TERRA: A feasibility study on local geoid determination in Bolivia with strapdown inertial airborne gravimetry.

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Abstract. Strapdown inertial airborne gravimetry as a practical and feasible tool for local and regional geoid determination is under research at the Institute of Geomatics (IG). Within the framework of the Spanish-Bolivian cooperation project TERRA, between the Instituto Geográfico Militar of Bolivia (IGM) and the IG, a feasibility analysis on geoid determination in Bolivia by means of INS/GNSS integration is being carried out. TERRA includes, among other goals, the specification of the geoid model that best fits the needs of Bolivia from a global point of view. Simulations in the spatial and spectral domain for GNSS and INS data will allow for an assessment of the performance of the technology. In addition, an empirical covariance model of the gravity anomalies has been derived from CHAMP-data, so that realistic simulations will be carried out. The contribution of other new satellite gravity missions —GOCE— will be also evaluated. Actual gravity data will be obtained from a test flight over various topographic conditions to analyze the system response to a highly variable gravity signal. The data will be also processed to empirically verify the simulation results. The aim of this paper is to introduce the project and present some preliminary results.

Keywords. Strapdown inertial airborne gravimetry, INS/GNSS integration, geoid specification, simulation, CHAMP, GOCE

1 Introduction

Around the middle of the last decade, the Instituto Geográfico Militar of Bolivia implemented a qualitative improvement of the national geodetic infrastructures. This general aim included the establishment of a GNSS-based geodetic network, with passive and active stations and coordinates in the SIRGAS reference system, the determination of a low-medium resolution digital elevation model (DEM) for the whole country, the revision of the leveling network and its extension to new lines and to the permanent stations, the expansion of the gravimetric network and, finally, the determination of a high resolution local geoid for Bolivia.

Within the framework of this main project, the Institute of Geomatics is conducting a feasibility study on the use of strapdown inertial airborne gravimetry for geoid determination, under both technical and economical points of view.

2 State-of-the-art

Since the early stages of gravity measurement for geoid determination, airborne gravimetry has been considered as the optimum technology for covering a huge area with a reasonable dense set of values. Stable platform-based modified gravity meters have been tested in some experimental flights (Brozena et al., 1997) and even for production-level missions (Klingelé et al., 1994).

Strapdown inertial airborne gravimetry has been a matter of research since the last decade, see (Schwarz and Wei, 1998) and (Forsberg et al., 1996). Both approaches show apparently similar performances (Glennie et al., 2000). However, to the best knowledge of the authors, very few geoid determination campaigns have up to now been conducted with this technology, although it has slight operational advantages and a lower cost of purchase —not operating— costs (Bruton et al. 2001). Those test flights have demonstrated an accuracy of to 2-3 cm in the geoid undulations, limited to the high frequencies (Schwarz and Wei, 1998); the low and medium frequency content are usually derived from global geopotential models, which adds several decimeters to the error budget.

Gravity-devoted satellite missions are intended to partially fill the gap between the accurate long wavelength provided by global models and airborne-derived data. The CHAMP mission will provide data with a maximum resolution of 250 Km (Reigber et al., 2003); GRACE-derived data will have reasonable accuracy for resolutions below 150 Km (García, 2002) and the future European mission GOCE (ESA, 1999) will recover wavelengths even below 100 Km.

3 The TERRA project

The aim of TERRA is to give answers to the following questions: What kind of geoid (i.e. specification of the geoid) fits the general needs of Bolivia? What budget of geodetic infrastructures are required for the determination of the geoid by means of the technology under research? Which should be the features —specification— of the inertial measurement unit (IMU) or combination of them to be used in order to meet the required resolution and accuracy? To what extent will the combination of airborne and satellite gravimetry avoid or minimize the need for terrestrial campaigns? And, last but not least, What kind of earth observation mission should be planned in order to make the economical effort become affordable for the country?

The key factor in the TERRA project is the comparison between the spectral characteristics of the INS/GNSS assembly-derived geoid and its combination with satellite data and the geoid specification for Bolivia.

