Gravity survey along a traverse from Patriot Hills to the South Pole

G. Reitmayr,[1] G. Casassa,[2] C. Iturrieta,[3] A. Wendt,[2] and R. Zamora[2]

[1]Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Germany
[2]Centro de Estudios Científicos (CECS), Valdivia, Chile
[3]Instituto Geográfico Militar, Ejército de Chile, Santiago, Chile

Summary Gravity and GPS measurement as well as accompanying ice thickness determinations were performed along a tractor traverse from Patriot Hills to the South Pole, covering a distance of more than 1100 km. Special considerations were necessary to reasonably calculate the drift of the gravimeter used. Bouguer and ice layer corrections were accomplished by two-dimensional model calculations. The resulting complete Bouguer anomaly oscillates around zero along the northern section of the profile and starts to decrease 200 to 300 km before entering the East-Antarctic craton where it stabilizes at about -130 mGal. Isostatic modelling yields a positive residual anomaly of about 70 mGal over East-Antarctica which can be explained by additional masses in the crust, e.g. assuming an increased density in the lower crust. Alternative models which incorporate lighter sediments in West-Antarctica or which are isostatically unbalanced are conceivable.

Citation: Reitmayr, G., G. Casassa, C. Iturrieta, A. Wendt, and R. Zamora (2007), Gravity Survey along a Traverse from Patriot Hills to the South Pole, in Antarctica: A Keystone in a Changing World – Online Proceedings of the 10th ISAES X, edited by A. K. Cooper and C. R. Raymond et al., USGS Open-File Report 2007-1047, Extended Abstract 012, 5 p.

Introduction

More than 98% of the Antarctic continent is covered by ice and for this reason it is not directly accessible to geoscientific observations. Geophysical methods in Antarctica are therefore very important. Gravity, especially as reported here, can effectively contribute to the elucidation of the subsurface structures, such as concealed intrusive bodies, sedimentary basins, rift systems, mountain roots, changes of crustal thickness or other inhomogeneities within the earth's crust or upper mantle. Gravity also provides information on isostatic conditions which is crucial in understanding geodynamic processes.

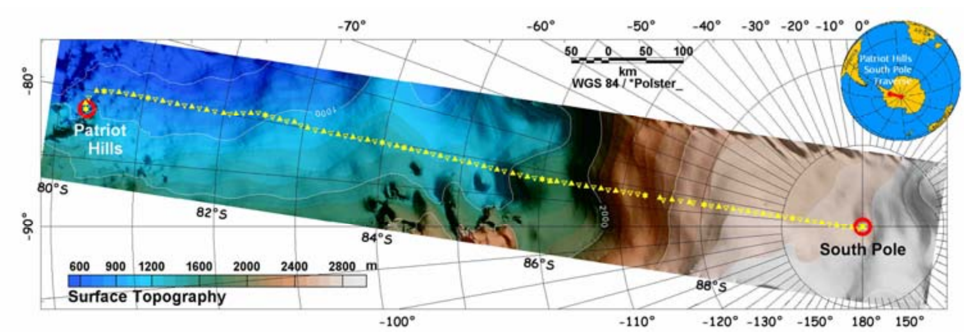

Figure 1. Location map of the traverse from Patriot Hills at 812 m altitude to the South Pole at 2825 m altitude. The gravity stations are marked by small yellow triangles: upright and filled outgoing leg, reversed and open triangles return leg.

The Centro de Estudios Científicos (CECS), Valdivia, in collaboration with the Chilean Army performed a tractor traverse from Patriot Hills to the South Pole covering more than 1100 km one way and returning the same route in 2004 (Casassa *et al.*, 2006). The tractor was a BERCO TL-6 which pulled three sledges carrying accommodation and dining facilities for 12 people, in addition to instrumentation space. The tractor traverse was a contribution of Chile, in collaboration with Brazil, to the International Trans-Antarctic Scientific Expedition (ITASE) programme (Mayewski et al., 2004).

