

A Geoid Model Of Northern Chile From Airborne And Surface Gravity

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Key words: Geoid, Airborne Gravity, Geodesy, Gravimetry

SUMMARY

In recent decades many countries have participated in projects related to the determination of local geoid models combining global geoid model EGM08 and airborne gravity.

Today airborne gravimetry is an important technique to quickly collect gravity data over large regions, where terrestrial gravity data are sparse and/or of poor quality for use in geoid determination. Airborne gravity provide an obvious mean of gravity field data over large, inaccessible regions, such as polar and mountainous areas.

The joint work of the National Geospatial and Intelligence Agency of the United States of America (NGA), the National Space Institute of Denmark (DTU-Space) and the University of Bergen, along with work and data captured on the ground by the Military Geographic Institute of Chile (IGM) for decades, have given Chile the opportunity to own a local geoid model of the northern part of the country. The IGM made the field support, logistics and some of the members of the Geodesic Section participated actively in the project.

The northern Chile geoid was computed on a grid of $0.02^\circ \times 0.025^\circ$ resolution (corresponding to roughly 2 x 2 km grid). The area of computation is 39°S to 17°S and 75°W to 66°W . As a main characteristic the model is a combination of surface, airborne and satellite gravity and terrain models.

As a final product, a data grid with geoid undulation was obtained from Visviri to Concepción and it was possible to code an interpolation application to obtain the value for any point in the country.

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1. INTRODUCTION

1.1 Military Geographic Institute of Chile (IGM)

The Military Geographic Institute of Chile (IGM) was founded in the year 1922. Since that date it has been the 'official body', representing the State of Chile, responsible for establishing the basic geographic information covering Chilean Territory.

Since its creation the IGM has created various types of cartographic information covering the whole of the country, this being at different scales and 99% of which is in digital format. The regular cartography at 1:50,000 scale is the basis for the development of other cartographic coverage at smaller scales (1:250,000 and 1:500.000). Moreover, urban digital cartography has also been developed (1:1,000 to 1:5,000) for a significant number of the cities in Chilean territory.

Currently the IGM is working on different projects in order to optimize the digital cartographic information by means of a process of checking and verifying the data contained in the cartography and storage at the Geo databases, in order to prepare it appropriately, both for processes related to its use in Geographic Information Systems and for publication and printing.

In addition to its efforts to create an adequate geodesic and cartographic set of information, the IGM is constantly cooperating with various initiatives both at national and international levels, by means of its contribution to basic geospatial data. At a national level there is adequate cooperation with other organisations possessing similar characteristics, such as the Hydrographic and Oceanographic Service of the Navy, the Aerophotogrammetric Service of the Air Force and the Center for Natural Resources Research.

The role of the IGM extends beyond the initially mentioned, represents the State in international scientific organizations related to geosciences (IPGH, UGI, IUGG, ICA, ISPRS), is an active member of the SNIT, is linked member of project for national geographic standardization INN-SNIT, by mandate of the NGA runs MGCP cartographic projects, is an active part of the Project inter-operability of Armed Forces and finally, within its organizational structure has a dedicated research and development technical unit.

1.2 Principles of airborne gravimetry

Airborne gravity measurements have since the early 1990s developed into a reliable production system to accurately measure the gravity field of the earth from aircraft and with the recent GOCE long wavelength global gravity field models, airborne gravity field mapping has become even essential to determine the medium wavelength features of the gravity field, and thus a precise geoid (Forsberg et al., 2015). In addition to that, today airborne gravimetry is a versatile technique to quickly collect gravity data over large regions, where terrestrial gravity data are sparse and/or of poor quality for use in geoid determination. (Sjeoberg, 2011)

Airborne measurement of gravity has been a goal for geodesy and geophysics for many years, in order to serve geodetic needs (such as geoid determination) and also to provide efficient and economic mapping of gravity anomalies for geophysical exploration. (Forsberg and Olesen, 2010). For geodesy, the need for airborne gravity is more large scale, with airborne gravity providing not only an obvious means of gravity field data over large, inaccessible regions, such as polar and mountainous areas, but also an opportunity for seamless surveys across land and marine areas, giving the possibility of accurate geoid models across coastal zones, useful for both geodetic surveying and oceanographic determination of mean dynamic topography (Forsberg and Olesen, 2010). In addition, satellite gravity missions, such as CHAMP, GRACE and GOCE, and airborne gravity campaigns in areas without ground gravity will enhance the present knowledge of the Earth's gravity field. (Kern et al., 2003)

1.3 Use of airborne gravimetry for geoid determination

There are different methods for geoid determination using airborne gravimetry, one of them by Serpas and Jekeli (2005) proposed a method for local geoid determination from airborne vector gravimetry concluding that the horizontal components of the gravity vector improved the quality of the geoid, which can be determined to accuracy better than 10 cm.

