2015	22:42:00	12775.5	-0.7	12774.8
P04	FD83	16/12/2015	15:09:00	12576.6	0	12576.6
P04	FD83	16/12/2015	21:22:40	12575.8	0.6	12576.4
P05	FD83	17/12/2015	10:04:30	12576.1	0.1	12576.2
P06	FD83	17/12/2015	15:57:00	12576.2	-0.3	12575.9
P06	FD83	17/12/2015	21:57:50	12575	0	12575
P07	FD83	18/12/2015	09:15:00	12575.1	0	12575.1
P08	FD83	19/12/2015	10:11:10	12573	0.2	12573.2
P10	FD83	20/12/2015	13:56:20	12570	0.3	12570.3
P10	FD83	20/12/2015	19:40:00	12570.4	0.3	12570.7
P11	FD83	21/12/2015	10:42:50	12570.2	-0.1	12570.1
Extra	FD83	22/12/2015	17:44:40	12569	0.1	12569.1
P12	FD83	25/12/2015	11:05:50	12565.2	0.1	12565.3
P13	Thiel	26/12/2015	16:53:50	12984.8	0.2	12985
P13	Thiel	26/12/2015	23:39:00	12984.7	0.2	12984.9
P14	thiel	27/12/2015	14:35:00	12983.8	-0.2	12983.6
P14	Thiel	27/12/2015	20:23:30	12983.9	-0.4	12983.5
P15	Thiel	28/12/2015	12:29:20	12980.9	2.1	12983
P16	Thiel	28/12/2015	23:10:30	12982.5	0.1	12982.6
P17	Thiel	29/12/2015	12:34:50	12981.8	0.3	12982.1
P18	Thiel	30/12/2015	00:24:40	12981.8	0.1	12981.9
P20	Thiel	31/12/2015	18:05:40	12980	-0.2	12979.8
P20	Thiel	31/12/2015	23:59:50	12979.5	0.1	12979.6
P21	thiel	04/01/2016	12:56:00	12976	0.1	12976.1
P23	Thiel	05/01/2016	02:27:00	12975.2	0.2	12975.4
P24	Thiel	06/01/2016	16:37:30	12974.4	-0.4	12974
P18	SP	29/12/2015	19:09:50	12600.6	0.2	12600.8
P24	SP	06/01/2016	22:19:50	12593	0.4	12593.4
P25	SP	07/01/2016	19:42:00	12591.5	0.8	12592.3
P25	SP	08/01/2016	01:59:10	12592	0.6	12592.6
P26	SP	08/01/2016	19:10:30	12591.8	0.1	12591.9
P27	SP	09/01/2016	06:28:30	12590.4	0.5	12590.9
P28	SP	09/01/2016	19:23:00	12591.1	-0.6	12590.5
P28	SP	10/01/2016	01:10:20	12590	0	12590
P29	SP	10/01/2016	20:16:40	12589.6	0.2	12589.8

P30	SP	11/01/2016	07:26:00	12588.6	0.2	12588.8
P31	SP	11/01/2016	19:41:00	12588.8	0	12588.8
P32	SP	12/01/2016	07:11:00	12588.5	0	12588.5
P33	SP	12/01/2016	21:35:00	12588	0.1	12588.1
P33	SP	13/01/2016	03:11:40	12587	0.2	12587.2
P34	SP	13/01/2016	19:26:00	12587.3	0	12587.3
P34	SP	14/01/2016	02:03:30	12586.6	0.4	12587
P35	SP	16/01/2016	18:59:30	12584.4	0.2	12584.6
P36	SP	17/01/2016	05:58:40	12584	0.2	12584.2

