# Evaluating EGM2008 over East Antarctica

**P.J. Morgan**

*Faculty of Information Sciences and Engineering,*

*University of Canberra, Canberra, ACT 2601, Australia*

*Phone: +61 2 6201 2557; Fax: +61 2 6201 5231; Email:peter.morgan@canberra.edu.au*

**W.E. Featherstone**

*Western Australian Centre for Geodesy & The Institute for Geoscience Research,*

*Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia*

*Phone: +61 8 9266 2734; Fax: +61 8 9266 2703; Email: W.Featherstone@curtin.edu.au*

**Abstract**

The release of EGM2008 and associated products such as grids of mean dynamic ocean topography offer the possibility of utilising the extensive historical record in Antarctica with today's modern satellite sensing techniques. In this study, we use data acquired at the Mawson, Davis, Casey and Scott and McMurdo stations in East Antarctica to investigate the performance of EGM2008 over this region. EGM2008 over Antarctica is entirely dependent on the EGM2008-adopted global GRACE satellite-derived gravity field. This is in contrast to most other regions of the Earth, where there are also contributions from terrestrial gravity and/or altimeter satellites. We determine, over East Antarctica, and at our four test sites that EGM2008 should be used with caution when precisions better than one metre are required. The precisions at the test sites are better than this, but the evidence is that the four test sites are probably not representative of the large area of East Antarctica they are being forced to represent. Notwithstanding any of the above, EGM2008 represents a significant step forward in East Antarctica and that the use of test stations and regions where there is little or no complementary data is a valid method of investigating the performance of the model.

## 1. Introduction

The needs and uses for heights relative to the geoid in Antarctica are as great as elsewhere over the Earth's surface; it is just that the applications are different. Of particular importance, at this moment, are studies aimed at re-evaluating and connecting historical surveys with modern surveys for the task of deducing ice mass change over decadal time periods.

In the Australian ANARE (Australian National Antarctic Research Expeditions) context, extensive optical levelling surveys were done on the Amery Ice Shelf and the Wilkes Local Ice Cap (cf. Figure 1).

- On the Amery Ice Shelf, Corry (1986, 1987 and 1996) observed a central flow line of some 400 km in 1968. In 1996, Phillips and Craven (Phillips 1999) recovered eight of the original poles placed by Corry in 1968. King et al. (2007) performed a complete re-adjustment of Corry's horizontal observations, and then made a comparison with GPS and INSAR data. The height data has now been reprocessed and comparative studies made with ICESat and GPS data (King et al. in press).
- On the Wilkes Local Ice Cap, optical levelling was undertaken by McLaren in 1965 (McLaren 1968) and Pfitzner the following year (Pfitzner 1980). A re-occupation program was trialled in the Austral Summer of 2004-2005 with GPS and ICESat observations. This data is not yet fully analysed due, in part, to the datum connection difficulties and, in part, due to difficulties associated with estimating ice flow velocities.

Figure 1 is an AVHRR (Advanced Very High Resolution Radiometer) image of Antarctica. It shows the Trans Antarctic Mountains, which divide the continent into East and West Antarctica. The two regimes are very different. East Antarctica is dominated by the high plateau, in-excess of 3000 m altitude, and steep slopes to the coast, which is generally in close proximity to the Antarctic Circle. West Antarctica is lower, generally about 2200 m in elevation. The West Antarctic coastline is far from uniform with two major seas, Ross and Weddell, extending to 78°S and a third smaller sea, Bellingshausen, extending to 72.5°S.

