TERRA: a cooperative feasibility analysis of airborne INS/GNSS gravimetry for geoid determination in Bolivia.

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Abstract

The Institute of Geomatics (IG) and the Instituto Geográfico Militar de Bolivia (IGM) are conducting an analysis on the feasibility of kinematic airborne gravimetry with strapdown inertial and satellite navigation technologies for geoid determination. This research is being conducted within the frame of the TERRA project which is funded with cooperation funds of the Spanish Ministry of Economy.

This paper will present the TERRA project, its goals, methodology, procedures and current status. In the methodological part we will discuss the principles of INS/GNSS gravimetry, its advantages, disadvantages and challenges. We will briefly present, as well, how airborne gravity measurements can be used for geoid determination.

In the current status of the project we will present a summary of its most relevant achievements: A geoid specification for Bolivia and the results of an experimental flight recently conducted by the IG and the IGM over the Bolivian Andes and rain forest.

Keywords: Airborne Gravimetry, Geoid Undulation, Geoid Specification, Satellite Gravimetry, Error estimation, Inertial, GNSS

1 Introduction

As a fundamental spatial infrastructure, the Instituto Geográfico Militar of Bolivia (IGM) is building the New Geodetic 3-D Reference Frame. This includes, among others, the establishment of a GNSS-based geodetic network, the generation of a low-medium resolution digital elevation model (DEM) and the determination of a high resolution local geoid for Bolivia. Within the framework of this project, the Institute of Geomatics (IG) is conducting a feasibility study on the use of strapdown inertial airborne gravimetry for geoid determination, under both technical and economical points of view.

Two main research lines are the core of the TERRA project: The technology is being evaluated through analysis of simulated and actual data.

The simulations are expected to allow the establishment of the most suitable INS/GPS system and mission design for a production-level geoid determination campaign. They will determine as well, from a theoretic point of view, the limitations in accuracy and resolution that can be expected from this technology. On the other hand, two test flights have been conducted in Bolivia. Therefore, the theoretic results will be assessed by means of actual data.

2 The technology: strapdown inertial airborne gravimetry

In the early stages of airborne gravimetry, stable platform-based modified gravity meters were used [1]. Although the inertial technology is actually older than GNSS, only after the works by Prof. Karl Peter Schwarz at the University of Calgary during the last decade, see [13] and [5], the possibility of conducting airborne gravimetry by means of an IMU/GPS assembly has gained interest. Both technologies show a similar performance [8]; some operational advantages —low purchase cost and ease of use among others— led the IG to choose this technology for evaluation for geoid determination in Bolivia.

2.1 Fundamentals

2.1.1 The concept

An INS/GNSS system mainly consists of an Inertial Measurement Unit (IMU) and a GNSS receiver, with fully operational capabilities. An IMU is an assembly of three gyroscopes, that measure angular velocities, and three accelerometers, that measure linear accelerations along the same axis. An acceleration along a particular axis can therefore be analytically obtained by means of the acceleration measurements and the rotation values. The measurement along a vertical axis would include two components: gravity and kinematic acceleration of the airplane in that direction. GNSS-derived accelerations are then used to isolate the gravity signal from the IMU measurement. GNSS data have high long-term stability but are noise in the low frequencies; IMU data show the opposite behaviour, and putting them together retains the best of each one [10].

2.1.2 Mathematical fundamentals

The mathematical formulation of the above concept, expressed in a local-level frame [12], reads:

$$\delta \mathbf{g}^l = \dot{\mathbf{v}}^l + (2\Omega^l_{ie} + \Omega^l_{el})\mathbf{v}^l - \mathbf{f}^l - \gamma^l$$

where $\delta\mathbf{g}$ is the gravity disturbance vector, γ is the normal gravity vector, $\mathbf{f}$ is the specific force, and $\mathbf{v}$ and $\dot{\mathbf{v}}$ are the velocity and acceleration of the aircraft, respectively. l denotes that the corresponding quantity is expressed in the local-level frame. Ω^l_{ie} and Ω^l_{el} are the skew-symmetric matrices containing the angular velocities ω^l_{ie} and ω^l_{el}. ω^l_{ie} is the angular velocity of Earth rotation with respect to the inertial frame, and ω^l_{el} is the angular velocity of the local-level frame rotation with respect to the Earth-fixed Cartesian frame.