In another study developed by Kearsley et al. (1998), it was proved that the results of comparisons of the geoid heights at on-shore geometric control showed that the geoid heights computed from the airborne gravity data matched in precision those computed using the marine data, supporting the view that airborne techniques have enormous potential for mapping the unsurveyed areas between the land-based data and the off-shore marine or altimetrically derived data.

In general, the geoid model is a surface (N) which describes the theoretical height of the ocean and the zero level surface on land. The geoid is required to obtain orthometric height H ("height above sea level") from GPS by

$$H = h^{GPS} - N \quad (1)$$

where h^{GPS} is the GPS ellipsoidal height, and H the orthometric height.

1.4 Aerogravity previous survey projects

Many countries and areas have been involved in projects related to the determination of local geoid by combining EGM08 and airborne gravity, generating plenty of papers, some examples were the geoid for Taiwan (Hâajkovâa, 2010), Arctic ocean of Canada and Alaska (Forsberg and Brozena, 1997), European Nordic countries (Marchenko et al, 2002). In addition, several national geoid models have been done from airborne surveys in recent years such as Malaysia, Mongolia, Indonesia, United Arab Emirates, Nepal and a geoid model of the UK and Ireland (Forsberg et al., 2003 – 2009 - 2014)

Many of these projects have been led by DTU Space that is Denmark's national space institute, a research organization with the basic funding and mandate to carry out space research. In collaboration with different universities, scientific or international organizations they have developed different aerogravimetry projects to model regional geoids as can be seen in the following list:

Country/Region	Year	Organizations	Aircraft
Malaysia	2002-3	JUPEM/GlobalTrak	AN38 aircraft
Mongolia	2004-5	ALAGAC/MonMap/NGA	Twin-Otter and Cessna Caravan
Ethiopia	2006-7	Ethiopian Mapping Agency/NGA/U Edinb	Cessna Caravan
Indonesia	2008	Bakosurtanal/NGA	Cessna Caravan
United Arab Emirates.	2009	Military Survey Department of the United Arab Emirates	Beech King Air 350
Nepal	2010	Nepal Survey Department / NGA	Beech King Air
Nordic and Baltic countries	1996	Nordic Commission for Geodesy NKG	

Table 1: Projects led by DTU Space.

2. DTU-SPACE/IGM/NGA, NORTHERN CHILE GEOID MODEL FROM AIRBORNE AND SURFACE GRAVITY PROJECT.

2.1 Background

The cooperation of National Geospatial and Intelligence Agency (NGA), Denmark's National Space Institute (DTU-Space) and University of Bergen with experience from previous and numerous surveys in polar areas and countries, has generated the opportunity to give Chile a new geoid model. The first stage in the northern area of the country was done with the participation of the Chilean Military Geographic Institute (IGM), performing the field support, logistic and some of the geodetic department members participated actively in the project.

As main characteristics the model is a combination of surface, airborne and satellite gravity and terrain models. The first campaign was held during October 2013 and the equipment was shipped to Chile with the help of the Danish Embassy in advance. The aircraft used was a Beech King Air 350i aircraft from the Chilean company Aviasur that can be seen in Fig.1.



Fig. 1. IGM/DTU-Space team and Aircraft Beech King Air 350i for the northern Chile geoid 2014 Project. In this picture can be seen Dr. Jens Emil from Technical University of Denmark, the IGM Principal Col. Jose Riquelme and the head of Geodetic Department Maj. Julio Neira.

Due to political restriction the flight tracks did not consider pass the border with Peru, Bolivia and Argentina as can be seen in Fig.2 and was completed the half of the country up to the city of Concepcion.

The Chilean geoid was computed in a global vertical reference system, without fits to the Chile GPS-levelling data (due to insufficient and no updated GPS-levelling data available). The main reason of this, is due to the destruction of the network due to recent earthquakes that have affected the area. In Fig. 3 can be seen the Chilean leveling data from the national network.