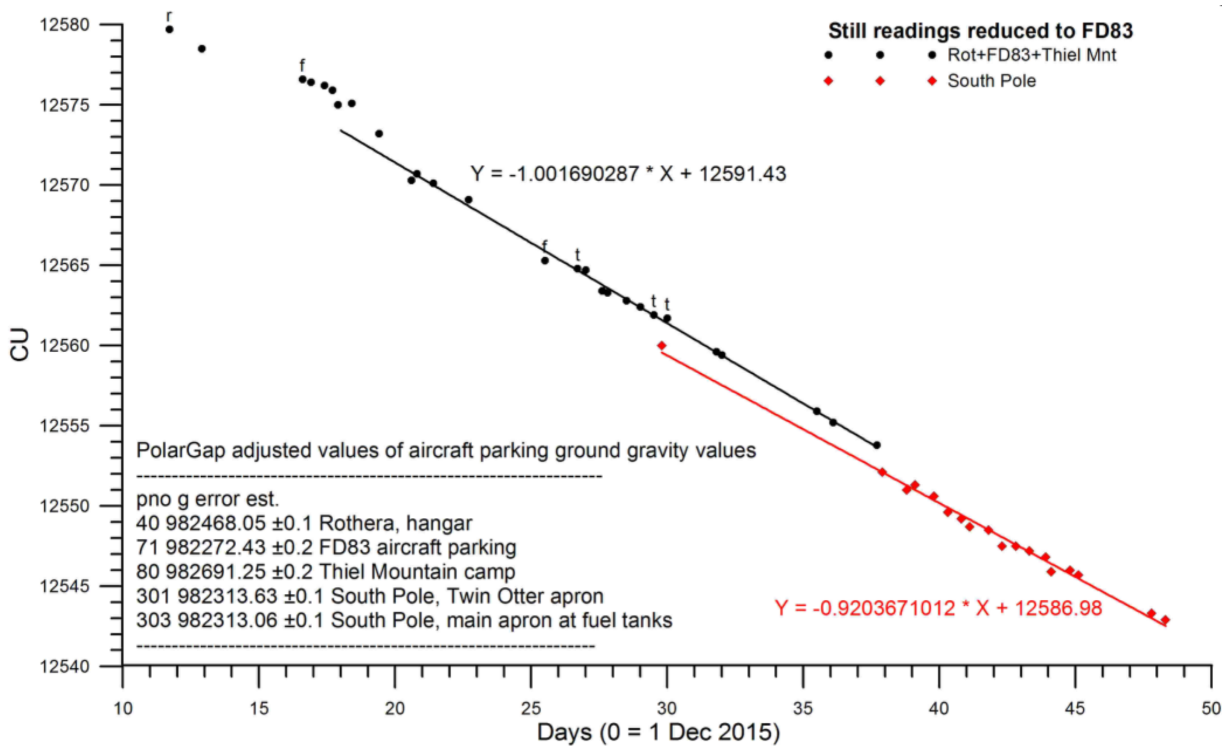

Fig. A3. Drift curve for the used S-83 LCR airborne gravimeter. Black is the drift based on Rothera-based gravity values (FD83 and Thiel Mts), and red the drift based on South Pole gravity values. Still readings are taken while the aircraft is stationary on the ground, in counter units (CU), which are approximately equivalent to mGal.

APPENDIX 4. LEVER ARMS BETWEEN SENSORS IN SURVEY AIRCRAFT.

Y forward +							
|							
|							
|_________X +	starboard						
Z up +		**Ref top centre IMAR**			**Ref IMAR centre of obs**		
		X cm	Y cm	Z cm	X cm	Y cm	Z cm
	Top FSAS IMU	0	0	0	1.62	-1.42	6.2
	Top laser	0	-203.6	-16.7	1.62	-205.02	-10.5
	Novatel	-4.8	-236.3	143.3	-3.18	-237.72	149.5
	Leica	50	77	146.2	51.62	75.58	152.4
	Javad	-53.1	-110	146.6	-51.48	-111.42	152.8
	Strapdown IMU (RQH) forward, left, top, corner	5.3	78.9	7.5	6.92	77.48	13.7

APPENDIX 5. OPERATIONS IN SOUTH POLE ANTARCTIC SPECIALLY MANAGED AREA #5.

Dates: 16/12/2015 to 19/01/2016
Author: Tom Jordan (tomj@bas.ac.uk)

PolarGAP is a major international aerogeophysical project funded by the European Space Agency (ESA) working in the South Pole region (Fig. A5.1a). The primary goal of the project was to carry out an airborne survey to fill in the "Polar Gap" (83.5°S- 90°S) in satellite gravity data coverage, thereby significantly improving global gravity field and geodetic models. Additionally, the combination of coincident airborne magnetic, radar, gravity and LIDAR measurements will provide critical information about the ice sheet surface, internal ice sheet layering, sub-ice topography, subglacial geology and deeper crustal and lithospheric architecture in a previously poorly surveyed region. The aims of the project required low altitude flights access both the Clean Air Sector (CAS) and Dark Sectors of the South Pole ASMA during the 2015/16 Antarctic field season.