Measurements

Gravity and differential GPS, indispensable for gravimetry, were measured during both expedition legs. Ice thicknesses measurements, also crucial in an ice-covered survey area, were performed during the first leg only. On the southbound leg we performed gravity measurements every 20 km, coinciding with the deployment of 54 stakes installed for ice velocity measurements. On the return leg to the north, gravity was measured again every 20 km at points in between the points of the first leg, effectively resulting in an average station separation of 10 km along the route. The instruments included:

- LaCoste&Romberg gravimeter G-142
- Dual frequency GPS receivers
- 150 MHz ice thickness radar, on loan from the University of Kansas
- 400 MHz radar for firn stratigraphy
- 400 MHz crevasse detection radar (Zamora *et al.*, 2006)

- firn drill and snow density sampler.

A GPS rover station was installed on the tractor convoy acquiring data every 5 s. Data from a GPS base station operated at Patriot Hills, and the base station data from the Amundsen-Scott Base at the South Pole were kindly made available to us.

More than 755,000 ice depth determinations were obtained. Data collection started 7 km east of Patriot Hills. A maximum ice thickness of ~ 3150 m was obtained at 88°52'S, and a minimum of ~ 500 m at 80°28'S. The mean ice thickness amounts to ~ 2130 m. Ice depth accuracy is estimated to be ± 10 m. Comparison of our ice depth data with BEDMAP (Lythe *et al*., 2001) data show in general good agreement, although differences of several hundred meters are detected in some places.

Surface snow samples were collected every 10 km, snow density of the upper 1 m layer every 20 km, and a total firn core length of 225 m was drilled in 5 sites, approximately every 2° of latitude. Results of these investigations will be reported elsewhere.

Processing of the gravity data

Correction of the instrumental drift

In order to provide a reasonable control of the unavoidable drift of field gravimeters, frequent loop measurements are conventionally performed in standard gravity surveys. In loop measurements the instrument is read at a base station at the beginning of a series of measurements and a concluding reading is taken at the end of the measurements after returning to the same base. Such loop readings should be made as often as possible, e.g. every few hours or daily. Usually a temporally linear drift is assumed between the two base readings. During long distance traverses intermediate loop closures are hardly possible and so the control of the instrument drift becomes rather uncertain. During our South Pole traverse we realized only one big closed loop, starting at the Patriot Hills base station *PH002* (81.4331°S, 80.32°W, 812 m) on November 11th and returning on December 31st, 2004. The change of the measured gravity within these 48 days amounted to 18.75 mGal, which means an average drift rate of 0.38 mGal/d.

The Patriot Hills base *PH002* was used for establishing the gravity reference for the whole survey. Its absolute gravity value was determined by NIMA (2000) to be 982,890.963 mGal. At the South Pole, the terminal station of the first leg of the traverse and the starting point of the return traverse, a second base station, called *Tunnel*, with the known absolute gravity of 982,316.011 mGal (Horgan, 2006) was occupied. This absolute gravity value was determined one year after our measurements had been taken. Due to ice dynamics, stations on glaciers such as at the South Pole are not stable. A decrease of -0.22 m/yr of the ellipsoidal height at the South Pole was found by Schenewerk and MacKay (1996) during the period 1991-1993. If we assume that the height in 2004 was 22 cm more than one year later than we have to subtract 0.068 mGal from the gravity value determined in 2005.

Drift of the gravimeter for the southbound and northbound legs

station	date	reading (mGal)	Δt (d)	Δg (measured)	Δg (true)	Δg (diff.)	drift rate (mGal/d)
PH002	13.11.2004, 18:00	6624.43	19.09	-569.62	-575.02	5.40	0.283
Tunnel	02.12.2004, 20:15	6054.81					
			5.77		0	5.97	
Tunnel	08.12.2004, 14:46	6060.78	23.12	582.06	575.02	7.04	0.304
PH002	31.12.2004, 17:41	6642.84					

With the two base stations mentioned the whole traverse can be separated into two legs, for which the drift behaviour of the instrument can be determined independently. During the first leg with a duration of 19.1 days an average drift rate of 0.28 mGal/d can be calculated and during the second leg of 23.1 days a somewhat larger rate of 0.30 mGal/d results. A considerable, unexplained jump of the instrument readings at the Tunnel station of nearly 6 mGal occurred during the 5.8 days stay at the South Pole between the two expedition legs. The drift of the instrument was positive during almost the entire expedition, i.e. the readings were permanently increasing.