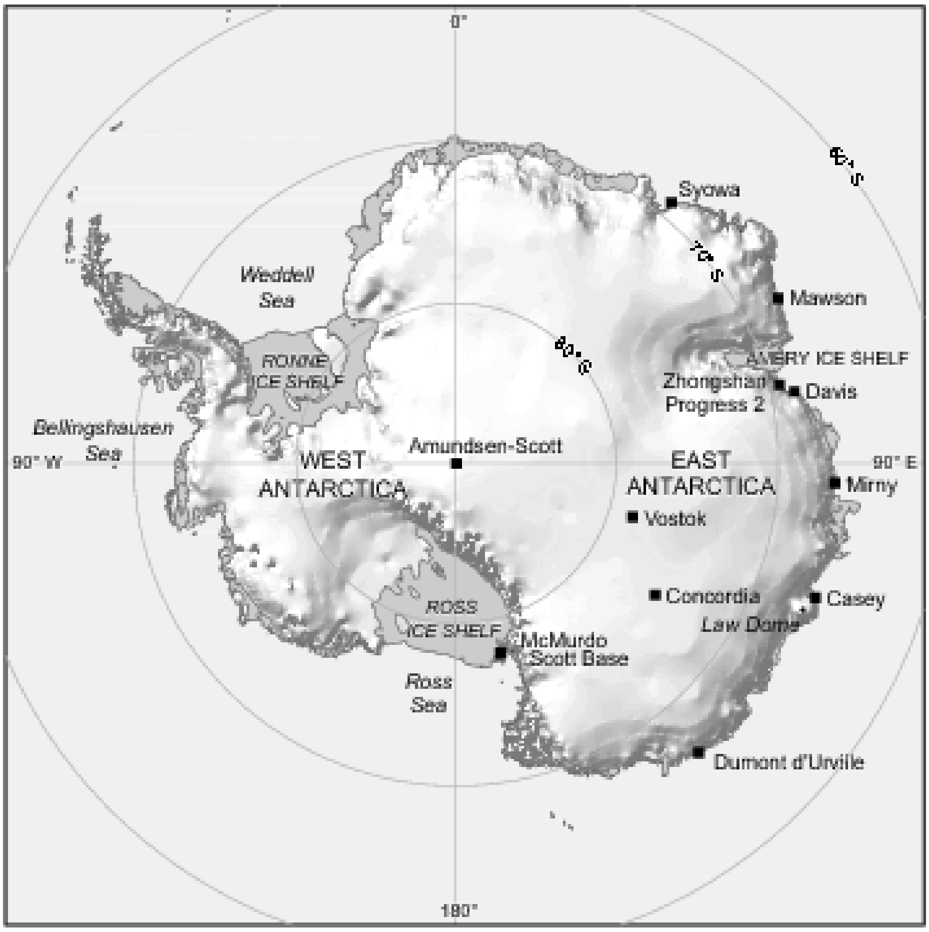


**Figure 1:** Map of Antarctica derived from AVHRR imagery. Polar stereographic projection with elevation shading and principal ice shelves and the three major regional seas.

EGM2008 (Pavlis et al. 2008) uses three principal data types to derive a new Earth Gravity Model, which seeks to overcome many of the limitations of the earlier EGM96 model (Lemoine et al. 1998).

1. Terrestrial gravity anomalies. In Antarctica, terrestrial gravity observations were an integral part of the major over-snow traverses programmes conducted during the IGY(International Geophysical Year) 1957-1958 and the decade there after (see, e.g., Thiel et al. 1959, Hollin 1961 and Walker 1966). Unfortunately, these positions were poorly constrained until satellite Doppler positioning was introduced in the late 1970s, at which time the height system was changed to the geometric ellipsoidal system. Thus, it is not too surprising that EGM2008 contains no terrestrial gravity data over Antarctica.
2. Altimeter satellite-derived anomalies. There are two sources of gravity anomalies derived from altimeter satellites.

The first is the Sandwell data (cf. Sandwell and Smith 1997; http://topex.ucsd.edu/marine_grav/). Sandwell uses data from GEOSAT and ERS1, which imposes two limitations on the data set. The first is that the inclination of GEOSAT, 108 degrees, limits GEOSAT data to the band 72°S to 72°N. ERS1 has an inclination of 92 degrees and therefore significantly extends coverage in the Polar Regions. The second limitation is the footprint of the imaging system. In radar satellites such as GEOSAT, the effective size of this footprint varies from 2 km to 10 km depending antenna characteristics, the width of the transmitted pulse and surface roughness (e.g., Rees 2001). The impact is that as the footprint size increases, the reliability of heights decrease, especially when there is significant surface roughness or surface slope.

The second data set is that from the Danish National Space Center, DNSC, (http://www.space.dtu.dk/english.aspx). DNSC use data from many more satellites including ICESat, which has a 70 m footprint and a 94 degree inclination. The use of ICESat data for the recovery of gravity anomalies was pioneered by DNSC staff (Forsberg and Skourup 2005). Zwally et al. (2008) have also shown that gravity anomalies and sea-ice fee board data can be recovered from ICESat data using data over the Weddell Sea offshore West Antarctica (cf. Figure 1). The caveats for such processing include the level of bias in the "lowest-level" filtering scheme and the level of *a priori* knowledge assumed.

EGM2008 seeks to use the strengths of both the Sandwell and DNSC data sets. Thus, EGM2008 uses Sandwell data over the open oceans, while the DNSC data is used for the 195-km-wide coastal zone. There is also a transition zone over which this change occurs (Pavlis 2008, pers. comm.).

3. Global satellite gravity fields are regularly determined from the GRACE satellites in several modes (http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html). GRACE-only solutions have been published by: The Center for Space Research at the University of Texas (//http://www.csr.utexas.edu/grace/), GeoForschungsZentrum Potsdam (http://op.gfz-potsdam.de/grace/index_GRACE.html) and Institut für Geodäsie und Geoinformation, University of Bonn (http://www.geod.uni-bonn.de/), among others. EGM2008 uses the ITG-GRACE03s model, extending to degree and order 180 (http://www.geod.uni-bonn.de/itg-grace03.html). The limiting degree of the model is controlled by the crossover between signal recovery and calibrated, formal, errors. The initial presentation of this model at the Joint

International GSTM and DFG SPP Symposium in Potsdam on 15 October 2007 discussed model striations, particularly their likely causes. An alternative static model by Tapley et al. (2005) only extends to degree 120.

The problem faced in East Antarctica is that only data type 3 contributes to EGM2008, whereas most other regions, including the Arctic, have at least one additional data type.

## 2. The Functional Model

This study uses the well-known relationship between ellipsoidal height, h; orthometric height, H; mean dynamic topography of the ocean, MDT, and the geoid-ellipsoid separation, N:

$$h = (H\_msl + MDT) + N \quad (1)$$

where H_msl is the mean sea level (MSL) height of the tide gauge bench mark (TGBM), which needs to be 'corrected' to the geoid with the prevailing MDT.

## 3. Description of the Data

Some 30 nations operate Antarctic stations or bases (http://en.wikipedia.org/wiki/List_of_research_stations_in_Antarctica). Many of these nations contribute GPS data to the IGS (International GNSS Service) network, (http://igscb.jpl.nasa.gov/network/netindex.html). Seven stations in East Antarctica also contribute tide gauge data to the GLOSS network (http://www.gloss-sealevel.org/). The Antarctic programmes undertaken by most nations, especially in this instance by Australia and New Zealand, include precision levelling between the TGBM and the IGS GPS antenna, and precision GPS observations at the TGBM (http://www.antarcticanz.govt.nz and http://www.ga.gov.au/geodesy/antarc/antgauge.jsp).

