WINGS OVER THE GEOID: EMPLOYING AIRBORNE GRAVITY DATA IN GEOID DETERMINATION

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ABSTRACT

This study focuses on the application of airborne gravity data to develop a regional geoid model of Nepal in the Remove-Compute-Restore (RCR) framework. In the scenario of difficulties presented by the rugged landscape of Nepal and the limited availability of terrestrial gravity data, airborne gravity measurements serve as an effective input dataset for geoid modeling. The research utilizes the XGM2019e for the reduction of long-wavelength signal reduction and employed LSC to compute geoid residuals, with model covariance functions established from spherical harmonic degree variances. Although greater discrepancies are observed in mountainous areas and near national borders due to the scarcity of data, the findings indicate reasonable geoid residuals, especially inside the boundary. The study suggested that higher-resolution airborne gravity surveys can be a feasible and economical approach for geoid determination in areas such as in Nepal that are either inaccessible or lack sufficient data.

KEYWORDS: GGM, Geoid, RCR, airborne gravity

1. INTRODUCTION TO GEOID

Geoid is defined as the equipotential surface that coincides with Mean Sea Level (MSL). It is defined as "one of the equipotential surfaces of the Earth's gravity potential, of which the (mean) surface of the oceans forms a part" (Hofmann-Wellenhof & Moritz, 2005, p1). Geoid is a complex surface and the most relevant physical figure of the Earth. Therefore, the significance of geoid modeling is well comprehended from former times. Precise determination of geoid has been done for several decades in engineering and science.

1.1 Gravity data for geoid determination

Today, many precise measurements on earth are possible with the application of modern satellite geodetic techniques such as GNSS, but GNSS alone cannot provide orthometric height. The ellipsoid heights provided by the GNSS are not quite useful for practical applications such as large construction or water flow [Hwang.et.al, 2007]. Among many available observables, gravity data is desired as the prime observables for geoid determination. This is because the geoid is defined by the Earth's gravity field and is the surface where the gravity potential remains constant. Therefore, geoid determination methods such as Stoke's integral or spherical harmonics use gravity anomalies. The calculations integrate gravity anomalies to compute geoid undulations.

1.2 Difference between ground and airborne gravity measurement

Gravity data can be obtained from different platforms, such as from the surface itself, airborne and spaceborne. Ground and airborne gravity measurements differ notably not only in their observation surfaces but by many other factors. Ground-based gravity data are collected as discrete samples from a continuous gravity field and airborne gravity measurements are taken along smoother, well-defined flight paths. The most critical difference between these two types of observations is in their frequency characteristics. Unlike ground data, airborne gravity measurements must be processed before they can be used for geoid modeling. Because airborne data is affected by high-frequency noise—mainly from aircraft movement and GNSS signal variations—low-pass filtering is applied, which removes these high frequencies. Unfortunately, this also eliminates useful high-frequency gravity information, presenting a major limitation of airborne gravimetry [(Meyer, 2014)].

2. DATA USED FOR GEOID DETERMINATION

For this study, airborne gravity data covering the whole of Nepal was used as the main input. The overall accuracy of the collected airborne gravity data was estimated to be 3.3 mGal (Forsberg, 2013). Figure 1 shows the observed gravity anomaly in mGal along the flight line. The reason behind using airborne gravity data is that Geoid determination using airborne gravity data is a powerful approach, especially in regions where terrestrial measurements are sparse or inaccessible (e.g., mountainous, forested, or polar areas). Just like Nepal. Furthermore, two Global Geopotential Models were analyzed; EGM2008 and XGM2019e. This Earth's gravitational potential model (EGM) was developed using the least square combination of the ITG-GRACE03S gravitational model up to degree and order 180 and its associated error covariance matrix, with the gravitational information obtained from a global set of area-mean of free-air gravity anomalies defined on a 5 arc minute equiangular grid (Pavlis et.al, 2012). XGM2019e is a combined global gravity field model that includes the latest satellite model, GOCO06s, in the longer wavelength area with terrestrial measurements over land and ocean of gravity anomalies having a resolution of 15ʻ for the shorter wavelengths (Zingerle et.al, 2019).