The simplest way to apply drift corrections was to assume linear drifts using the constant rates determined for each leg as described. Fortunately, however, the drift behaviour of the instrument could be observed at a series of measuring points during short-time standstill intervals of the tractor convoy (3.6 to 30 hours) while the team was either resting during the southward leg or carrying out shallow firn drillings during the northward leg. The drift rates derived in this way are plotted in fig. 2. It can clearly be seen that the drift rate is by far not constant. Interestingly the rates are increasing continuously on the leg towards the South Pole and decrease again on the return route, even becoming negative at the end. This apparently strange performance of the instrument might be due to the systematic changes in altitude. In spite of the considerable scatter of these drift rates, the assumption of a somehow linearly changing rate seems to be justified, which correspond to the ascending straight line of the southern leg and descending line of the northern leg in fig. 2. The drifts can readily be calculated as the integrals over the straight lines which consequently yield quadratic polynomials. They are plotted as well in fig. 2 as a red concave curve for the southbound leg (left half) and a convex curve for the northbound leg (right half). It should be mentioned that the

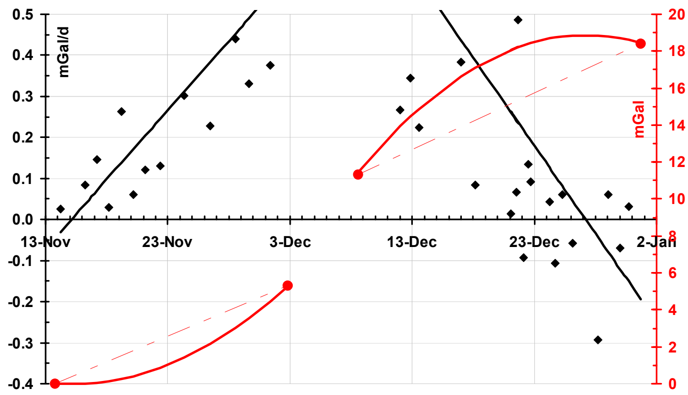

Figure 2. Drift behaviour of the gravimeter G142 during the traverse from Patriot Hills to the South Pole and back. Black diamonds: drift rates (in mGal per day) determined during short standstill times of the tractor convoy. Black lines: linear approximations of these measured drift rates. Red curves: approximation of the corresponding drift by quadratic polynomials calculated as the integrals over the black straight lines. Small red circles: readings at the two base stations with known absolute gravity.

finally selected straight lines representing the general tendency of the drift rate changes are only approximately coinciding with best fitting lines. A straight regression line for the part of the northern leg in particular would be less steep. Considering straight lines from a regression analysis, however, did not sufficiently conform to the necessity that the drift curves have to end at the values measured at the terminal base stations of each leg (the right red dot on each curve in fig. 2). The straight lines finally used are compromises and were found by trial and error. Experimenting with higher-order fits did not supply better results.

Latitude correction

An important correction to be applied to gravity measurements is the latitude correction. Due to the flattening of the earth the gravitational attraction increases systematically from the equator to the pole by more than half a percent. Our traverse starts at approximately 81°S and the increase in gravity until the South Pole amounts to almost 150 mGal. We used the formula of the Geodetic Reference System of 1980 (Torge, 1989).

Free Air correction

The next important correction to the gravity field data is the Free Air correction **(**FA**)**, which eliminates the effect that gravity decreases with height. It is known that actual vertical gradients can deviate substantially from the theoretical value of -0.3086 mGal/m (Reitmayr and Thierbach, 1996). The altitudes along the Patriot Hills-South Pole traverse vary between ~ 800 m to 2800 m, i.e. the corresponding change in Free Air correction amounts about 617 mGal. A wrong vertical gradient can easily cause substantial bias in the final FA anomaly. However, there exist very few empirical determinations of vertical gravity gradients in Antarctica and moreover apparently none close to the South Pole; so it does not seem to be justified to take another value than the theoretical one.

Bouguer and ice layer corrections

The Bouguer correction is to be applied in order to remove numerically the force of attraction of the variable masses below each point measured. With the simple Bouguer correction one assumes an infinitely extending horizontal slab below the point with a constant thickness - equal to the point's altitude. These simplifying assumptions usually need an additional second order correction, the terrain correction. In our ice covered Antarctic environment we ought to apply such corrections twice, firstly a correction due to the surface topography and secondly due to the bedrock or sub-ice topography. Both corrections together are called then the complete Bouguer correction CB.