3.1 Geodetic and social context analysis

One of the main objectives of the study is to establish the features of the geoid model for Bolivia. This model should meet the needs of the

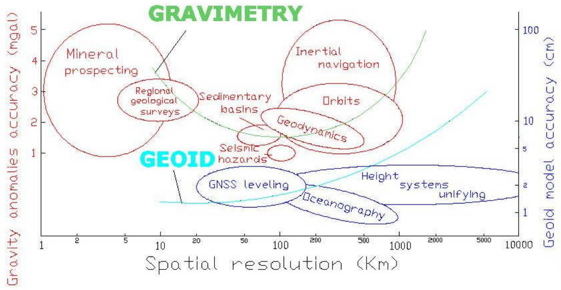

Figure 1: Preliminary geoid specification.

country from a general point of view, that is, not only technical but also socioeconomic reasons.

The geoid specification will take into account the opinion of local potential users and will be supervised by Prof. Carl Christian Tscherning. The requirements for the various depicted applications are taken from (ESA, 1999).

Documentary research and personal talks with members of the Marine and Photogrammetric Service of the Bolivian Army lead to a preliminary draft of the geoid specification shown in Figure 1. Natural resources have a strategic interest for the country; therefore, special attention is paid to the suitability of gravity data for mineral prospecting from local to basin scales. The geoid specification reflects the need of Bolivia for a unified physical height system —a must in hydrographic engineering, i.e. for channel planning—. The proposal takes also in account the advantages of turning GNSS into a leveling tool for engineering issues.

3.2 Test flight

In order to empirically assess the results that come from simulations, two experimental complementary flights are planned.

The first one is intended to cover a reasonably extensive area and will follow a photogrammetric path near from La Paz, with main direction N - S; it will allow for cross-over checking and for external comparison with upward-continued independent data. Although the straight lines are no longer than 150 Km, the topographic variation of the overflown terrain will be significant. Its trajectory can be seen in Figure 2.

The second flight has a different purpose. It will consist of a long straight line between La Paz and Ixiamas, in the Amazonic rainforest. Its

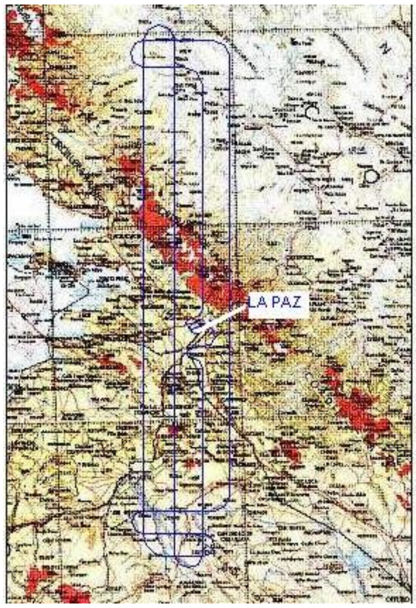

Figure 2: Trajectory of flight 1.

Figure 3: Trajectory of flight 2.

length, about 400 Km, will allow for an empirical estimation of the maximum wavelength that can be recovered with the Institute of Geomatics' INS/GNSS system, within a certain range of accuracy. The final purpose is to evaluate how would this value combine with the current satellite gravimetry resolution capacities. An added value is that it will overfly the whole range of topographic signatures, from 4000 m height in La Paz airport (El Alto) to more than 5000 in the Andes, north from La Paz, and then going down to 500 in the rainforest. Some interesting conclusions are therefore expected from this flight, whose planned trajectory is shown in Figure 3.

3.2.1 The INS/GPS system

The device to be flown is called TAG (Trajectory, Attitude and Gravimetry), that mainly consists of an IMU/GNSS assembly with fully operational capabilities. Figure 4 shows the system, with the IMU inside the small metallic case in close-up. The IMU will be installed in an Aluminium bench (Figure 5 shows an assembly of the present IMUs owned by the IG, actually placed in the bench). The inertial sensor is a Northrop Grumman —former Litton— LN-200. For more information about the system the reader is referred to (Wis et al., 2004).

3.2.2 Data processing

A preliminary processing of the trajectory will be carried out by means of an extended Kalman Filter with smoothing. The extension accounts for a state for the gravity anomaly.

Nevertheless, a new geodetic approach is under development at the IG. It is intended to avoid the problems of Kalman Filter when dealing with gravity, whose correlation is basically space- and not time- dependent. The new approach takes advantage of cross-over data, ZUPT, CUPT and any other information that may be supplied to the system. More information about this topic can be found in (Colomina and Blázquez, 2004) and (Térmens and Colomina, 2004).