This data provides the classical estimates of both the levelled height with respect to MSL, H_msl, and the ellipsoidal height, h, at the station IGS GPS receivers, the local TGBM and associated reference and intermediate marks of interest, e.g., marks used in previous geodetic missions such as PAGEOS (http://en.wikipedia.org/wiki/PAGEOS) or old IGS sites. In addition to this need, there have been special needs for levelled heights to determine the elevations of raised beaches, and aircraft runways. A notable example is the Vestfold Hills Survey, in the vicinity of the Davis Station (Johnston and Digney 2001).

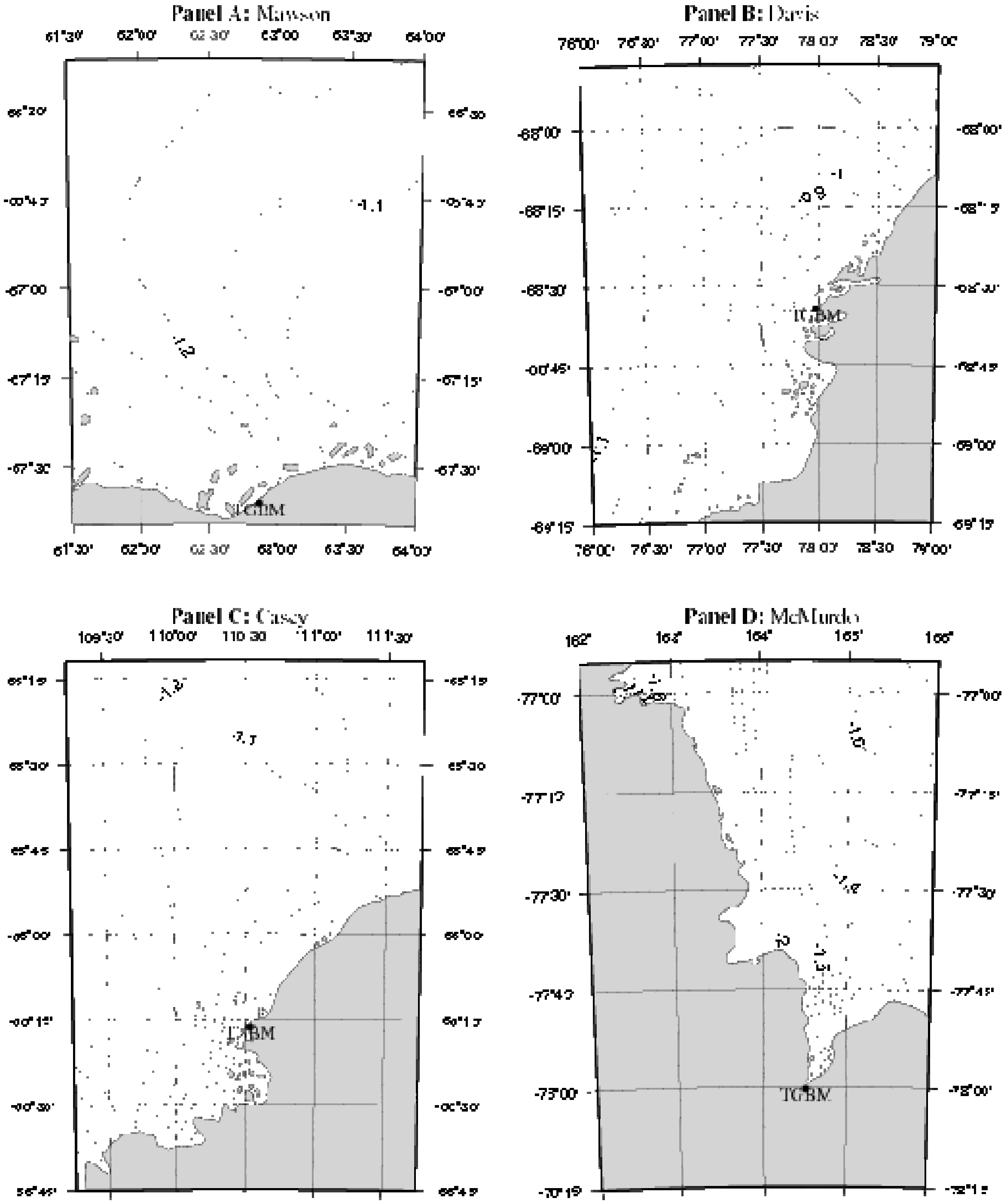


**Figure 2:** Panels showing contours, 0.1 m interval, of MDT from DNSC08 near the Mawson, Davis, Casey and McMurdo stations.

For the MDT in this study, we used the DNSC08 model (Andersen and Knudsen 2008). The behaviour of this model at the Mawson, Davis, Casey and McMurdo stations is shown in Figure 2, which plots MDT with a 0.1 m contour level. Because this data set uses the same altimeter satellites used in developing EGM2008, it will be beset by similar problems of coastline contamination and data continuity. It is estimated from Figure 2 and a general understanding of coastal effects that values of MDT are likely to be unreliable within 10 km to 20 km of the coast. For this reason, the value at the TGBN is likely to be in error by several contour intervals before an open water steady-state condition is reached. This is especially so at Davis and Casey, where there are many small peninsulas, bays and off-shore islands in the immediate vicinity. The case in McMurdo Sound is complex because data is limited and sea-ice covers the ocean for much of the year. The use of the GLOSS tide gauge at Cape Roberts will alleviate some of these problems. As such, GPS and spirit-levelling connections have been programmed for the forthcoming field season.