We realized this CB by means of a two-dimensional model calculation: the ice cover is subdivided into thin vertical prisms of rectangular cross-section and infinite extension perpendicular to the gravity profile. The responses of the whole ensemble of prisms are finally summed. The top edge of each prism is defined by the ice surface and the bottom by the sub-ice topography measured. Additional assumptions have to be made about the width of the prisms, as well as the densities of ice and bedrock. We used the plausible values of 2.5 km for the prism's width and 0.9 and 2.7 g/cm^3 for the densities of ice and rock, respectively. The algorithm adopted is published in Parasnis (1997) and it was programmed in Matlab©.

A problem arises at the beginning and the end of the profile as the masses beyond these ends have to be accounted for. Beyond the Pole we assumed a mirror image of the whole known subsurface section along the traverse. For the section before the beginning of the profile at Patriot Hills we assumed an ice slab some hundred km wide with the average thickness of the first few points of the profile. The gravity responses of these two extensions of the model are added then in order to get the final complete Bouguer correction.

Results

Free Air and complete Bouguer anomalies

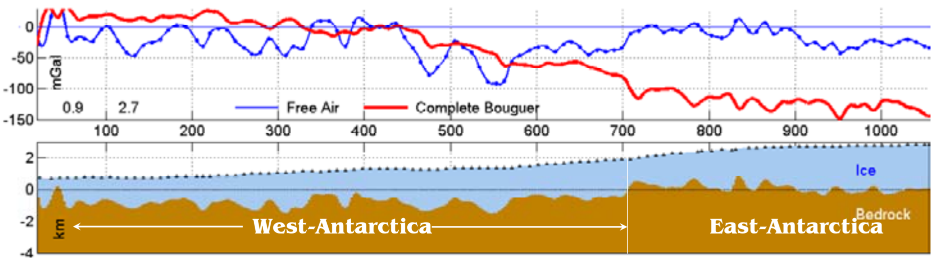

Figure 3. Free Air and complete Bouguer anomalies (on top) and surface and sub-ice topography along the traverse from Patriot Hills to the South Pole as measured during the traverse. The gravity points are marked by small triangles.

Fig. 3 displays the results of the gravity, GPS and ice thickness surveys. The surface topography changes smoothly from an altitude of 812 m at Patriot Hills (left most point) to 2825 m at the Pole (right most point). The sub-ice topography, however, shows strong variations along the entire profile. Most parts of the bedrock surface below the ice cover lie below the actual sea level, in particular the first 700 km, which correspond to the West-Antarctic section. The deepest spots reach depths of almost 1.5 km below sea level.

The Free Air anomaly oscillates between 20 and -90 mGal and it shows a strong correlation with the bedrock topography and the ice thickness: where the ice thickness decreases, Free Air gravity increases. This is to be expected because of the considerable density contrast between ice and rock.

The Bouguer values of the left half of the profile, until about 450 km, are slightly positive or around zero. From there, some 250 km before entering East-Antarctica, Bouguer values decrease considerably and stabilize from 800 km southward at approximately -130 mGal. Obviously the ice correction is not perfect everywhere, as there are still some (negative) correlations with short wavelength bedrock variations. In addition, the bed might not be composed only of rock underlying glacial ice as has been modelled, but also of a layer of sub-glacial till, particularly under fast-moving ice streams and topographic features such as a sub-glacial valley in between two sub-ice peaks. If sub-glacial till indeed exists, then the density contrast between bedrock and ice assumed might be too big, and the ice correction is overestimated. The Bouguer anomaly shows in general a strong long wavelength inverse correlation with surface topography, i.e. the higher the altitude the smaller the Bouguer anomaly. This is a clear indication of the existence of an isostatic root at depth.

Isostatic anomaly

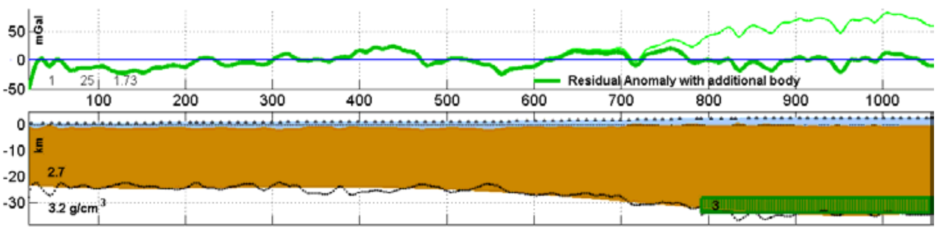

Figure 4. Residual isostatic anomaly (light green) calculated as the difference of CB and the gravity response of the isostatic root. Incorporating an additional heavier body within the crust of East-Antarctica causes the anomaly to stay around zero along the whole profile (dark green).

