Exploring the Recovery Lakes region and interior Dronning Maud Land, East Antarctica, with airborne gravity, magnetic and radar measurements

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Abstract: Long-range airborne geophysical measurements were carried out in the ICEGRAV campaigns, covering hitherto unexplored parts of interior East Antarctica and part of the Antarctic Peninsula. The airborne surveys provided a regional coverage of gravity, magnetic and ice-penetrating radar measurements for major Dronning Maud Land ice stream systems, from the grounding lines up to the Recovery Lakes drainage basin, and filled in major data voids in Antarctic data compilations, such as AntGP for gravity data, ADMAP for magnetic data and BEDMAP2 for ice thickness data and the sub-ice topography. We present the first maps of gravity, magnetic and ice thickness data and bedrock topography for the region and show examples of bedrock topography and basal reflectivity patterns. The 2013 Recovery Lakes campaign was carried out with a British Antarctic Survey Twin Otter aircraft operating from the Halley and Belgrano II stations, as well as a remote field camp located at the Recovery subglacial Lake B site. Gravity measurements were the primary driver for the survey, with two airborne gravimeters (Lacoste and Romberg and Chekan-AM) providing measurements at an accuracy level of around 2 mGal r.m.s., supplementing GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) satellite data and confirming an excellent sub-milligal agreement between satellite and airborne data at longer wavelengths.

The ICEGRAV campaigns of DTU Space (National Space Institute, Denmark) were part of an international effort to intensify the coverage of gravity data in Antarctica, in support of global geodetic reference models (such as EGM2008, Pavlis *et al.* 2012). The campaigns, following numerous Arctic gravity campaigns around Greenland and in the Arctic Ocean (Forsberg & Olesen 2010; Døssing *et al.* 2013), were carried out in cooperation with the University of Texas Institute of Geophysics (UTIG), the British Antarctic Survey (BAS), the Argentinean Antarctic Institute (IAA) and the Norwegian Polar Institute (NPI). The primary goal of the campaigns was to cover major voids in the gravity coverage of Antarctica to boost current and future international cooperative efforts to secure the complete coverage of Antarctica with airborne gravity measurements within a reasonable time span. Given the logistical challenges of operating long-range airborne surveys in Antarctica and the excessive costs, it was natural to carry out cooperative measurements with a full suite of geophysical measurements, including magnetic surveys, ice-penetrating radar and LiDAR for surface elevations. This paper gives an overview of the ICEGRAV campaigns, with a special focus on the interior East Antarctica survey flights, and gives some examples of the acquired data, with particular emphasis placed on the accuracy of the acquired gravity data. More detailed investigations of the geophysical and glaciological interpretations of the ICEGRAV datasets presented here will be given elsewhere.

From: Siegert, M. J., Jamieson, S. S. R. & White, D. A. (eds) 2018. *Exploration of Subsurface Antarctica: Uncovering Past Changes and Modern Processes*. Geological Society, London, Special Publications, **461**, 23–34.
First published online September 20, 2017, https://doi.org/10.1144/SP461.17

ICEGRAV airborne geophysics campaigns 2010–13

The ICEGRAV campaigns were initiated in 2009 to cover those parts of the Antarctic Peninsula that had not been mapped geophysically. The campaigns were a response to both the lack of gravity data (prior to the NASA IceBridge operation) and the ease of setting up the required logistics in cooperation with the IAA and Chilean partners. The ICEGRAV campaigns were followed by airborne surveys in East Antarctica in 2010–11 from the Norwegian Troll station and later from a remote camp at Recovery Lakes in 2012–13. The latter surveys covered the biggest gap in the AntGP gravity compilation at that point in time.

In the first three ICEGRAV seasons, a Basler-BT67 (modernized DC3) aircraft, operated by Kenn Borek Air Ltd, Canada was used as the platform for collecting airborne gravity, magnetic and radar data. The aircraft platform was the same as that used by the UTIG for the ICECAP programme (Young *et al.* 2011) in collaboration with the NASA operation IceBridge (ICECAP/OIB; Greenbaum *et al.* 2015). DTU Space used a similar Kenn Borek Basler-BT67 aircraft for extensive long-range gravity and magnetic surveys in the central Arctic Ocean in March–May 2009, with excellent gravity results (estimated r.m.s. accuracy 1.5 mGal; Døssing *et al.* 2013). However, as this aircraft could not be used for the ICEGRAV surveys, the ICEGRAV operations were restricted to the ICECAP shoulder seasons, causing week-long delays in the Antarctic Peninsula flights due to bad weather, especially summer fog conditions at the elevated runway at the Argentinean Marambio base. Luckily, the 2010–11 ICEGRAV inland operations from the Norwegian Troll station were carried out under more