3.3 Simulations

An IMU-simulator is under development at the IG. It will allow for measuring the impact of the sensor features in the final error estimates and, for this reason, recommendations will be made about the kind of sensor assembly (accelerometers, gyros, number of IMUs or maybe the use of redundant units) to be used if a certain level of accuracy has to be reached.

Meanwhile, by using least-squares collocation (LSC), see (Moritz, 1980) it is possible to obtain error estimates of the quality of height anomalies (quasi-geoid heights) from various combinations of data and from various types of gravity field

Figure 4: The TAG System

variations. It is only necessary to know the position, type and error estimate of the data and its statistical characteristics (covariance function). The GRAVSOFT package (Tscherning et al., 1992) have been used to execute the computations described below.

Files concerning the simulations can be found in http://cct.gfy.ku.dk/bolivia/bolivia.htm.

In the preliminary stages of the project, we have computed error-estimates for a part of SW of Bolivia. The topography has been obtained from DTM2002.

CHAMP-data (Howe and Tscherning, 2004), see Figure 6, were used to generate gravity

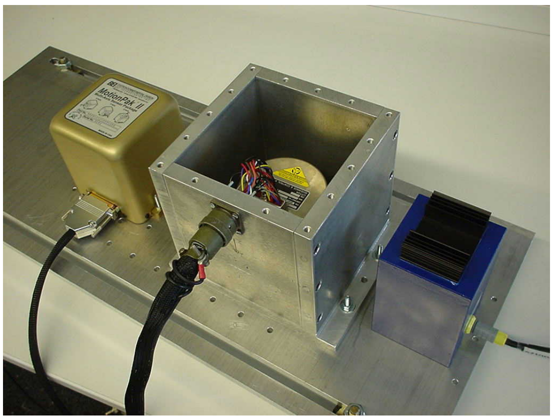

Figure 5: IMU Bench.

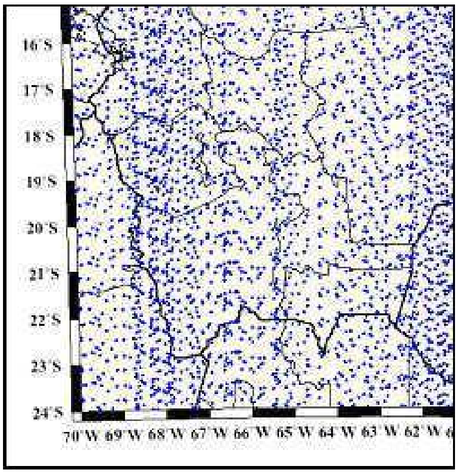

Figure 6: Champ ground track, 1 year, SW of Bolivia.

anomalies at an altitude of 300 m above the terrain in order to simulate 32400 airborne gravity data. The creation of this data-set was in principle not necessary since the simulations —as mentioned above— may be carried out without using real data. Only positions and error-estimates of the data are needed. As a reference field, EGM96 to degree 24 was used. The effect of the residual terrain was also subtracted from the CHAMP data.

These data were used to generate empirical covariance functions in two sub-areas,(-24 deg. - -13 deg. in latitude and -70.0 deg. -63 deg. in longitude) one with high mountains and one in the lowland, (-24 deg. to -13 deg. in latitude and -63 deg. to -55 deg. in longitude).

The main result is that a gravity field variance of 413.5 $mgal^2$ and 1226.6 $mgal^2$ were found in the low and in the high area, respectively, for data from which EGM96 to deg. 24 and residual topographic effects have been subtracted. The value from the high area is probably underestimated. Real data are necessary in order to obtain a better value.

These values were then used in the computation of simulated error estimates of height anomalies in two sub-areas within the two areas, bounded by (-24.0 -13.0) in latitude and (-63.0 -55.0) in longitude, and (-24.0 -13.0) in latitude and (-70.0 -63.0) in longitude. About 3000 CHAMP height anomalies and 2000 gravity anomalies were used in each case.