The surface and sub-ice topographies ascend towards the pole, with a corresponding increase of extra loads. Assuming isostatic equilibrium an increase of the crustal thickness must occur in consequence. This thickening can be calculated using a simple Airy type model. Subtracting its gravity response from the CB yields the residual isostatic anomaly. As can be seen in fig. 4 this residual anomaly oscillates around zero in the West-Antarctic section and rises to about 70 mGal over East-Antarctica. Incorporating an additional heavier body within the crust can explain this anomaly. The depth of this body, however, is rather uncertain. For example, the body could also be assumed to be located in the upper crust. A possible alternative model might be designed assuming less heavy material, e.g. a substantial sedimentary cover in the West-Antarctic section. A further option is to consider an isostatic disequilibrium due to changes of the ice load: we may see a situation where the heavier mantle material in reality is closer so the surface, i.e. there was less ice load in the past – in contradiction to the prevailing general opinion, and the increased load of today is not yet compensated. At the moment we cannot rule out any of these hypotheses for explaining the positive residual anomaly over East Antarctica.

Acknowledgements. The expedition was funded jointly by the Chilean Defense Ministry, the Chilean Army and CECS, with logistic support of FACH. The contribution of the following organizations are acknowledged: National Science Foundation, USA, Office for Polar Programs (OPP), Antarctic Sciences Section, Raytheon Polar Services (RPS), USGS, Antarctic Logistics and Expeditions (ALE), Instituto Antártico Chileno (INACH), Ohio State University, University of Kansas, NASA-Wallops and EG&G, JPL, BERCO Production AB Sweden. We are also grateful for the comments and corrections to the manuscript of the editor A. K. Cooper and the co-editor F. Davey.

References

Casassa, G., L. Urrutia, C. Bunster, P. Carrasco, C. Iturrieta, F.Ordenes, J. Quinteros, A. Rivera, J. Simoes, R. Zamora, A. Wendt and J. Wendt. (2006), Chilean traverse from Patriot Hills to South Pole 2004: preliminary results. Libro de Resúmenes, II Simposio Latino-americano de Investigaciones Antárticas, Concepción, Chile, 16-18 agosto 2006, 85-89.

Horgan, H. (2006), Gravity tie from McMurdo to the South Pole in Nov. 2005 (pers. comm.).

Lythe, M., D.G Vaughan and The Bedmap Consortium (2001), BEDMAP: a new ice thickness and subglacial topographic model of Antarctica. Journal of Geophysical Research, Solid Earth, 106(B6):11,335-11,351.

Mayewski, P., K.A. Maasch, J.W.C. White, E.J. Steig, E. Meyerson, I. Goodwin, V.I. Morgan, T. Van Ommen, M.A.J. Curran, J. Souney and K. Kreutz (2004), A 700 year record of Southern Hemisphere extratropical climate variability. Annals of Glaciology, 39(1): 127-132.

Nima (2000), Patriot Hills Gravity Survey, Antarctica November 2000, GIGA - 01 – 030.

Parasnis, D. S. (1997), Principles of applied geophysics. Chapman and Hall, London – New York.

Reitmayr, G. and R. Thierbach (1996), Gravity Surveys in Northern Victoria Land, Antarctica during GANOVEX VI. Geol. Jb., B 89, pp 343-370, Hannover.

Schenewerk, M. S. and J. R. MacKay (1996), Determination of Ice Flow Velocities at the South Pole Using Measurements from the Global Positioning System (GPS). http://www.ngs.noaa.gov/GRD/GPS/Projects/SOUTH_POLE/south_pole.html.

Torge, W. (1989), Gravimetry. W. de Gruyter, Berlin - New York.

Zamora, R., G. Casassa, F. Ordenes, G. Gacitúa, C. Bunster, R. Mella and A. Rivera (2006), Detection of crevasses within glaciers in the Andes and Antarctica by means of GPR. Proceedings 11th International Conference on Ground Penetrating Radar, June 19-22, 2006, Columbus Ohio, USA.