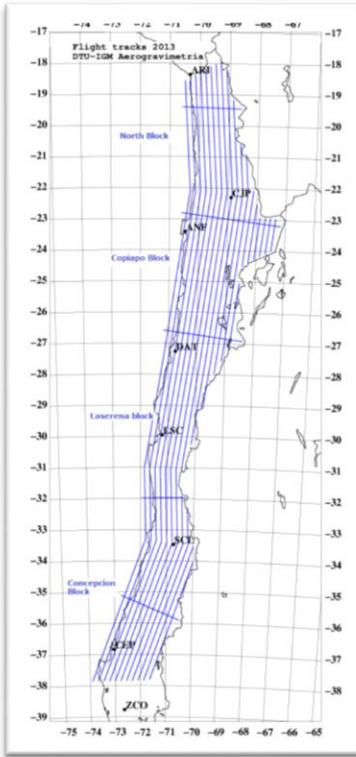


Fig. 2. Flight Tracks Northern Chilean Campaign (2013) NGA/DTU/IGM Aerogravimetry

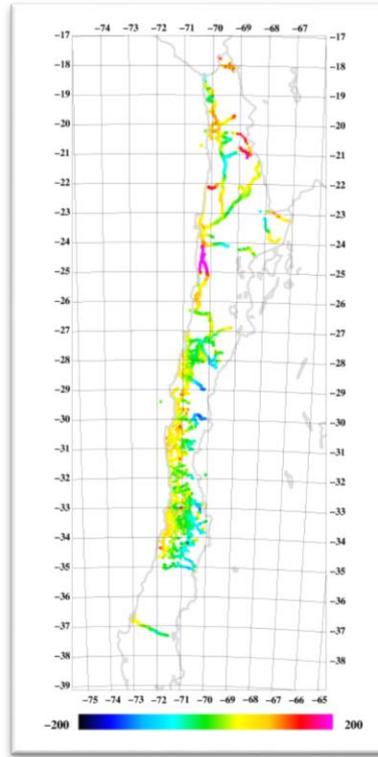


Fig. 3. Chilean leveling data from the national network.

The Chile geoid computations was done in connection with a workshop on airborne and strapdown inertial gravity held at the Astronomical Observatory in the city of Porto in Portugal on May 12-15, 2014, with support of prof. Luisa Bastos and with the participation of one Military Geographic Institute team member, Ing. Sergio Rozas. The primary purpose of the workshop was for processing and evaluating of airborne iMAR RQH IMU data collected along with the primary airborne data (LCR) during the Chile field survey. The IMU gravimetry data, processed by TU Darmstadt, was used to fill voids in the LCR data around aircraft turns using a draping technique.

2.2 Gravimetric geoid computation

The Chile gravimetric geoid was computed by the use of GRAVSOFIT system, which is a set of FORTRAN routines developed through many years of research and project work at DTU-Space and Niels Bohr Institute of the University of Copenhagen (Forsberg, 2008).

The Chile geoid has been computed by a "remove-restore" technique, where a spherical harmonic earth geopotential model (EGM/GOCE combination) is used as a base, and the geoid is computed from the global contribution N_{EGM} , a local gravity derived component N_2 , and a terrain part N_3 .

$$N_{grav} = N_{EGM} + N_2 + N_3 \quad (2)$$

The spherical harmonic expression as a function of latitude, longitude and height is of form:

$$N(\phi, \lambda, r) = \frac{GM}{R\gamma} \sum_{n=2}^N \left(\frac{R}{r}\right)^n \sum_{m=0}^n (C_{nm} \cos m\lambda + S_{nm} \sin m\lambda) P_{nm}(\sin \phi) \quad (3)$$

where GM, R and γ are earth parameters.

For the EGM08/GOCE models used, involves a very large set of global satellite data and regional (average) gravity data from all available sources, both open-file and classified provided by the NGA. Some of them can be found on the link <http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html>.

The EGM08 model is incorporating GRACE satellite data, which determines the error spectrum of the EGM08 up to spherical harmonic degree 80. New satellite data from the GOCE mission have been made available by the European Space Agency, data and details can be found in the link www.esa.int/goce.

For the Chile geoid the latest GOCE spherical harmonic model was used (“Direct” Release 4 model), complete to degree and order 260. The EGM08 field has been updated with the GOCE data according to:

- EGM08 used unchanged in spherical harmonic degrees 2-80, and from 200 up
- GOCE R4 direct model used in band 90-180
- A linear blending of the two models done in bands 80-90 and 180-200

The mixed spherical harmonic model (termed EGM08/GOCE) has here been used to spherical harmonic degree $N = 720$, corresponding to a resolution of 15’ or approximately 28 km. This choice of resolution is based on experience from DTU geoid projects in France (Auvergne), Malaysia, and Nepal, and appears to be a good ”trade off” between the full resolution of EGM08 (degree 2160) and the local gravity data.

Because the full-resolution gravity data used in the construction of EGM08 are classified, there is no good information on the quality of the errors in EGM08 at the short wavelengths, and only 15’ mean gravity data are assumed to be underlying EGM08 in South America. All spherical harmonic computations were done in a grid using the geocol17 program in grid mode.