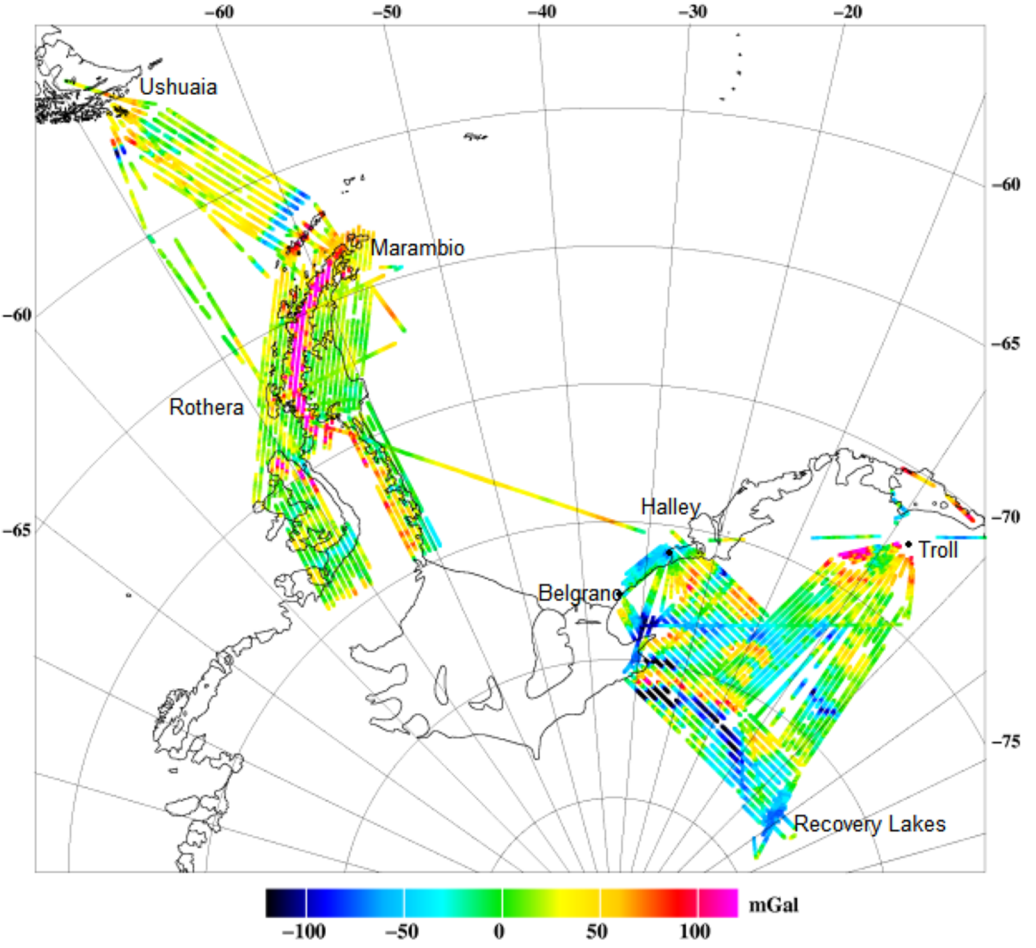

Fig. 1. Free-air gravity anomaly data for the ICEGRAV 2010–13 campaigns showing main logistics bases.

stable weather conditions and minimal delays were encountered.

No long-range Basler aircraft was available for charter for the 2012–13 campaign, which aimed to fill in one of the major remaining voids in the BEDMAP2 compilation (Fretwell *et al.* 2012). Flights were therefore carried out with a BAS Twin Otter aircraft operating out of Halley and Belgrano-2 bases and a remote field camp at Recovery Lakes (FD83), organized by the NPI. Fuel for the operations was air-dropped by an IL-76 Russian jet flight organized by Antarctic Logistics Centre International (ALCI) (www.alci.co.za), who also provided put-in and pull-out flights. At the closing of the field camp in February 2013, the temperature had reached −44°C, highlighting the challenging conditions encountered. The 2013 campaign was a major and costly logistics operation, but with highly successful science flights, with nearly 100% completion relative to the plan.

The location of the flight lines (Fig. 1) was selected based on opportunities, logistics needs and coverage of the major gaps in the Antarctic gravity data, especially in East Antarctica (Scheinert *et al.* 2016) (Fig. 2). An overview of the ICEGRAV campaigns is given in Table 1. Figure 3 shows the Basler