## 4. Data Analysis

Our analysis is based on the remove-restore principle since the summation of individual spectral bands is equal to the full model. This approach readily allows for the contribution of individual bands to be determined by differencing two sequences, usually a sequence that is near full with a sequence that is band limited. This concept is shown in Figure 3.

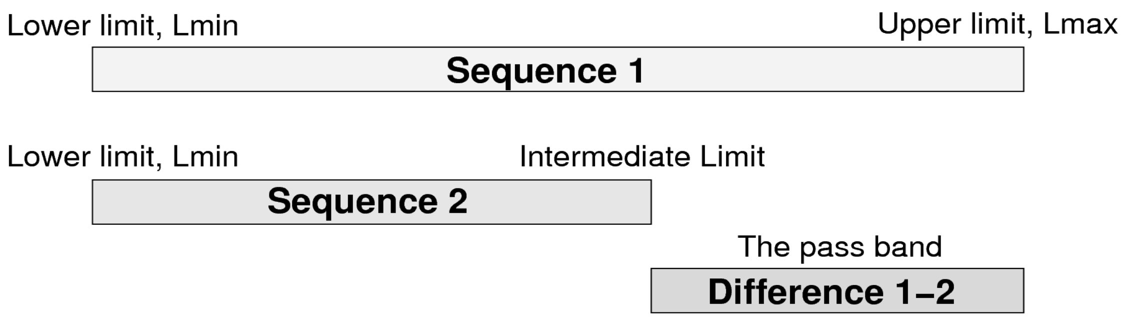


**Figure 3:** Schematic explanation of generating the contribution of a pass band.

Figure 4, with four panels, shows the effect of increasing the pass band by progressively reducing the maximum degree to which the coefficients of sequence 2 (cf. Figure 3) are evaluated.

Panel A in Figure 4 shows that there is little or no high-frequency contribution over

East Antarctica. Additionally, there is some low-level noise that parallels the Antarctic coast. These two features are almost certainly consistent with the EGM2008 model. The first is consistent with no terrestrial Antarctic gravity data and a complete reliance upon the GRACE-only ITG-GRACE03s global gravity field model. The second is consistent with the use of satellite altimeter data, which abruptly ends as the satellite crosses from an ocean to land environment or begins with a crossing from an ice to ocean environment. Additionally, there is a transition zone, 195 km off the coast of Antarctica, where the principal altimeter data set changes from the open-ocean Sandwell data set to the coastal DNSC data set, which is expected to have better performance characteristics close to the Antarctic coastline (Pavlis 2008, pers comm.).

Panel C in Figure 4, whose residual scale is twice that of Panels A and B, shows further increases in noise. It is also clear that the four test regions of Table 1 are not in regions of particularly bad noise and hence the determined residuals may not be reflective of the magnitudes that exist in other regions; see, for example, the Amery Ice Shelf south of Davis and the Bunger Hills/Mirny region to the west of Casey at about 105°E.

**Table 1:** A summary of data used in the study. The positions are the mean values for sites in the local region. In the case of Mawson and Casey, all locations were within 10 km of each other and hence have been assigned a point attribute with no residual, (h-H_msl-MDT-N), standard deviation. N has been computed using EGM2008 to degree 2190.

| **Station Area** | **Latitude (degrees)** | **Longitude (degrees)** | **Data Type** | **No. of sites** | **MDT at TGBM (m)** | **Mean Residual (m)** | **STD of residual (m)** |
|---|---|---|---|---|---|---|---|
| Mawson | -67.60276 | 62.87097 | Point | 5 | -1.166 | -0.796 | NA |
| Davis | -68.55535 | 78.13456 | Area | 21 | -0.422 | -0.267 | +/- 0.063 |
| Casey | -66.28012 | 110.53078 | Point | 5 | -0.551 | -0.924 | NA |
| McMurdo | -77.82861 | 165.72620 | Area | 7 | -1.859 | 0.236 | +/-0.123 |