The terrain part of the computations were based on the RTM method, where topography are referred to a mean elevation level, and only residuals relative to this level is taken into account. The mean elevation surface were derived from the SRTM height model through a moving average filter with a resolution of approximately 37 km. The difference in resolution between

reference field and RTM is not a theoretical issue, as the remove-restore method takes any “double accounted” topography into account fully.

The method for the gravimetric geoid determination is spherical FFT with optimal kernels. This is a variant of the classical geoid integral (“Stokes integral”), in which there is a proper weighting of the long wavelengths from EGM08 and the shorter wavelengths from the local gravity data. Mathematically it involves evaluating convolution expressions of the form:

$$N_2 = S_{\text{ref}}(\Delta\varphi, \Delta\lambda) * [\Delta g_2(\varphi, \lambda)\sin\varphi] = F^{-1}[F(S_{\text{ref}})F(\Delta g\sin\varphi)] \quad (4)$$

Here S_{ref} is a modified “Stokes” kernel, $\Delta g_2 = \Delta g - \Delta g_{\text{EGM}}$ is the EGM08GOCE-reduced free-air gravity anomalies, and F is the Fourier transform operator. (Porto Workshop, 2014)

The northern Chile geoid was computed on a grid of $0.02^\circ \times 0.025^\circ$ resolution (corresponding to roughly 2×2 km grid). The area of computation is 39°S to 17°S and 75°W to 66°W , covering a major part of the Pacific Ocean offshore Chile as well.

The computations have been based on least squares collocation and Fast Fourier Transformation methods. The FFT transformations at the 5 km resolution involve 880×360 grid points. The geoid was subsequently refined to 2 km resolution in the terrain restore step. (Porto Workshop, 2014)

The data are gridded and downward continued by least squares collocation using the planar logarithmic model. A number of GRAVSOFTE programs were involved in the process (gpcoll, spfour, gcomb, geiop).

Several geoid models were computed, either by simple set ups based on surface data only, or more elaborate setups incorporating full three-dimensional handling of airborne and surface gravity data.

The final gravimetric geoid solution was computed by the following steps:

1. Subtraction of EGM08GOCE spatial reference field.
2. RTM terrain reduction of surface gravimetry, after editing for outliers.
3. RTM terrain reduction of airborne gravimetry.
4. Reduction of DTU-10 satellite altimetry in ocean areas away from airborne data.
5. Downward continuation to the terrain level and gridding of all data by least-squares collocation using a $1^\circ \times 1^\circ$ moving-block scheme with 0.6° overlap borders.
6. Spherical Fourier Transformation from gravity to geoid.
7. Restore of RTM and EGM08GOCE effects on the geoid.

The above scheme technically results in a quasigeoid, and a correction based on 2 km-resolution height and Bouguer anomaly grids was added in the end to obtain the classical geoid. An alternative setup, producing directly the classical geoid using the Helmert condensation method, was also implemented and tested, and gave similar results. No real evaluation of different geoid results by precise GPS-levelling was possible, due to the limited accuracy of the available GPS levelling data provided by IGM.

Based on experience in other regions the general accuracy of the geoid is around 10 cm, and larger errors in the border regions, where data in neighboring countries are absent (data in these regions are implicitly taken from EGM2008).

No formal error propagation has been done, though, and with the long, narrow shape of Chile, and the very rough gravity field, the error estimate might be too optimistic. To improve the geoid, more data should be added in the border zones of neighboring countries, especially Argentina.

2.3 Data use and Quality control for the geoid computation

The Chile geoid is based on the following data:

1. DTU airborne gravity data, augmented with additional IMU data from TU Darmstadt (processed by D. Becker), using a draping technique.
2. Land gravity from IGM compilations
3. DTU10 global gravity anomalies from multi-mission satellite altimetry. (Only in the open ocean area).
4. SRTM 30" DEM data for the region.
5. EGM08 and GOCE RL4 satellite data.

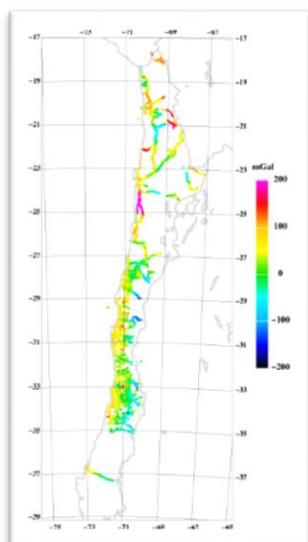


Fig 4. North Chile IGM land gravity data used for the geoid determination. Colors show the free-air anomalies.