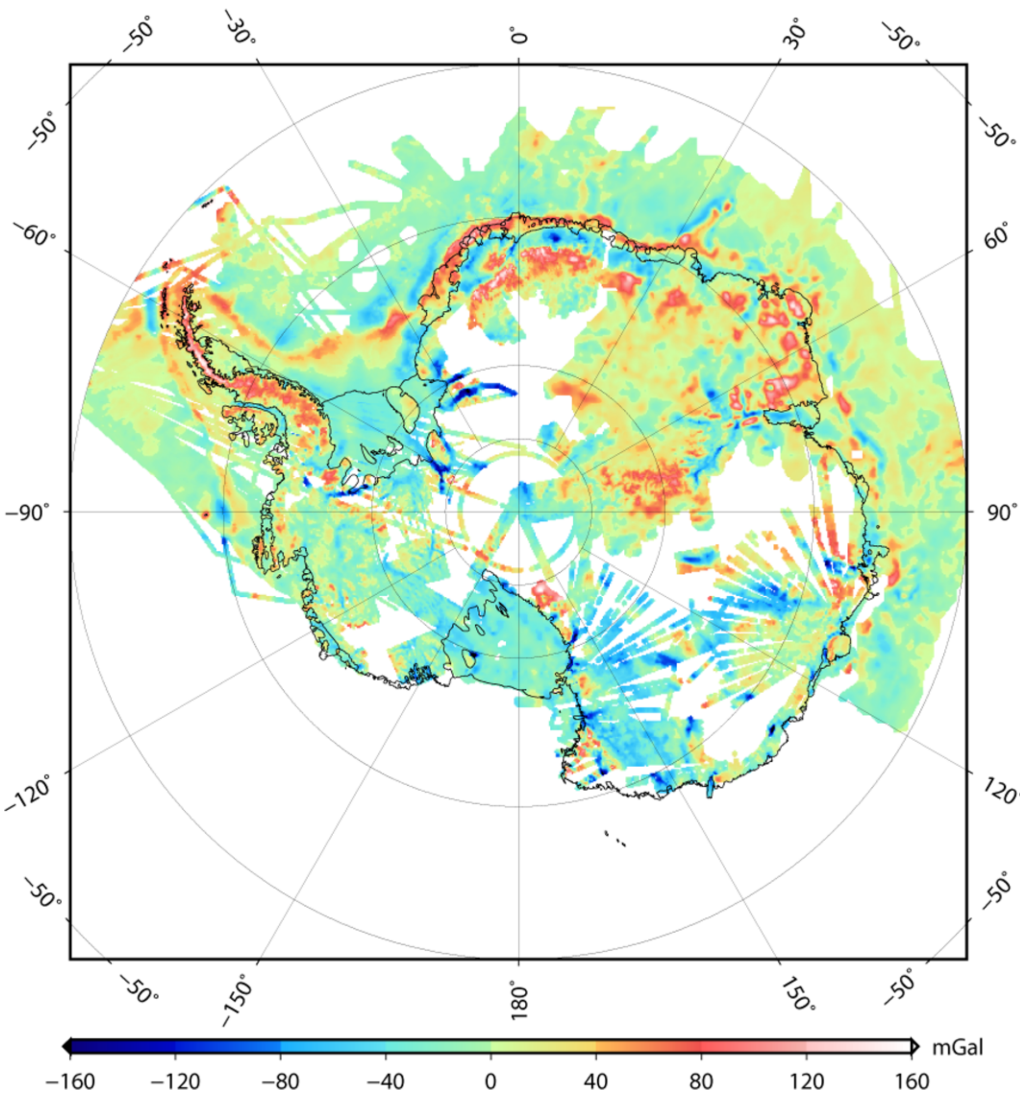

Fig. 2. Data in the current Antarctic gravity compilation, showing a large gap in interior Dronning Maud Land, now covered with ICEGRAV data (figure courtesy of M. Scheinert, TU Dresden).

Table 1. *Overview of the ICEGRAV campaigns in Antarctica*

Campaign/airborne data acquisition time	Region/primary bases	Aircraft	Cooperation partners
ICEGRAV-2010a (24 January–13 February 2010)	Antarctic Peninsula (Marambio/ Teniente Marsh)	Basler DC3	IAA, INACH (Chile), UTIG
ICEGRAV-2010b (21 October–8 November 2010)	Antarctic Peninsula (Marambio/ Rothera)	Basler DC3	IAA, BAS, UTIG
ICEGRAV-2011 (3–28 February 2011)	East Antarctica + Antarctic Peninsula (Troll, Halley, Rothera)	Basler DC3	NPI, BAS, UTIG
ICEGRAV-2013 (4 January–4 February 2013)	Recovery Lakes region (Troll, Belgrano-2, Halley)	Twin Otter	BAS, NPI, IAA, ALCI (support flights for FD83 field camp)

aircraft used at the British Rothera base, the remote Belgrano-2 field base (Argentina) and the NPI field camp at FD83.

The scientific instruments flown in the ICEGRAV campaigns included gravimeters of the Lacoste and Romberg S-type, as modified by ZLS Corporation (Valliant 1991), supplemented in 2012–13 with a Chekan-AM gravimeter (Krasnov *et al.* 2011). In addition, magnetic, radar and LiDAR sensors were flown. As part of the 2009–11 cooperation with UTIG, the HICARS 60 MHz ice-penetrating radar system (Blankenship *et al.* 2012) was used for ice thickness measurements, with radar data processed by UTIG. Airborne and reference Geometrics 823A Cesium magnetometers were provided by UTIG and DTU Space, respectively, for magnetic measurements on the ICEGRAV flights. Ice-penetrating radar (150 MHz) and airborne magnetometer instruments for the 2013 survey were similarly provided by BAS. In the 2010–11 survey from Troll, a novel DTU Space P-band (435 MHz) polarimetric ice-penetrating radar system was additionally flown on an experimental basis, demonstrating the capability to sound several kilometres into the ice sheet (Dall *et al.* 2012). Additional sensors flown included single-beam laser altimeters, inertial measurement units and various geodetic global positioning system receivers, provided by DTU Space, UTIG or BAS. In 2011, UTIG additionally operated a photon-counting scanning LiDAR system during the ICEGRAV flights (Young *et al.* 2015).

Airborne gravimetry and comparison with GOCE satellite data

The airborne gravity measurements were the focus of the ICEGRAV campaigns and great care was taken to provide reference values for the airborne surveys to secure bias-free, geodetic-quality gravity surveys. Airborne gravimetry is not new, with development driven by commercial needs for accurate and high-resolution gravity anomaly mapping for oil, gas and mineral exploration (e.g. Williams & MacQueen 2001; Elieff & Ferguson 2008). In the government and academic domains, long-range aerogravity mapping for regional geophysics based on the global positioning system was pioneered by US researchers (Brozena 1992; Bell *et al.* 1992). The DTU Space aerogravity applications were developed in the mid-1990s, mainly for geoid and geodesy applications, as part of the European Union Airborne Geoid Mapping System for Coastal Oceanography (AGMASCO) project (Forsberg *et al.* 1996). The system setup and

Fig. 3. ICEGRAV aircraft and logistics. (**a**) Basler at Rothera; (**b**) BAS Twin Otter at FD83 Recovery Lakes field camp; and (**c**) Belgrano-2 station, Argentina (photos courtesy of DTU Space photos).