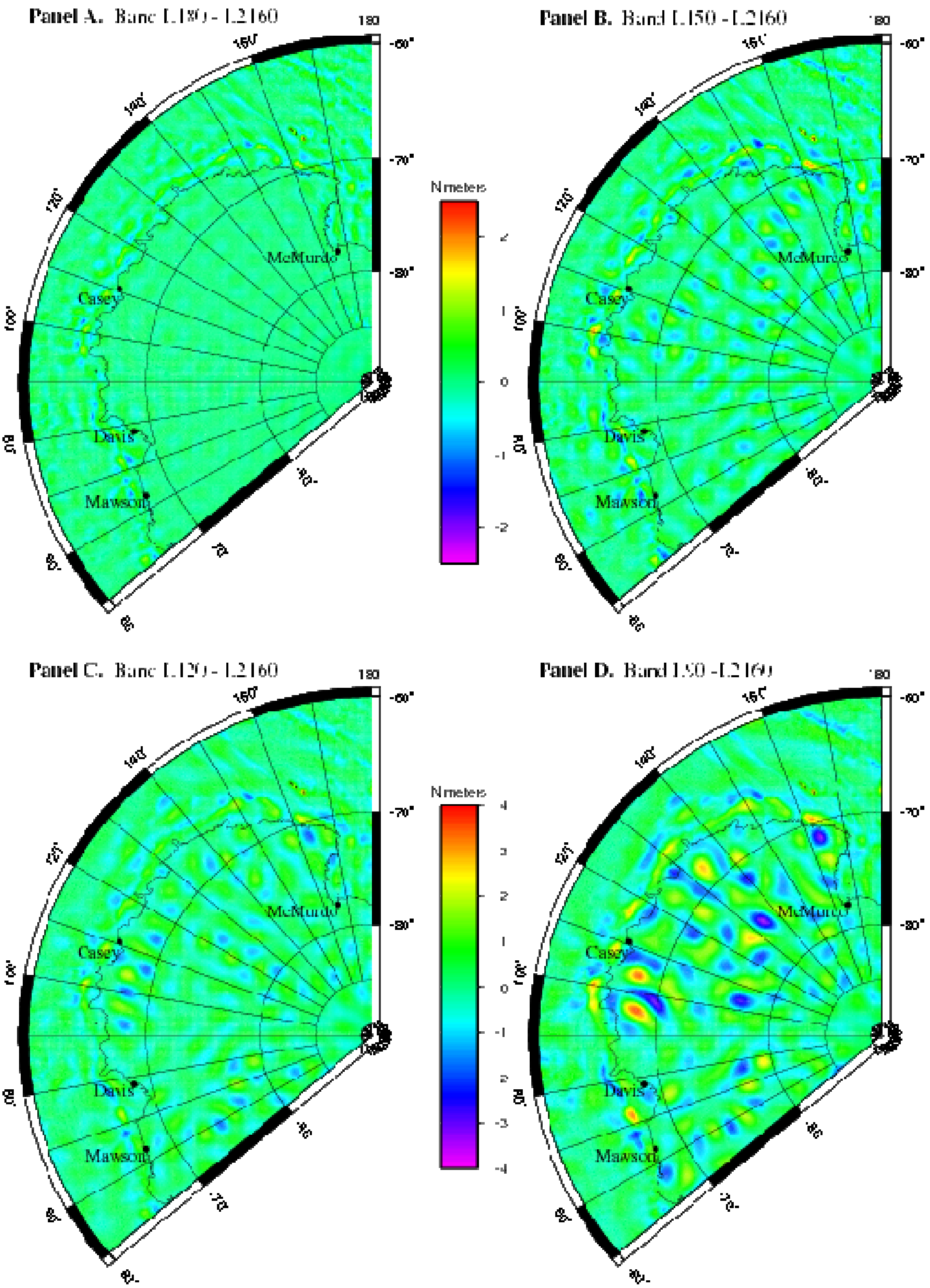


**Figure 4:** Four panels showing increasing information from a near zero level for pass band L180-L2160, Panel A, to a possible noise-dominated pass band L90-L2160, Panel D. Panel B shows an increase in noise as the pass band is increased at the low frequency end. The noise does not appear to be random because striations start to appear as well as regions where the residuals oscillate.

Panel D in Figure 4, with the same residual scale as Panel C, shows an amplification of noise as the bandwidth is further increased. Since the patterns in Panels C and D are similar and regionally repetitious, there is the strong suggestion that it is structured noise rather than signal that is causing the difference.

Figure 5, showing EGM2008 in the band between L=90 and L=120, Panel A, and the band between L=120 and L=150, Panel B, supports the structured noise hypothesis as the patters are similar, although of different magnitudes in the two panels. The reduced signal level in Panel B is consistent with the expected lower signal levels that can be detected as the degree of the model is increased. The patterns to the west of Casey at 100°E and to the north of McMurdo are two regions where pattern similarity is high.