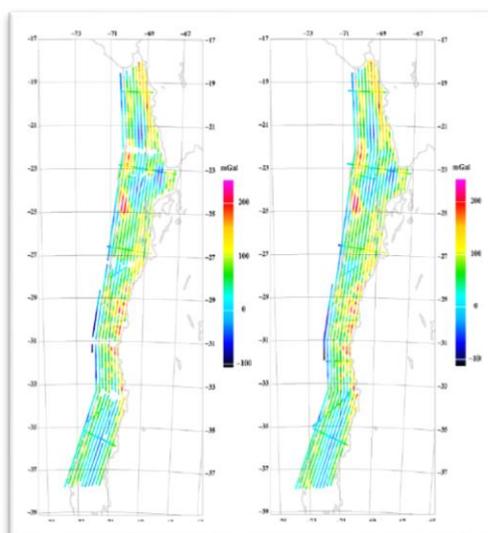


Fig. 5. Airborne gravity data. Left: LCR data processing, with gaps at turns Right: new merged LCR/IMU data for final airborne survey results.

The available data from the airborne and surface sources were quality controlled through plotting of the EGM08GOCE and terrain reduction residuals, showing a few (~ 1%) obvious surface gravity outliers, which were deleted in the final geoid processing.

The draping method for extending the original processing of Lacoste and Romberg (LCR) gravimeter data is basically a linear bias fill-in technique where the LCR data are kept unchanged, and the Kalman-filter iMAR IMU data are then used to fill in voids at minor turns, and extend the airborne gravity data closer to major turns. The noise in the IMU data are mainly in the form of long-period drifts, which are well constrained by the LCR data. The precise error characteristics of the IMU vs LCR data will be quantified in future studies, but the good agreement of the two datasets after draping are confirmed by cross-over error analysis, cf. Table 1, where only a very small degradation of accuracy is seen when incorporating the IMU before the downward continuation process. It is seen that the “best” estimate of error for the airborne data (rms crossing/ $\sqrt{2}$) is 2.5 mGal, a very satisfactory result.

	Mean	r.m.s. x-overs	r.m.s. error
LCR free-air anomaly data (April 2014, 57 x-overs)	1.1	5.0	3.4
LCR after terrain and EGM corrections	-1.0	3.6	2.6
LCR after continuation to 5600 m	-0.8	3.5	2.5*
LCR/IMU merged data set (May 2014, 68 x-overs)	0.7	5.2	3.7
LCR/IMU after terrain and EGM corr.	-1.0	3.9	2.8
LCR/IMU after continuation to 5600 m	-0.8	3.5	2.5

*this value in the original LCR processing document was in error due to a x-ing software error

Table 2: Estimated errors of the airborne gravity data (Cross-over analysis mGal).

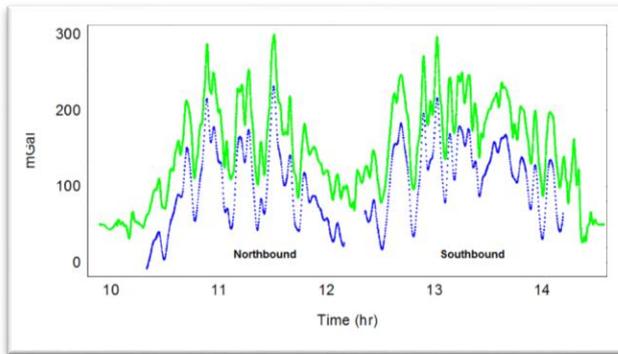


Fig. 6. Example of IMU data (green) and LCR data (blue), day 288. IMU data shifted for clarity.

Many outliers appeared to be caused by coordinate key punching errors. The overall EGM/GOCE and RTM terrain “reduce” statistics for the data are shown in Table 2. Overall this statistics is good, with relatively small bias and standard deviation for all data sets.

Unit: mGal	Mean	Std.dev.
IGM Land gravity data (3548 selected pts)	34.7	55.5
Land gravity minus EGM08GOCE and RTM	2.9	19.9
Airborne gravity data (27596 pts)	59.7	52.3
Airborne minus EGM08GOCE and RTM	0.2	15.7
DTU10 altimetry gravity (5768 selected pts)	-31.8	70.3
DTU10 data minus EGM08GOCE and RTM	0.0	7.5

Table 3: Statistics of the remove steps in the Chile gravimetric geoid computation (mGal).

Final geoid statistics are shown in Table 3.

Unit: m	Mean	Std.dev.	Min.	Max.
Reduced geoid (after spherical FFT)	0.00	0.22	-3.36	1.95
RTM restore effects (computed by FFT)	0.00	0.13	-0.64	1.27
Correction quasigeoid to geoid	-0.35	0.57	-2.72	0.14
Final gravimetric geoid statistics	25.43	10.23	8.26	48.32

Table 4: Statistics of the restore quantities on the geoid.