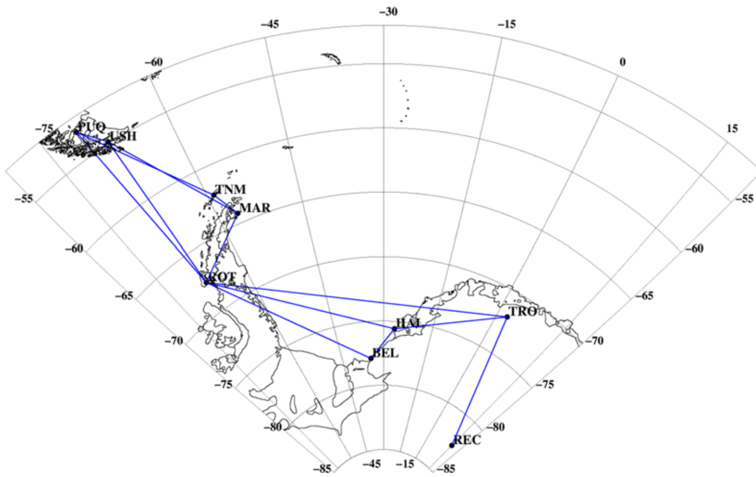

Fig. 4. Reference gravity network established in support of the ICEGRAV flights, tied to IGSN71 or absolute reference gravity stations in Punta Arenas (PUQ), Ushuaia (USH) and Troll (TRO).

experience developed have since been used extensively for small aircraft, long-range surveys in many different regions of the world (e.g. Olesen 2002; Forsberg *et al.* 2007; Forsberg & Olesen 2010). In general, most of these surveys have been at an accuracy of 2 mGal r.m.s., with a resolution of 5–7 km depending on the speed of the aircraft.

To secure a match to the satellite data, the ICEGRAV surveys were tied with several hand-held relative gravimeters to reference IGSN71 and absolute

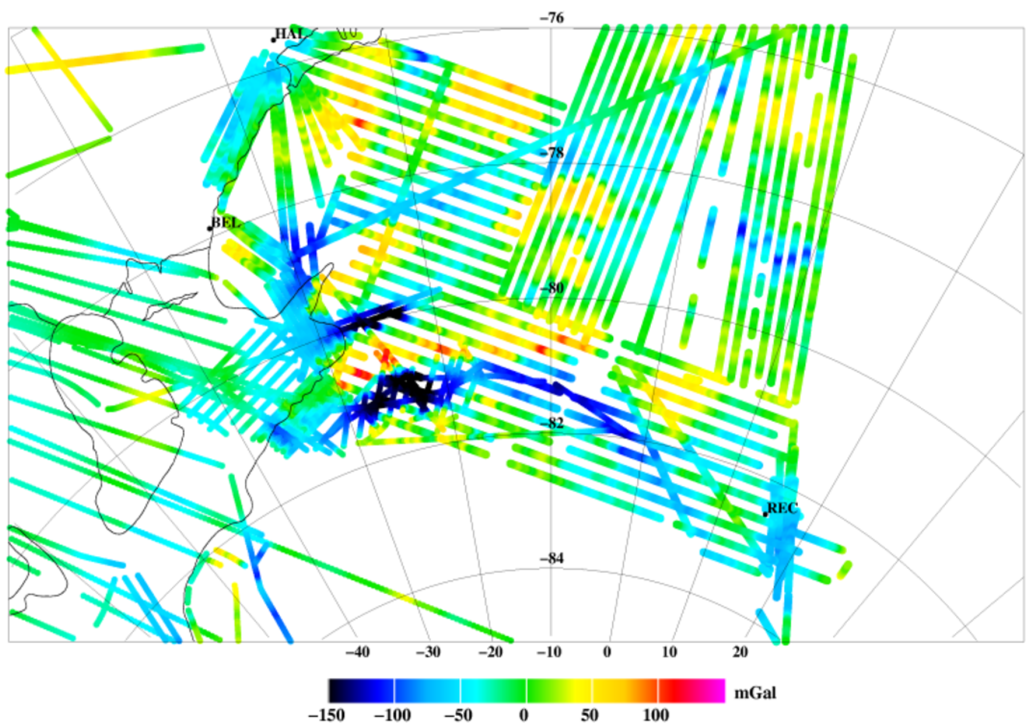

Fig. 5. IceBridge free-air anomaly gravity data (thinner lines, left) and ICEGRAV data (thicker, right) in the Dronning Maud Land region between Filchner-Ronne ice shelf and Recovery Lakes (REC).

sites in South America (Punta Arenas and Ushuaia, respectively), as well as a 2011–12 absolute gravity measurement at Troll (Mäkinen, pers. comm. 2013), to ensure that the measurements were as bias-free as possible. Ties between Punta Arenas and Ushuaia confirmed the sub-milligal agreement between the newer absolute and older IGSN71 references.

Figure 4 shows the ties of this reference gravity network, giving base values for the airborne measurements at 0.1–0.2 mGal accuracy. As a result of the rough flight conditions, the relatively poor performance of the Basler autopilot system and the lack of an autopilot on the BAS Twin Otter aircraft, the r.m.s. gravity error for the Antarctica surveys was estimated at 2–3 mGal r.m.s. from cross-overs, with no cross-over adjustment applied (to avoid long-wavelength error aliasing from a cross-over adjustment, which is of specific concern for geodetic use of the gravity data; cf. Olesen *et al.* 2000). Processing of the airborne data was based on the Lacoste and Romberg gravimeters, with the Chekan-AM only being used for quality control and the fill-in of some minor data gaps. The typical along-track filtering was 150 s full-width at half-maximum,