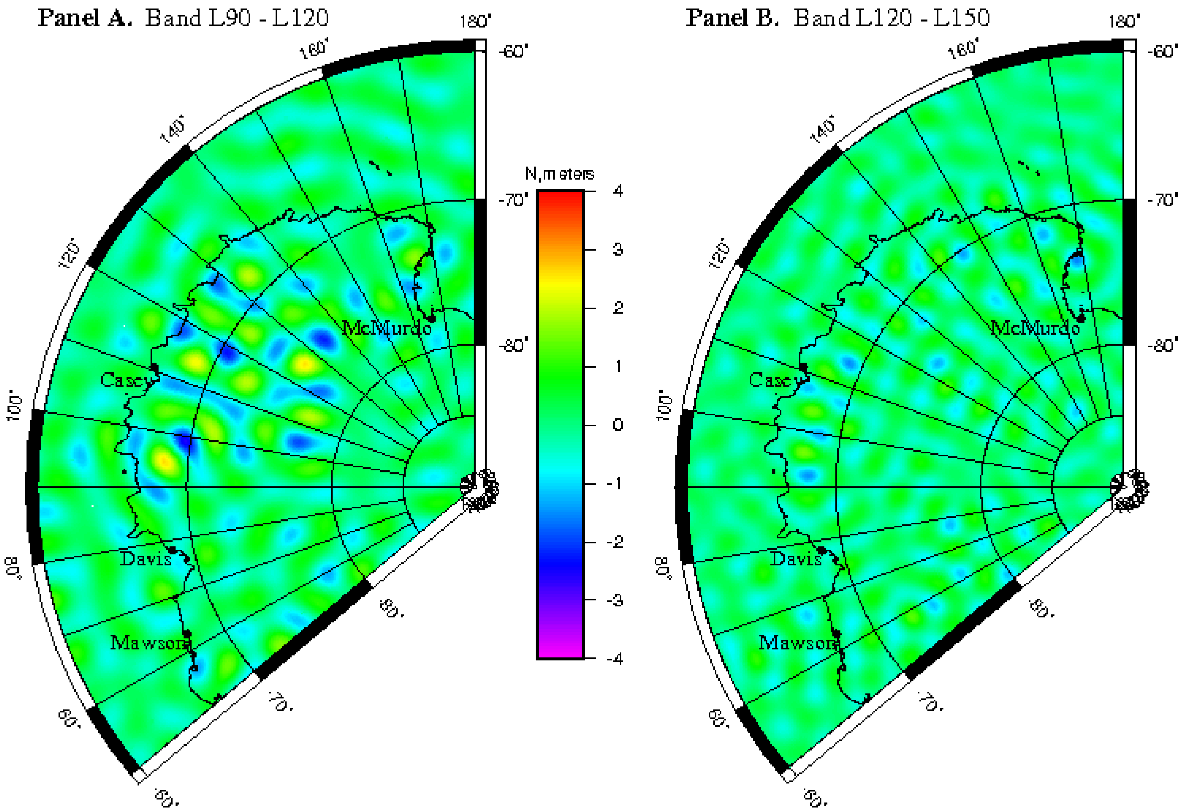


**Figure 5:** Two pass bands, L90-L120 and L120-L150, which highlight low-level regional signal or noise in the EGM2008 model.

We computed formal correlation coefficients between the two panels in Figure 5 in an attempt to support these impressions. However, we found that the correlation coefficient was only -0.03, a value that is indicative of no correlation. An investigation of this null result showed, using auto-correlation techniques, that the correlation coefficient rises to 0.7 when the grid is displaced, relative to itself, by 0.5 degrees. A fall to 0.17 occurs when the displacement is 1 degree. The visible displacements of the features of Panels A and B in Figure 5 are of this order. We therefore conclude that the panels of both Figures 4 and 5 show a subtle mixture of signal and noise, which cannot be separated or characterised in this case. This is entirely consistent with the behaviour of spherical harmonics which are oscillatory by their very nature and depend on superposition cancellation and addition to represent local features (e.g., Moritz 1980).

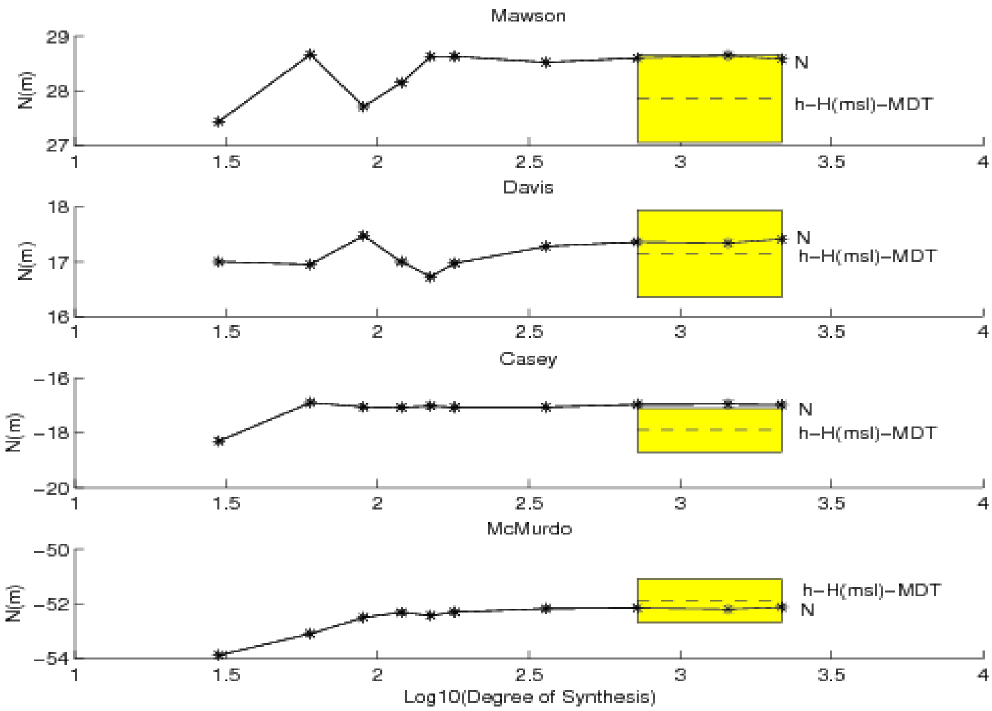


**Figure 6:** Characterization geoid separation and residuals at the four East Antarctic sites. The solid lines represent a mean position N computed from the EGM2008 model while the dashed lines represent the observed mean value after correcting for MDT. The yellow patch is an estimated 95% confidence interval.