The final geoid covers the region 39-17°S, 75-66°W, and has a resolution of 0.02° x 0.025°. The internal reduced gravity grid has a resolution of 0.05°, as the data density does not warrant a more detailed gridding. The airborne and surface gravity data were gridded by spatial least squares collocation (gpcol1, using covariance parameters $\sqrt{C0} = 24$ mgal, $D = 6$ km, $T = 60$ km). A priori errors assumed were 3 mGal for both the airborne data and the surface data (averaged in 0.02° blocks).

2.4 Use of the GRID

With the data grid provided by the project, and after preparing the data properly, through the use of the software Surfer 8, Global Mapper and Matlab, the author of this technical report generated different outputs that have not been produced by the IGM yet. The purpose of the generation of this output is allow to non-specialist figured the form of a geoid in a visual form.

The plot in Fig.7 shows the northern Chile geoid and Fig.8 shows a wireframe map 3D of the same area.

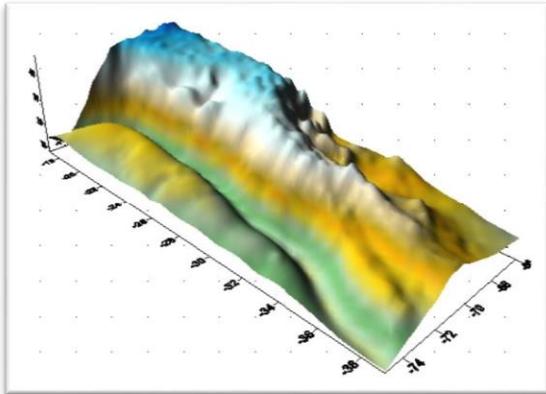


Fig. 7. Plot 3D of the Northern Chile geoid 2014 (Surfer output).

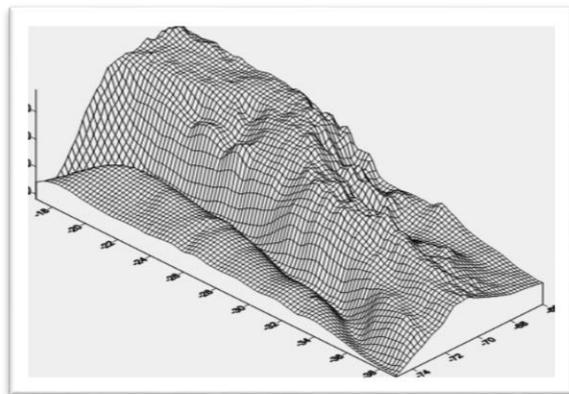


Fig. 8. Wireframe map 3D of the Northern Chile geoid 2014 (Surfer output).

It has been the first time that IGM generates a plot of a local Geoid of the north of the country.

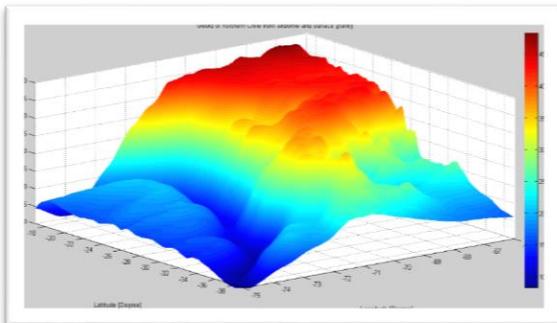


Fig. 9. 3D Northern Chile geoid 2014 (Matlab output with function surf & shading interp)

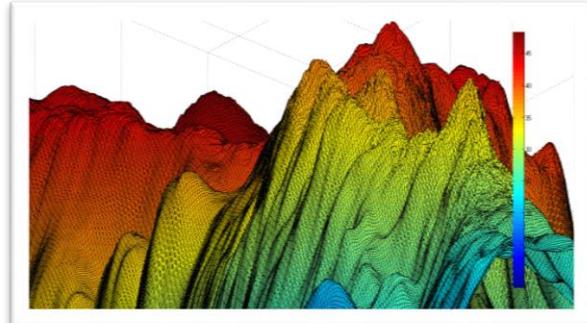


Fig. 10. Zoom 3D Northern Chile geoid 2014 (Matlab output with function surf).