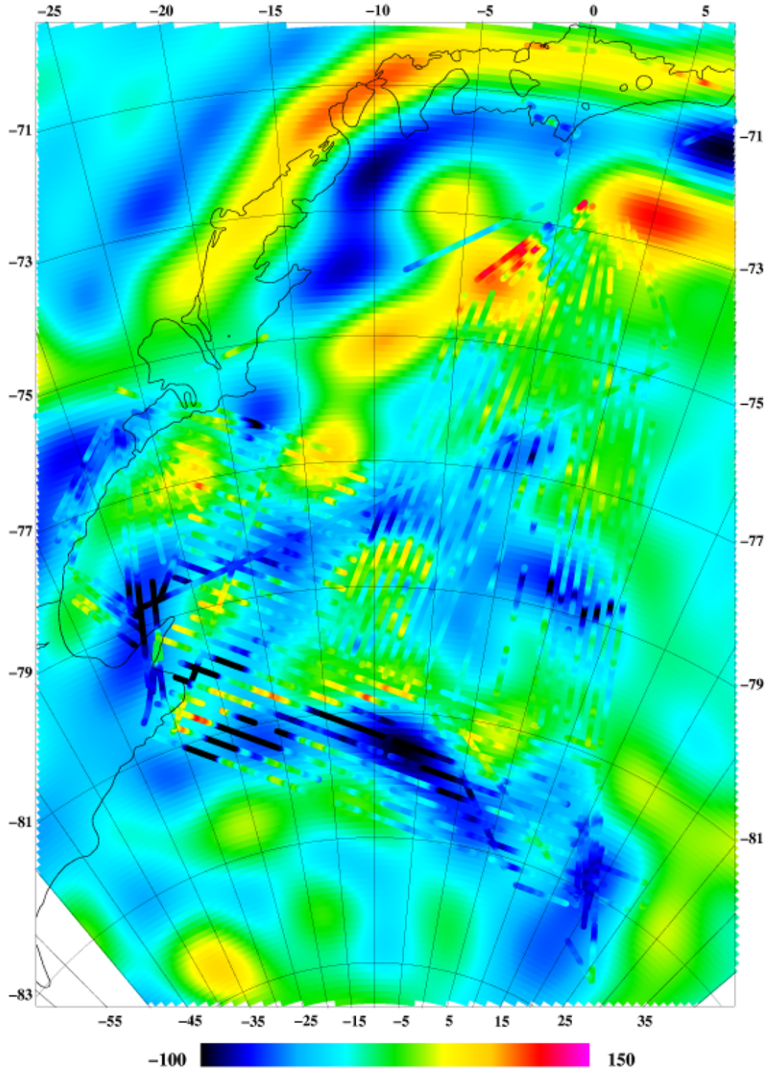

Fig. 6. Free-air anomalies from the 2011 (NNE–SSW-trending lines) and 2013 airborne gravity surveys in East Antarctica, overlaid on GOCE satellite grid data. Unit mGal. The central negative anomalies reflect mainly major ice stream subglacial valleys.

using forward–backward multiple Butterworth filters, corresponding to a resolution of *c.* 8 km (Olesen 2002).

All flights were flown at constant elevation, but varying the elevation from flight to flight, as necessitated to clear the terrain and avoid clouds and turbulence. A comparison with the 2009–12 NASA IceBridge gravity data over the Antarctic Peninsula (Cochran & Bell 2010) showed cross-over statistics with a mean of −0.3 mGal and a standard deviation (r.m.s.) of 6.9 mGal after conversion of the IceBridge data from gravity disturbances to geodetic free-air anomalies. This confirms the absolute accuracy of both the ICEGRAV and IceBridge gravity data. The large standard deviation was dominated by the altitude continuation effects (with ICEGRAV data mostly flown at 3–4 km elevation and IceBridge mostly as low-level 'draped' glacier flights). For the IceBridge–ICEGRAV cross-overs in East Antarctica (Fig. 5), the standard deviation of the intercomparison was 3.9 mGal (confirming the 2–3 mGal r.m.s. accuracy estimate), albeit with a larger bias of 3.6 mGal, probably due to flight elevation differences and because the IceBridge flights followed the deep minimum gravity anomalies of the major ice streams (see Fig. 7), whereas the ICEGRAV data cross the same features and will therefore have a tendency to smooth out the deepest minima due to filtering.

Table 2. *Comparison of atmosphere-corrected ICEGRAV data with GOCE gravity (units mGal)*

Maximum degree of GOCE expansion	East Antarctica 2011–13	
	Mean	SD
Data	*4.0*	*32.7*
180	0.1	26.6
200	0.3	24.6
220	1.2	22.5
240	1.2	22.1
260	1.1	22.2

To compare the absolute bias level of the ICEGRAV data, Figure 6 shows a comparison in Dronning Maud Land of the ICEGRAV data and the latest Release-5 data of the GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) gravity field satellite mission (Pail *et al.* 2011; www.esa.int/goce). Figure 6 shows that the visual agreement of the GOCE and airborne gravity data is excellent, given the limited spatial resolution of GOCE. Table 2 shows the difference between the ICEGRAV data corrected for atmospheric attraction