The second part of our data analysis concerned the individual station data of Table 1. Figure 6 shows the evolution of $N$ from EGM2008 as a function of the degree of the model and the value computed by differencing the observed ellipsoidal height with MDT-adjusted MSL heights. Figure 6 uses a log10 abscissa scale so that the high degree expansions do not dominate. No error bounds are shown for $N$, even though it has clearly been demonstrated that there are errors due to model inadequacies in East Antarctica. Figure 6 also shows the mean difference between the GPS-determined ellipsoidal heights and the MDT-adjusted MSL height. This estimate of $N$ is plotted as a yellow patch, which has a width equal to a 95% confidence level (two sigma) of 0.8 m. The major contributor to this error is the reliability of the MDT. While the sample is too small to draw reliable conclusions, we are heartened by the fact that the sign of the residual is not constant and that an estimate of sigma based on the range of residuals is consistent with the adopted one-sigma level of ±0.4 m.

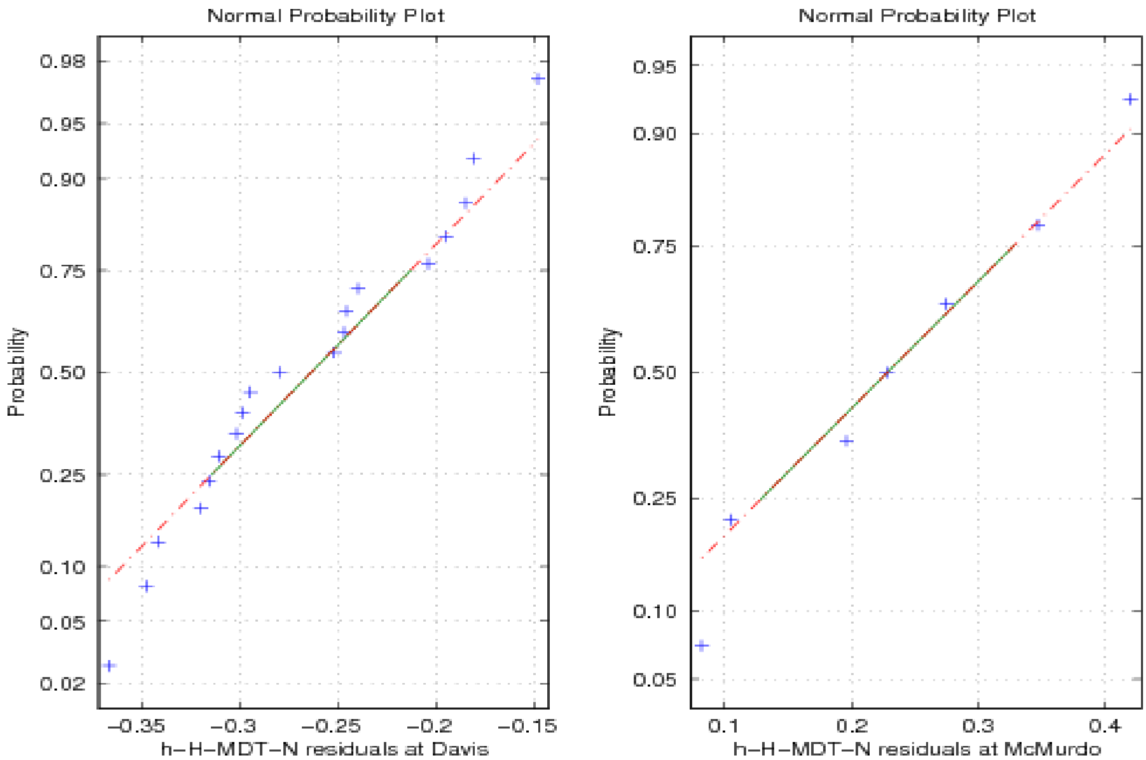


**Figure 7**: Normal probability plots of the residuals, h-H-N, at Davis and McMurdo. The solid line is the regression line from the inter-quartile range of 25 to 75 percent. The dashed line is the extension of this regression line to the full data set.

Figure 7 shows the behaviour of residuals at Davis and McMurdo where levelling data extended beyond the immediate station perimeter. Figure 7 shows that the data is normally distributed. This local normally distributed feature supports the hypothesis that the bias is principally due to regional issues in EGM2008 and/or DNSC08_MDT and that Antarctic levelling operations, which are frequently performed in adverse conditions, are usually consistent with third-order geodetic standards (Intergovernmental Committee on Surveying and Mapping 2007), which is the normal operational goal.

## 5. Discussion and Conclusion

It is clear from the pass band and individual station data that there are significant biases in EGM2008 and/or DNSC08_MDT over East Antarctica. From the very small sample, it is clear that these biases will approach and may even exceed one metre even though the formal one-sigma value is ±0.4 m. This study indicates that separating the relative contributions of the Earth Gravity Model and the MDT model will remain a challenge for the immediate future. We think that this is achievable by two methods.

1. By collecting data in regions showing anomalous behaviour. Two candidate areas are the Mirny/Bunger Hills region at about 100°E and Synder Rocks, about 100 km west of Casey. Both regions are currently regularly visited for other activities including the maintenance of Automatic Weather Stations, AWS.
2. By utilising the resources being assembled by the Antarctic Geoid Project (Scheinert 2005) and ICECAP (http://www.ig.utexas.edu/research/projects/icecap/) for local and regional models.

The importance of this study for Antarctic glaciology is clear. It is that EGM2008 and/or DNSC08 in their current forms are not entirely reliable products in East Antarctica for climate studies, where surface changes are needed to a precision level of 0.1 m to 0.2 m, which is consistent with the precision level of the old optical surveys and more modern satellite altimeter data. However, EGM2008 is likely to be of great value for many other applications including airfield construction and preparations.