Some approaches have been developed to solve this equation; three of them will be briefly discussed later in this chapter.

2.1.3 Data acquisition

In a strapdown inertial system for the acquisition of airborne gravity data the fundamental components are a GPS receiver, an inertial measurement unit (IMU) and a computer that synchronizes and registers the measurements and controls the system. The registered data is referenced to GPS time.

The system assembly that the Institute of Geomatics has used in the TERRA project (figure 1) mainly consists of a tactical-grade Northrop Grumman —former Litton— LN-200 IMU and a Novatel GPS card with fully operational capabilities. It is called TAG (standing for Trajectory, Attitude and Gravity). For more information, the reader is referred to [16].

2.1.4 Data processing

In order to correct the IMU sensors' drifts and biases with the help of GPS measurements, the classical approaches apply a Kalman filter. The integration level between GPS and IMU features the different particular approaches. In a stepwise procedure [2], kinematic accelerations are derived from GPS observations and then subtracted from the measurement of the IMU which have been previously corrected for biases and other errors by means of the GPS measurements. Alternatively, an extended Kalman filter is applied where gravity disturbance ($\delta\mathbf{g}$) is considered as an unknown [5]. A new "genuine" geodetic approach ([14], [3]), is under development at the IG. It takes advantages of additional information like cross-over data, ZUPT (Zero Velocity Update Points), CUPT (Coordinate Update Points), and any other available information and prevents from the defects of Kalman Filter when dealing with space-correlated values like gravity —or gravity disturbances—.

2.2 Challenges

Some tests on Strapdown Inertial Airborne Gravimetry for geoid determination have demonstrated an accuracy at the cm-level for wavelengths between 5 and 100 km [12]. At the same time, the ESA Gravity

Figure 1: setup of the IG's TAG system in the airplane.

field and Steady-State Ocean Circulation Mission (GOCE) satellite mission will provide global coverage data with maximum resolution below 100 km [4]. Therefore, the challenge for the TERRA project is to theoretically show the possibility of obtaining high accuracy for resolutions near 100 km in Bolivia and to establish the features of the system that would make it possible, in order to avoid the need for terrestrial gravimetry.

3 The TERRA Project

3.1 Objectives

The aim of TERRA is to assess the validity of the Inertial Gravimetry as a suitable solution for local geoid determination in Bolivia. Its first objective is to specify the geoid that best fits the general needs of Bolivia. The second objective is to determine the set of geodetic infrastructures required for the determination of the geoid by means of the technology under research. The features of the inertial measurement unit to be used and the design of the gravimetric flights in order to meet the required resolution and accuracy is another objective of the TERRA project. The contribution of the gravity-devoted satellite mission GOCE to aerial geoid determination will be studied as well. Last but not least, the economical and financial aspects of a global airborne geoid campaign will be also analyzed.

3.2 Methodology

3.2.1 Simulations

Simulations are the basis for the correct design of a global campaign for airborne geoid determination in Bolivia. Error propagation techniques allow the evaluation of the impact of some flight and system parameters on the quality of the derived quasi-geoid heights.

Four parameters have been chosen for evaluation: Flight altitude, data density —which can be considered as strip separation—, data coverage and accuracy of the calculated gravity anomalies. In any case, estimations of the absolute geoid undulation errors and —of higher interest for our research— relative geoid undulation errors have been obtained.

3.2.2 Empirical Analysis

Gravity values have been reckoned within two test flights in Bolivia. Therefore, the theoretical conclusions provided by the simulations will be assessed by means of the analysis of actual data.