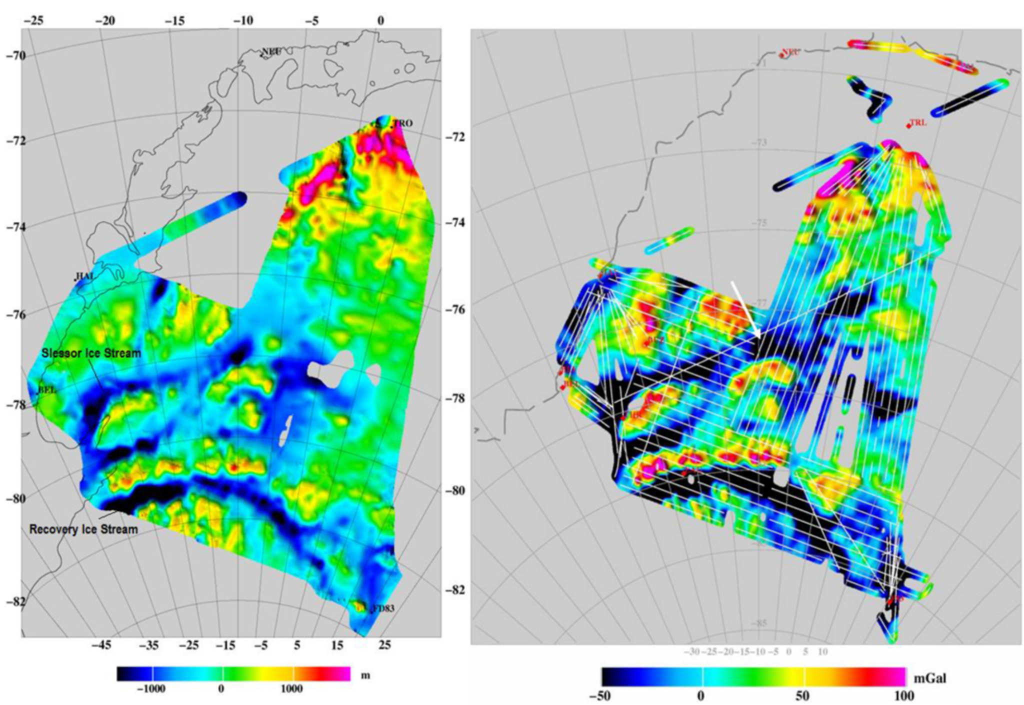

Fig. 7. Bedrock topography (left; blue colours below sea-level) and gravity anomalies with superimposed flight tracks (right); white arrow on right shows location of radar gap in Figure 8.

and the GOCE gravity field for various maximum spherical harmonic degrees in the expansion of the RL5 gravity data. The bias-free comparison serves as a confirmation of the GOCE data, providing useful gravity field information up to harmonic degree *c.* 200, effectively serving as a validation of the GOCE data. The relatively large r.m.s. comparison with the GOCE data is due to omission error (i.e. the short-wavelength power spectrum, which cannot be resolved from the altitude of the satellite) and not due to a problem with either the GOCE or the airborne data.

Overall, given the comparisons with IceBridge and GOCE, and the challenging logistics, the ICEGRAV campaigns may be considered to be a major success, providing new and accurate gravity data over large, hitherto poorly known regions of Antarctica.

Examples of geophysical data in the Recovery Lakes/interior Dronning Maud Land regions

The ICEGRAV-2011 and -2013 surveys covered a major void in both ice-penetrating radar and magnetic data. Figure 7 shows the bedrock topography, from a combination of UTIG- and BAS-processed radar data, side-by-side with the measured gravity anomalies in the region. It is clear that the gravity field variations are dominantly controlled by the deep Slessor and Recovery ice stream subglacial valleys, reaching depths below sea-level of >1 km and confirming the potential of these ice streams to be potentially rapid conduits of future ice sheet mass loss, following the predicted Filchner-Ronne ice shelf melting (Hellmer *et al.* 2012). The Recovery ice stream, the

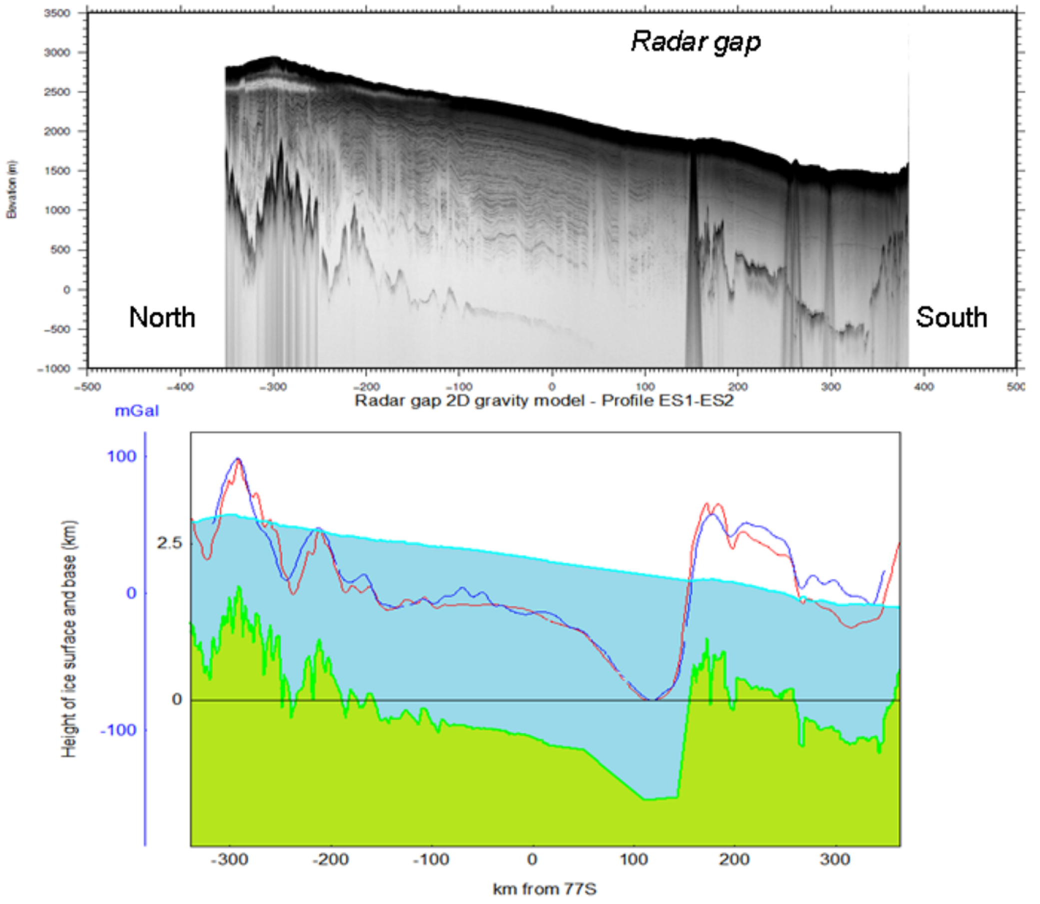

Fig. 8. Example of radar data along the westernmost ICEGRAV 2011 line, crossing the northern branch of the Slessor ice stream. Bedrock shown in yellow, ice in blue. The blue and red curves (top) are observed and modelled gravity, respectively (scale of lower plot in kilomtres for rock and ice topography).

lowest shown in Figure 7, also illustrates the continuous hydraulic pathways from the Recovery subglacial lakes A and B into the ice streams (for reference, FD83 is located on top of Lake B).