The subtraction of EGM96 to degree 24 from

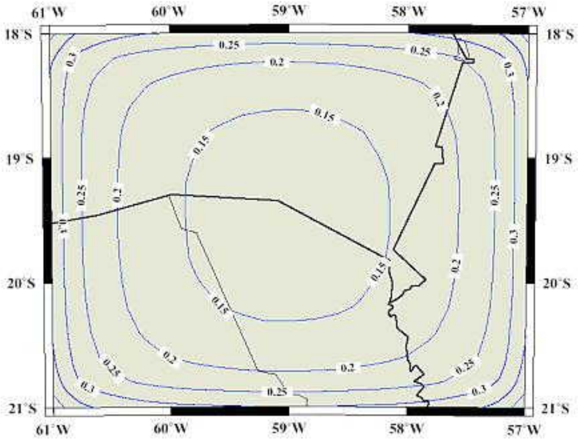

Figure 7: Error estimate for a low-height area.

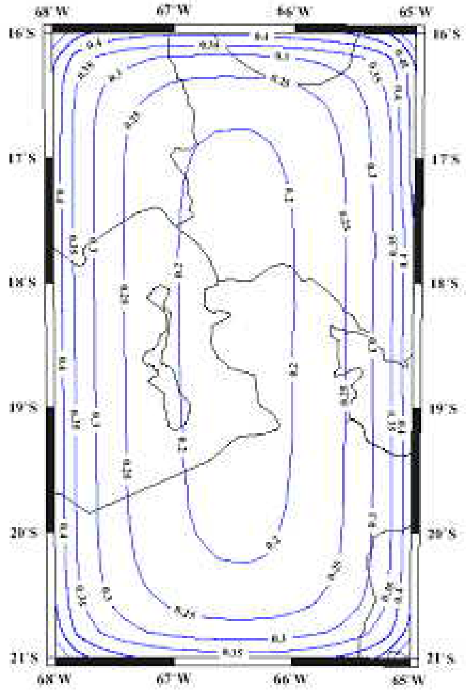

Figure 8: Error estimate for mountainous area.

the data, results in a height anomaly standard deviation of about 3 m. Using the CHAMP data without topography then permits the prediction of height anomalies with overall errors around 1 m. The error will be larger in the high area and lower in the low area.

Using gravity data with a 5' spacing in the above mentioned sub- areas, the error decreased to between 0.14 m and 0.43 m for the low area and between 0.18 m and 0.56 for the high area, see Figure 7 and Figure 8.

3.4 The contribution of the new satellite mission GOCE

Some studies have already shown that the expected resolution of the ESA GOCE mission for a centimetric geoid accuracy is at the 70 Km level (Suenkel, 2002). If the current limitation of airborne gravimetry can be extended up to this level, the combination of data from both sources might be a definite solution for production- level gravimetric geoid determination with no need for terrestrial campaigns.

Within the TERRA project, the performance of the ESA GOCE mission in combination with airborne gravimetry will be estimated by means of both an empirical and a numerical-stochastic analysis based on simulations.

4 Final remarks and further developments

A local geoid model is nowadays a necessary infrastructure. Bolivia aspires to have such a model with a certain accuracy in the following years, as a tool for development.

Given the special conditions of Bolivia in terms of size, orographic complexity, logistic problems and difficulty of access to extensive parts of the country, the Instituto Geográfico Militar of Bolivia has seen in strapdown inertial airborne gravimetry a suitable solution, which is being evaluated by the Institute of Geomatics.

The first task will be the specification of the geoid model in Bolivia.

Simulations of gravity anomaly errors from an INS/GNSS assembly in Bolivia are being conducted at the IG. The final aim is to establish the features of the system that should be used in a production flight.

Until full development of an own IMU-simulator, some performance analysis have been carried out from CHAMP-data. It can be up to now concluded that using CHAMP data combined with airborne gravity data (with 2.0 mgal mean error) spaced 5' apart it is possible to obtain height anomalies with mean errors of 0.14 m in low areas and 0.18 m in high areas. Improvements may be obtained using a DTM of higher resolution than the one used here and more dense gravity data. The use of a complete higher order reference field like EGM96 to degree 360 is not expected to give much improvement because the regional data used to construct the model is not of high quality.

Two planned experimental flights will provide realistic error estimates. They will include some cross-overs, where intrinsic accuracy of the data can be assessed; moreover, an area of Bolivia with some terrestrial gravity covering will be overflown, that will allow for external checking of the data.

Finally, the combination of GOCE and airborne gravimetry data will be evaluated. The aim is to establish the spectral validity window where both technologies can avoid the cumbersome terrestrial gravity campaigns.

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