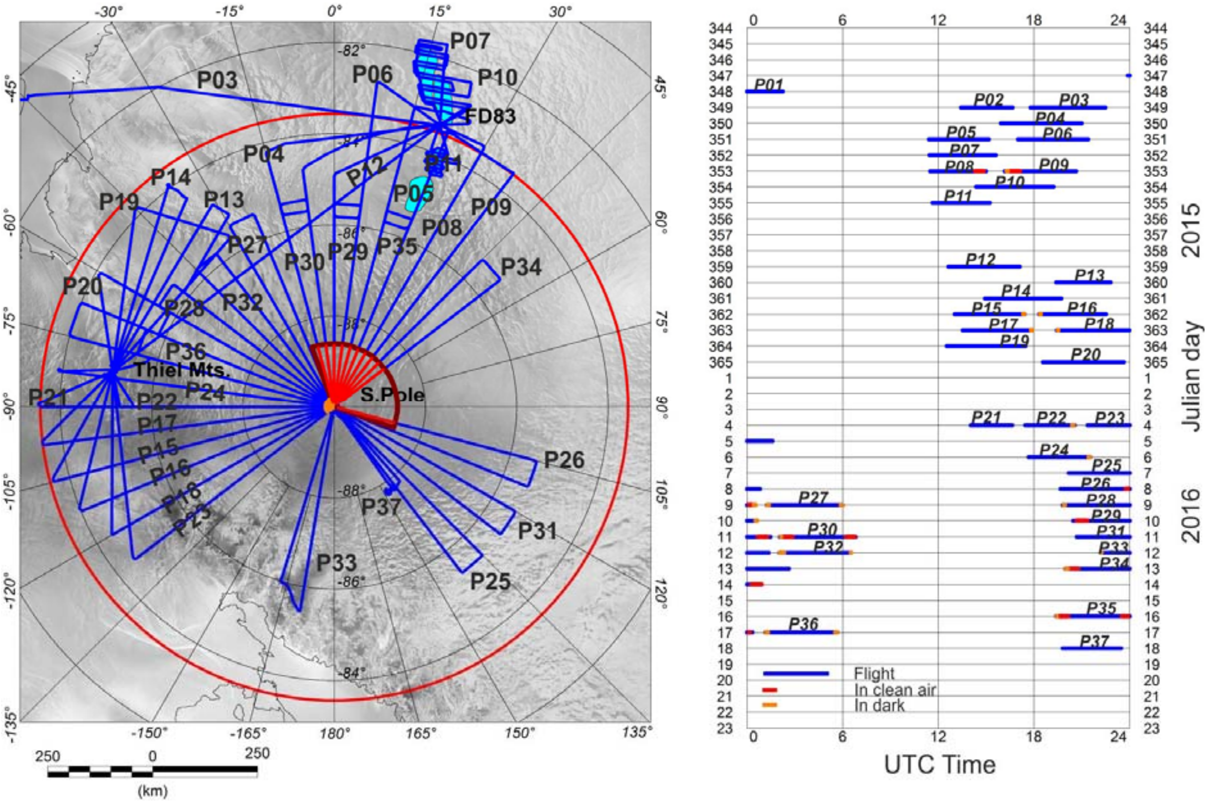

Fig. A5.1 a) PolarGAP flights (P03 to P37). Red lines cross the CAS (brown outline), while orange lines mark flights in the smaller Dark Sector. Red circle marks polar gap in satellite gravity coverage. b) Survey time line showing date and time of entry into CAS and Dark sectors. Note flights P01, P02 are outside the displayed map.

Prior to the PolarGAP field campaign contact was made with the ASMA management team to ensure airborne operations created minimum disruption to ongoing science within the South Pole ASMA. No specific constraints were placed on the PolarGAP flights or operations over the Dark Sector. Within the CAS the prescribed minimum ground clearance in the ASMA document is 2000m. However, this would have very significantly compromised the quality of the data collected by the PolarGAP field project. A compromise minimum flight altitude of 400m above ground level within the CAS was therefore decided on, specifically for the PolarGAP survey flights. This allowed collection of ice thickness data with the airborne radar system, while keeping the survey aircraft above the typical atmospheric boundary layer.

In addition, once at South Pole discussions with staff on the ground revealed that there were specific, approximately weekly, sampling events which could be contaminated by PolarGAP operations. Survey flying within the CAS was therefore timed to avoid these sampling days. It transpired that the majority of the crossings of the CAS coincided with periods when the wind direction as out of sector (from South Pole station in to the CAS), and the PolarGAP operations therefore reflect limited additional impact on the CAS. Details of entry and exit from CAS are shown in Fig. 1b and the table below. If further information is required please contact Tom Jordan (tomj@bas.ac.uk) or Fausto Ferraccioli (ffe@bas.ac.uk) at the British Antarctic Survey.

The entire PolarGAP team wish to thank Kevin Hughes from the BAS environmental office and Polly Penhale from NSF for helping arrange flights through the South Pole ASMA. Additionally we thank NOAA for their cooperation with our flights through the clean air sector and Refael Klein for providing additional help and advice with our operation when we were on the ground at South Pole.

Clean air sector activity					
In		Out			
Date	Time	Date	Time	Survey line longitude	Flight
19/12/2015	14:18:50	19/12/2015	14:51:10	30	P08
19/12/2015	16:29:35	19/12/2015	17:07:10	37.5	P09
08/01/2016	23:45:16	09/01/2016	00:21:18	105	P26
10/01/2016	20:41:10	10/01/2016	21:20:08	0	P29
11/01/2016	00:40:49	11/01/2016	01:16:12	7.5	P29
11/01/2016	02:14:07	11/01/2016	02:52:20	-15	P30
11/01/2016	06:11:16	11/01/2016	06:45:33	-7.5	P30
13/01/2016	20:10:37	13/01/2016	20:47:16	45	P34
14/01/2016	00:16:21	14/01/2016	00:54:49	52.5	P34
17/01/2016	19:33:30	17/01/2016	20:09:14	15	P35
17/01/2016	23:30:03	18/01/2016	00:11:01	22.7	P35