To illustrate the depths of the ice streams and the usefulness of gravity to model the deep glacial troughs, Figure 8 shows a profile across the northern branch of the Slessor ice stream where it crosses the

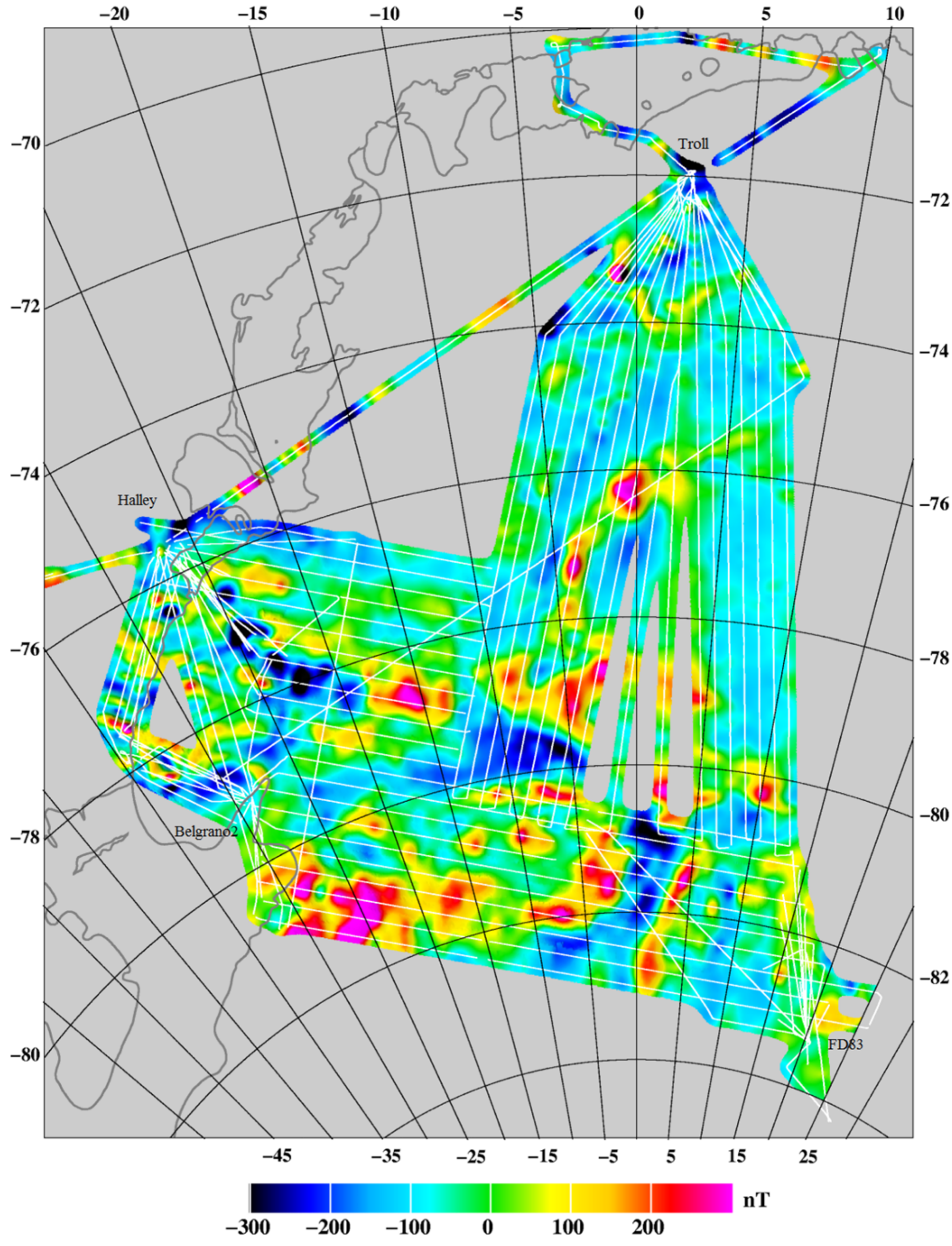

Fig. 9. Composite magnetic total field anomaly map of the ICEGRAV 2011–13 campaigns. Flight lines shown in white, with the field camp (FD83) at lower right located at Recovery Lake B.

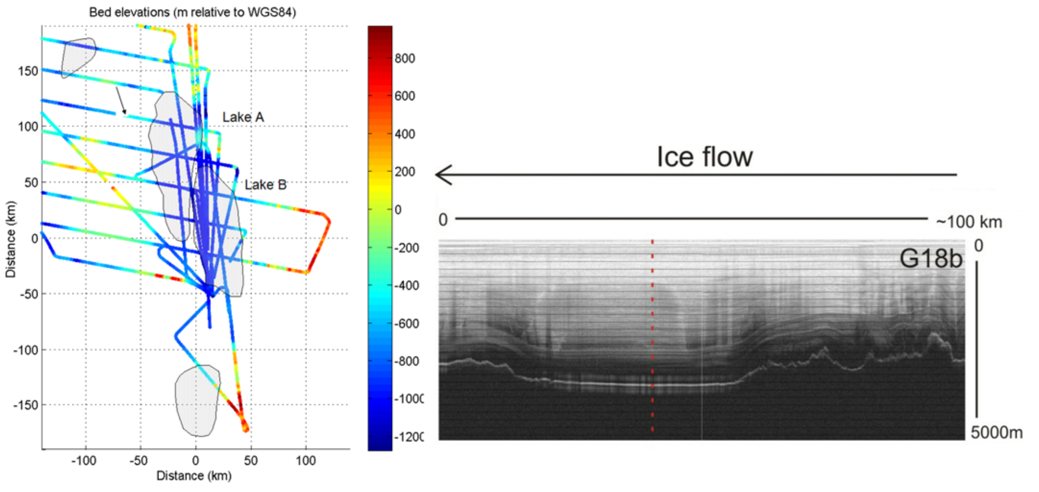

Fig. 10. Example of radar profile across Recovery Lake A (line indicated by arrow in left-hand plot). The bright reflection surface indicates the presence of liquid water in the subglacial lake.