3. COMPARISON OF NEW GEOID TO EGM2008

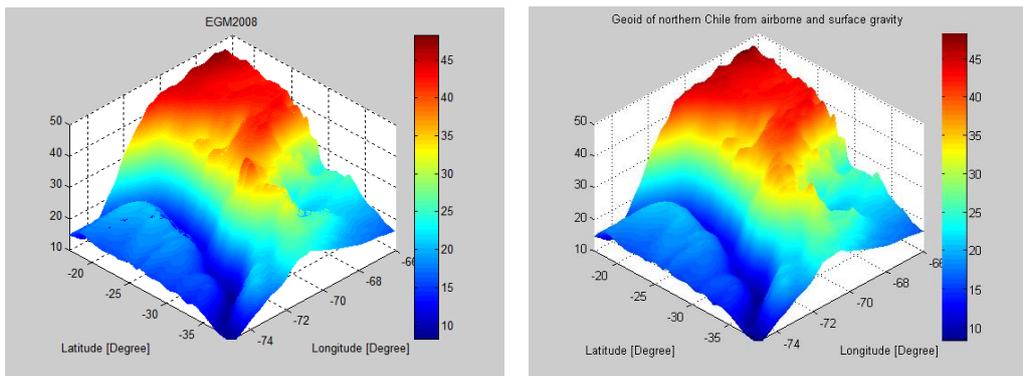


Fig. 11. Left: EGM2008 Geoid. Right: Chile Geoid.

In order to compare the Northern Chile Geoid with the EGM2008 as can be seen in Fig. 11, it has been established the difference between both shown in Fig. 12.

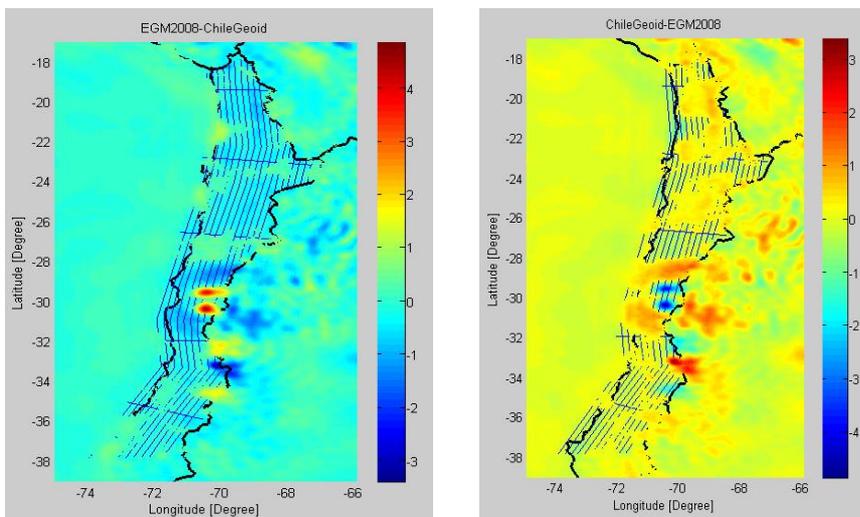


Fig. 12. Difference between Chile Geoid and EGM2008. Left: EGM2008 minus Chile Geoid. Right: Chile Geoid minus EGM2008.

As can be seen in Fig. 13 closer to the Chilean land borders it is seen large differences to EGM2008, large effects are seen along the border of Argentina, where lack of data will make the geoid uncertain.

The apparent outliers around 30 S is real (Fig. 13), and appears to be due to errors in EGM2008 and not related to data error in the Chile Geoid, the peaks are not in the same flight track as can be seen in Fig.14. Large differences are seen especially in very high mountains.

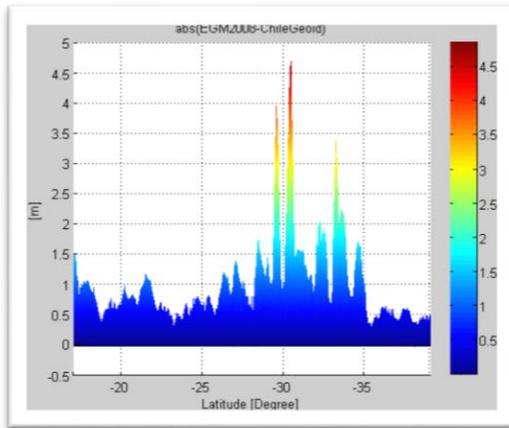


Fig. 13. Absolute value of the difference between Chile Geoid and EGM2008.

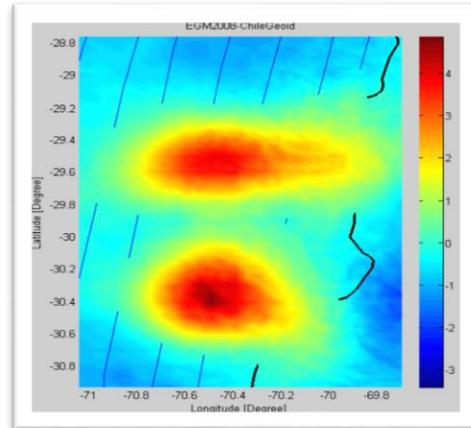


Fig. 14. Zoom of the peaks in the difference between Chile Geoid and EGM2008.