This will be done through upward continuation of a priori known gravity data in Bolivia, that will allow the evaluation of the accuracy and precision of the airborne measured values.

3.3 Preliminary results

The achievements of the TERRA project will be described within this section. The current status includes a preliminary geoid specification, some estimations on quasi-geoid height error by means of simulations and partial results for the experimental flights that were conducted in September 2004 over Bolivia.

3.3.1 Geoid specification

A preliminary geoid specification has been established for Bolivia, see the draft in figure 2. It takes into account the opinion of some local potential users and is based on documentary sources on the topic. The geoid and gravity data requirements that are depicted are taken from [4]. This first geoid and gravity data specification considers the advantages of turning GNSS into a levelling tool for engineering issues and take into account the needs of Bolivia for a unified height system. High importance is also given to gravity data for geological prospecting, since it is a topic of strategic interest for the country.

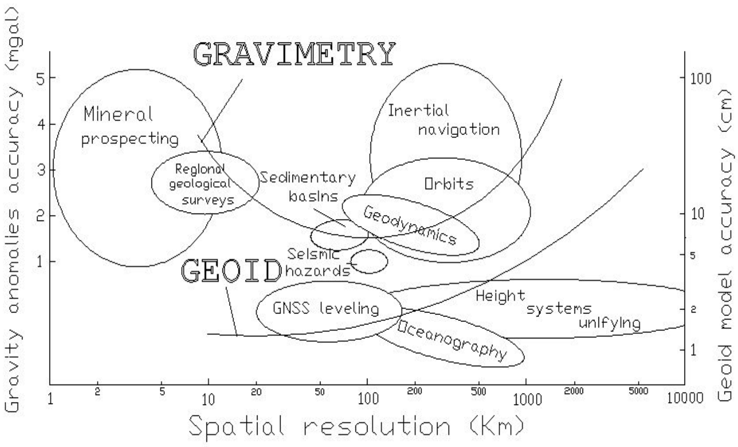


Figure 2: Preliminary geoid specification.

3.3.2 Error estimation: Simulations

In order to simulate particular flight and system configurations, synthetic positions and gravity anomaly error estimates have been generated at the IG.

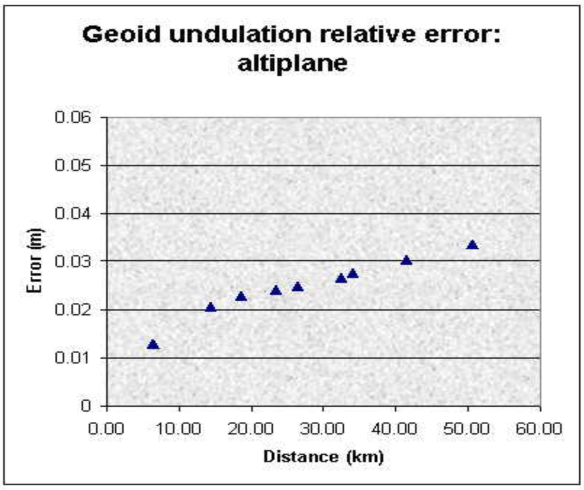
A number of different scenarios have been analyzed, by varying the four basic parameters: Flight height and data accuracy, density and coverage. Two particular cases will be discussed here. It should be remarked at this point that although the required covariance function for the gravimetric data could be derived from the actual data reckoned within the flights, an independent model has been preferred. This covariance model has been obtained from data supplied by GETECH Inc and data from the Bureau Gravimetrique International (BGI). The terrain contribution has been obtained by means of the GTOPO30 [15] DEM and, as a reference field, EGM96 to degree 360 has been used.

The first significant simulation has been conducted at the Bolivian Altiplane, (-21 to -18.5 deg. in latitude and -68.5 to -66 deg. in longitude); a flight height of 7000 m.a.s.l., a data density of 5' —around 10 km— and an error estimate of 2 mGal for the gravity anomalies are assumed in this case. A gravity field variance of 289 $mgal^2$ has been derived from the existing data. The results show a relative error at the 1 ppm level for distances up to 60 km, actually in good agreement with the geoid specification.