westernmost 2011 ICEGRAV lines at about latitude 78° S (cf. Fig. 7). A two-dimensional forward gravity modelling was performed (Talwani *et al.* 1959), including a sector where the HICARS radar did not detect any bed echoes (and where BEDMAP2 has no data at all). It can be seen that the ice stream is >3 km deep here, with a sharp border to higher subglacial terrain towards the southern side of the ice stream.

The gravity signatures and bedrock maps of Figure 7 also show SW–NE-striking features, probably associated with subglacial fault systems (Paxman *et al.* 2017), and also a highland-like subglacial region to the east of Recovery Lakes, towards the Gamburtsev Subglacial Mountains region (Ferraccioli *et al.* 2011; Paxman *et al.* 2016). The SW–NE-striking features also show up in the magnetic data in Figure 9. The ICEGRAV magnetic data provide a new geophysical tool with which to study the largely unknown tectonic architecture of this region, thereby augmenting previous exploration efforts in other parts of East Antarctica (e.g. Aitken *et al.* 2014), and also to investigate geological boundary conditions and their influence on ice stream dynamics in interior Dronning Maud Land and Coats Land (e.g. Shepherd *et al.* 2006).

Figure 10 shows an ICEGRAV 2013 radar profile across northern Recovery Lake A, along with the radar bedrock topography data. A marked bright reflection is observed along the lake surface, indicating the presence of liquid water, which is also seen on other radar lines crossing lakes A and B. The flat gravity field across the lakes shows that these lakes cannot be very deep, at most a few tens of metres, in accordance with earlier observations by Langley *et al.* (2011), and suggesting possible infilling of part of these lakes by 2013. A more thorough investigation of the lake flights will be presented elsewhere, falling outside of the gravity-focused scope of this survey overview paper.

Conclusions

Major hitherto unknown data voids in East Antarctica have been filled by the ICEGRAV 2010–13 campaigns, providing new information on the gravity field, magnetic data and bedrock topography, and providing major new data for improving the Antarctic compilations of gravity (AntGG), magnetics (ADMAP) and ice thickness (BEDMAP). The ICEGRAV campaigns were driven by the need to complete the gravity coverage of Antarctica, with the new airborne surveys providing robust gravity anomaly data at a 2–3 mGal r.m.s. accuracy, with absolute biases better than 1 mGal, satisfying the needs for satellite geodesy and future updates of the global gravity field models, such as EGM2008. The consistency and bias-free nature of the new gravity data were confirmed by intercomparisons with the IceBridge gravity data, as well as comparisons with satellite gravity data from the GOCE mission.

The airborne gravity of interior Dronning Maud Land, Antarctica provided an indirect validation of the GOCE mission, confirming that the GOCE spherical harmonic models contain gravity field information up to degrees *c.* 200–220, corresponding to a spatial resolution of *c.* 80–90 km. The major ice streams of the region, and Antarctica in general, thus show up well in the GOCE data north of the orbit coverage limit of GOCE (83° S). Following the successful ICEGRAV surveys and experience, a new follow-up DTU–BAS–NPI cooperative survey (PolarGap 2015–16) has subsequently been completed, resulting in a fill-in of the southern polar gap of the European Space Agency GOCE mission, closing yet a another major gap in Antarctica and globally.

The ICEGRAV Antarctic airborne surveys were sponsored by the US National Geospatial-Intelligence Agency, the European Space Agency, DTU Space and the Centre of Ice, Climate and Ecosystems of the Norwegian Polar Institute, with significant logistics and in-kind contributions by the British Antarctic Survey, the Norwegian Polar Institute and the Instituto Antartico Argentino. We appreciate the cooperation with Don Blankenship and Duncan Young, Jackson Institute of Geophysics, University of Texas (UTIG), for sharing of aircraft and instruments in the first ICEGRAV campaigns, as well as processing of the radar, laser and preliminary magnetic data. The late Arne Gidskehaug, University of Bergen, and Jens Emil Nielsen, DTU Space, participated in various parts of the Basler campaigns; Carl Robinson, British Antarctic Survey, was the key science technician for the 2012–13 Recovery Lakes campaign. DTU Space additionally thank Andres Rivera, Centro de Estudios Cientificos, Chile, Ambassador Henrik Hahn, Danish Embassy in Buenos Aires, and Sergio Marensi, former director of the Instituto Antartico Argentino, for invaluable assistance in preparing for the first ICEGRAV Antarctic Peninsula surveys. UTIG acknowledges NASA grants NNX09AR52G and NNG10HP06C (ARRA) covering the participation of Jamin Greenbaum in the 2010-11 ICEGRAV campaigns; this is UTIG contribution 3127.

Data availability

Ice-radar sounding, single beam and swath lidar altimetry, and preliminary processed magnetic data of the 2010-11 ICEGRAV campaigns are available at https://nsidc.org/data/icebridge. British Antarctic Survey processed data are currently being combined with interleaving/adjoining datasets and will be available later on request or through the NERC Polar Data Centre. Gravity data are available from DTU Space on request, and will be available on ftp.space.dtu.dk following the upcoming data release Sep 2017 from the ESA 2015–16 PolarGap survey. See, e.g., http://www.bbc.com/news/science-environment-38333629.

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