4. INTERPOLATION FUNCTIONS IN MATLAB FOR ANY LATITUDE AND LONGITUDE.

The final geoid “geoid2.gri” can be interpolated with a user-friendly interpolation matlab function generated by the author, as shown in Fig.15. The function shows in 3D $1^\circ \times 1^\circ$ the Geoid Undulation for the input Latitude and Longitude.

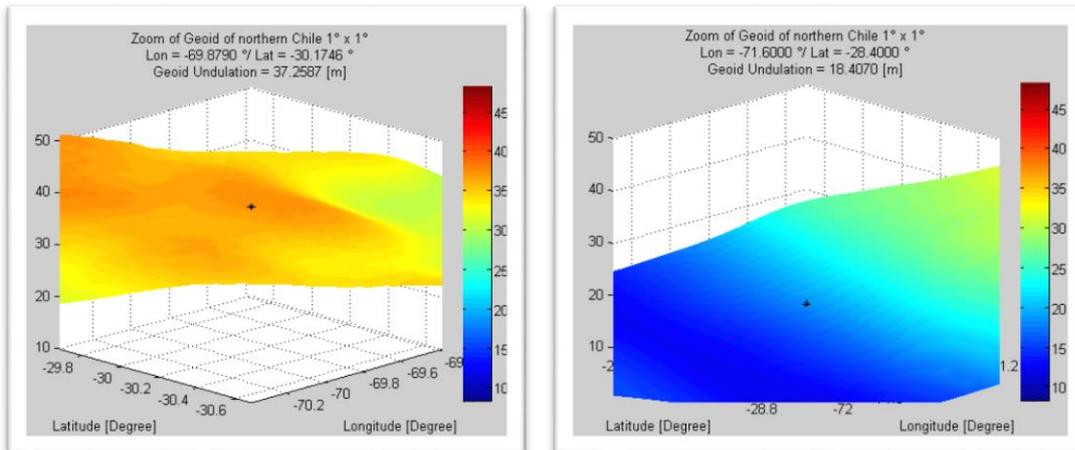


Fig. 15. 3D View of the interpolation function for any Latitude & Longitude $1^\circ \times 1^\circ$

5. CONCLUSIONS

Airborne gravity measurements have since long time used to accurately measure the gravity field of the earth from aircraft and with GOCE global gravity field models, airborne gravity field mapping has become even essential to determine features of the gravity field, and thus a precise geoid.

Today airborne gravimetry is an important technique to quickly collect gravity data over large regions, where terrestrial gravity data are sparse and/or of poor quality for use in geoid determination.

Airborne measurement of gravity has been a goal for geodesy and geophysics for many years, in order to serve geodetic needs (such as geoid determination) and also to provide efficient and economic mapping of gravity anomalies for geophysical exploration.

For geodesy, the need for airborne gravity is more large scale, with airborne gravity providing not only an obvious means of gravity field data over large, inaccessible regions, such as polar and mountainous areas.

Satellite gravity missions, such as CHAMP, GRACE and GOCE, and airborne gravity campaigns in areas without ground gravity will enhance the present knowledge of the Earth's gravity field.

Many countries and areas have been involved in projects related to the determination of local geoid by combining EGM08 and airborne gravity. As a main characteristics the model is a combination of surface, airborne and satellite gravity and terrain models.

Due to political restriction the flight tracks did not consider pass the border with Peru, Bolivia and Argentina and is very difficult develop international joint projects.

Unfortunately the IGM GPS-levelling data appears to have relatively large errors (due to insufficient and no updated GPS-levelling data available), and it is therefore difficult to use these data. The main reason of this, is due to the destruction of the network due to recent earthquakes that have affected the area.

The northern Chile geoid was computed on a grid of $0.02^\circ \times 0.025^\circ$ resolution (corresponding to roughly 2×2 km grid). The area of computation is 39°S to 17°S and 75°W to 66°W

Based on the experience and collocation error estimates from other regions with similar data quality and coverage, the geoid error is estimated to be on the order of 10 cm for most of the region, with larger errors closer to the Chilean land borders. It is seen that large differences to EGM2008 exist in these regions, also corrections to the geoid are huge due to mountains and

large differences are seen especially in the mountains, in addition, large effects are seen along the border of Argentina, due to the lack of data.

The apparent outliers around 30 S appears to be due to errors in EGM2008 and not related to data error of the airborne gravity data used in the Chile Geoid, but can be analyzed in depth in a future study.

The cooperation of National Geospatial and Intelligence Agency (NGA), Denmark's National Space Institute (DTU-Space) and University of Bergen has generated the opportunity to give Chile a new geoid model.

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