### Acknowledgments

*Many groups helped in this evaluation by supplying data and information on their data bases. The following groups supplied data and access to their respective databases: Graeme Blick and team from Land Information New Zealand, LINZ; Garry Johnston and team from Geoscience Australia, GA; and Henk Brosmla and team from the Australian Antarctic Division, AAD. We are especially thankful for comments and suggestion from Matt King and Nikos Pavlis. We used the GMT package (Wessel and Smith 1998) to generate and display the grids used in this study.*

## References

Andersen OB, Knudsen P (2008) The DNSC08 global mean sea surface and bathymetry Presented to EGU-2008, Vienna, Austria, April, 2008. Also see http://www.space.dtu.dk/upload/institutter/space/data/data_og_modeller/mean%20dynamic%20topography/dnsc08mdt.pps

Corry M (1986-1987) Amery Ice Shelf Saga: Parts1 to 4. *Aurora*, ANARE Club Journal 5(5):17-20, 6(2):28-34, 6(3):25-29 and 6(4):21-24

Corry M (1996) Those Amery Ice Shelf glaciological marker snowpoles. *Aurora*, ANARE Club Journal 15(4):18-20.

Forsberg R, Skourup H (2005) Arctic Ocean gravity, geoid and sea-ice freeboard heights from ICESat and GRACE, *Geophys Res Lett* 32, L21502, doi:10.1029/2005GL023711.

Hollin JT, Cronk C, Robertson R (1961) Wilkes Station Glaciology, Project 825, Report 2, Part X, The Ohio State University Research Foundation, Columbus, Ohio.

Intergovernmental Committee on Surveying and Mapping (2007) Standards and Practices for Control Surveys, Special Publication 1, Version 1.7. Also see http://www.icsm.gov.au/icsm/publications/sp1/sp1v1-7.pdf

Johnston GM, Digney P (2001 unpublished), Antarctic Summer 2000-2001, Technical Report 5, Geoscience Australia, Canberra, Australia.

King MA, Coleman R, Morgan PJ, Hurd RS (2007) Velocity change of the Amery Ice Shelf, East Antarctica, during the period 1968–1999, *J Geophys Res* 112, F01013, doi:10.1029/2006JF000609.

King MA, Coleman R, Freemantle A-J,Fricker HA, Hurd RS, Legresy B, Padman L, Warner R (2008) A four decade record of elevation change of the Amery Ice Shelf, East Antarctica, *J Geophys Res* (accepted Oct 2008)

Lemoine FG, Kenyon SC, Factor JK, Trimmer RG, Pavlis NK, Chinn DS, Cox CM, Klosko SM, Luthcke SB, Torrence MH, Wang YM, Williamson RG, Pavlis EC, Rapp RH, Olson TR (1998) The development of the joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) geopotential model EGM96, NASA/TP-1998-206861, National Aeronautics and Space Administration, Greenbelt, USA, 575 pp.

McLaren WA (1968) A study of the local ice cap near Wilkes, Antarctica, ANARE Scientific Reports, Series A (IV) Glaciology, Publication 103, Antarctic Division, Department of External Affairs, Australia.

Moritz H (1980) *Advanced Physical Geodesy*, Herbert Wichmann Verlag, Karsruhe.

Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2008) An Earth Gravitational Model to Degree 2160:EGM2008, Presented to EGU-2008, Vienna, Austria, April, 2008. Also see http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html.

Pfitzner ML (1980) The Wilkes Ice Cap Project, ANARE Scientific Reports, Series A (IV) Glaciology, Publication 127, Australian Government Publishing Service, Canberra.

Phillips HA (1999) Applications of ERS satellite radar altimetry in the Lambert Glacier-Amery Ice Shelf system, East Antarctica, PhD Thesis, University of Tasmania, Hobart, Australia, 308 pp.

Rees WG. (2001) *Physical Principles of Remote Sensing*, Second Edition, Cambridge University Press, Cambridge.

Sandwell D, Smith WHF (1997) Marine gravity anomaly from Geosat and ERS 1 satellite altimetry, *J Geophys Res* 102(B5): 10039-10054.

Scheinert M. (2004) The Antarctic Geoid Project: Status Report and Next Activities in

International Association of Geodesy Symposia 129 :137-142, doi:10.1007/3-540-26932-0_24. See also http://www.tu-dresden.de/ipg/antgp/antgp.html

Tapley B, Ries J, Bettadpur S, Chambers D, Cheng M, Condi F, Gunter B, Kang Z, Nagel P, Pastor R, Pekker T, Poole S, Wang F. (2005) GGM02 - An improved Earth gravity field model from GRACE, *J Geod* 79(8): 467-478, doi: 10.1007/s00190-005-0480-z.

Thiel E, Bentley CR, Ostenso NA, Behrendt JC (1959) Oversnow traverse programs, Byrd and Ellsworth Stations, Antarctica, 1957-1958: Seismology, Gravity and Magnetism IGY World Data Center A Glaciology, American Geographical Union, New York, New York.

Walker DJ (1966) Wilkes Geophysical Surveys, Antarctica 1962, Bureau of Mineral Resources Record 1966/129, Department of National Development, Canberra, Australia.

Wessel P, Smith WHF (1998) New, Improved version of Generic Mapping Tools released, *EOS - Trans Amer Geophys U* 79(47): 579.

Zwally HJ, Yi D, Kwok R, Zhao Y (2008) ICESat measurements of sea ice freeboard and estimates of sea ice thickness in the Weddell Sea, *J Geophys Res* 113, C02S15, doi:10.1029/2007JC004284.