The second simulation considers an area located at the Bolivian rain forest (-20 to -22 deg. in latitude and -62 to -64 deg. in longitude) and the same parameters except for the flight altitude —4000 m.a.s.l. here—. A gravity field variance of 184 $mgal^2$ has been derived in this case. The results demonstrate a slightly higher error estimates. Nevertheless, they never exceed 1 ppm up to 60 km. Both results are shown in figure 3.

3.3.3 Experimental flights

Two experimental flights were conducted over Bolivia on the 20th and 21st of September, 2004. The airplane was a Beechcraft King C-90 and belongs to the Aviation Company of the Bolivian Army.



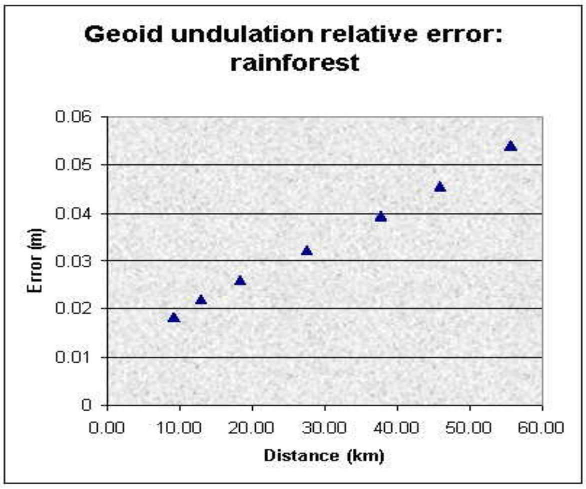
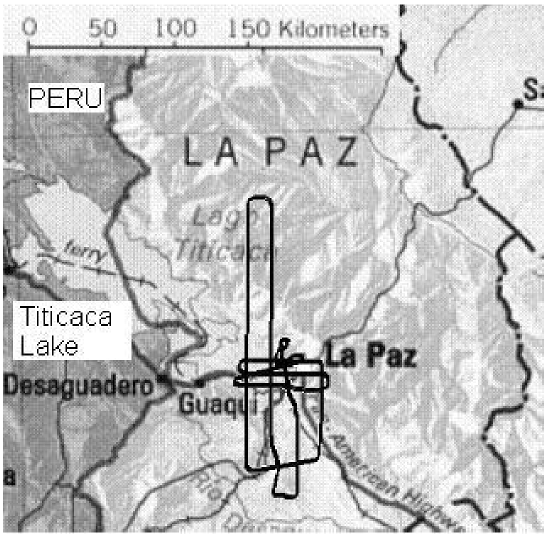


Figure 3: Geoid relative errors.

The first flight followed a photogrammetric path near La Paz, with main direction N-S and covered a relatively extensive area; it allows for cross-over checking and for comparison with upward continued data. It enables as well a rough determination of the geoid in a small area and the estimation of its error.

The second one had a different purpose. It consisted of a long straight line between La Paz and Rurrenabaque, in the Amazon rain forest and allows an empirical estimation of the maximum gravity signal wavelength that can be recovered with the IG's INS/GNSS system. Moreover, the flight covered terrain altitudes from 5000 to 300 m.a.s.l.; the evaluation of a wide range of topographic signatures in the signal is thus possible. The final purpose of the flights is to evaluate how would the strapdown inertial airborne gravimetry resolution combine with the current satellite missions resolution capabilities. Both trajectories are depicted in figure 4.



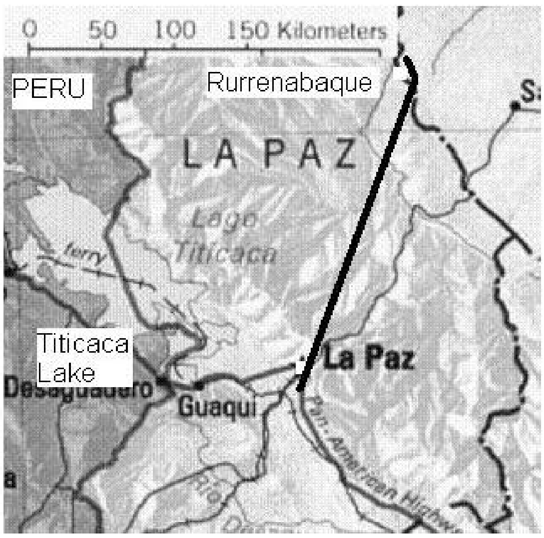


Figure 4: Flight trajectories.

The IG's systems provides gravity data at a frequency of 400 Hz, far beyond the needs; moreover, the correlation of data makes this density become unnecessary. In order to downsample the data, a FFT transformation is applied by means of a Hanning filter, that reduces the frequency to 1/6 Hz. Figure 5 shows the measurements of the vertical accelerometer within the second flight. In order to derive a gravity disturbance profile, accurate calibration values for the sensors must be estimated. This topic is currently under research at the IG.

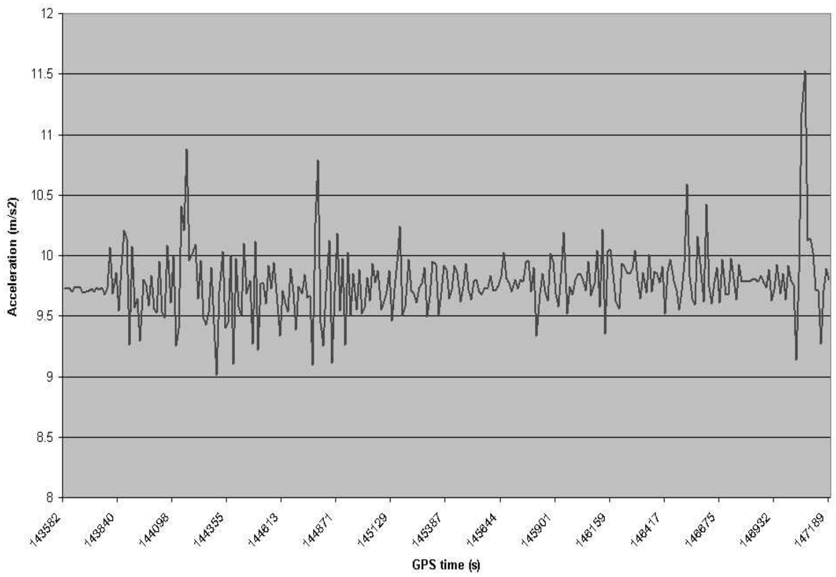


Figure 5: Vertical accelerometer measurements.

4 Final remarks and further developments

A local geoid model is nowadays a necessary infrastructure. Within an ambitious project to build a new 3-D Geodetic Reference Frame for the country, the IGM of Bolivia is looking forward to obtain an accurate enough model within the next years.

Due to the special conditions of Bolivia in terms of relief complexity and difficulty of access to extensive parts of the country, the IGM has seen in strapdown inertial airborne gravimetry a suitable solution, which is being evaluated at the IG.

The fist objective has been the specification of the geoid model for Bolivia, i.e. the model that best fits the general needs of the country —under social and technical points of view—.

By means of simulations, the theoretical performance of Strapdown Inertial Airborne Gravimetry is being analyzed at the IG. Simulations are the key for the design of a local geoid determination campaign and for the setting-up of the features for the sensors that should be used. Preliminary tests show a relative accuracy of 1 ppm for geoid undulations for wavelengths up to 60 km. The scope of the simulations will be extended, so that new areas with significant topographic features will be analyzed as well. Further simulations with higher distances —beyond 60 km— are also planned.

Two experimental gravimetric flights have been conducted over Bolivia. Comparisons of the reckoned data with external upward continued values will provide realistic error estimates. Some calibration aspects are still under research at the IG.

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

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