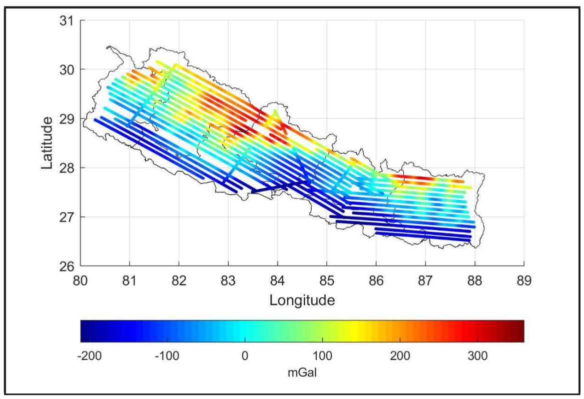

Figure 1. Observed gravity anomaly (mGal) along the flight line

3. BASIC WORKFLOW OF GEOID DETERMINATION

After filtering the high frequency from airborne gravity data, the general Remove-Compute-Restore method can be used for regional/local geoid modelling. Remove-Compute-Restore method is based on the assumptions that the gravity signal observed at certain location is the sum of its long, medium and short wavelength (Gaetani, 2016). The long wavelength component can be characterized by the application of GGM. Removing the effects of long wavelength component removes the gravity signal from Earth's crust, upper mantle and long wavelength topographic signals. This reduction acts as high pass filter to the observed data. Usually, the medium to short wavelength component are due to high frequency topographic effect. This effect can be removed by the use of Residual Terrain Correction. The remaining short wavelength component has mean and standard deviation near to zero. Gravimetric geoid model computation basically comprises of following components:

$$\Delta g = \Delta g_{GGM} + \Delta g_{topo} + g_{res} \qquad (1)$$

where Δg_{GGM} is the long wavelength component (trend field), Δg_{topo} is the topography related short/medium wavelength component, and g_{res} is the residual short/medium wavelength component. g_{res} is residual terrestrial gravity quantities that can address the local effects such as density anomalies. The determination of geoid of Nepal was done using air borne gravity data and Least-Squares Collocation approach in Remove-Compute-Restore framework.

3.1 REDUCTION: Gravity Model Simulation

The GGM that results in the best statistical fit to gravity observations is considered the most suitable for modeling of the long-wavelength signal of the gravity field (Zhang 1997). Therefore, the removal or reduction of the long wavelength component from the observed gravity anomaly was done by using the best possible global model. The gravity simulation between global models (EGM2008 and XGM2019e) suggests that XGM2019e fits better to the input data than EGM2008 (Timilsina et.al., 2021). The terrestrial data in XGM2019e is augmented with topographically derived gravity over land (Earth2014), and it is complete up to spherical harmonic degree and order 5539 (Zingerle et al., 2019). So, the medium and long wavelength components of the gravity anomaly are reduced in a single step. Therefore, XGM2019e was chosen for further computations in this study.

The reduction step of gravity anomalies using XGM2019e undergoes following

$$\Delta g_{red} = \Delta g_{obs} - \Delta g_{GEM} \qquad (2)$$

where Δg_{obs} is the input observed gravity anomaly, Δg_{GEM} is the gravity anomaly computed using XGM2019e at same position as input data, and Δg_{red} is the reduced gravity anomaly obtained by subtracting long to medium wavelength component of gravity anomaly computed using XGM2019e from the input observation.

3.2 COMPUTE: Least-Squares Collocation

The least squares collocation (LSC) method was used to compute geoid residuals from gravity anomalies. LSC has been widely applied in geodesy for estimating the gravity field of the Earth both locally and globally (Gaetani, 2016). The main aspect of this method is the statistical interpretation of proper covariance functions of the gravity data as a kernel function which describes the spatial correlation of the observations. Determination of Covariance Function is one of the main parts of the Least-Square Collocation. Figure 4 shows that with the increase in the distance there is a decrease in the covariance value, and with a further increase in distance the empirical covariance function (ECF) oscillates around zero. This is a good indicator that no significant trend is left in the reduced input data. From this data, the variance of gravity anomaly and the correlation length of the covariance function were computed to derive a model covariance function that can properly model the empirical data.

The Model Covariance function is derived to fit our empirical covariance function and later to be used as the basis covariance function for LSC. The Model Covariance function is derived from the degree variances of the GGM. Degree variances are the sum of square of spherical harmonic coefficients, which describe the decay of gravity signal or reflects the signal power contained in all coefficients of same degree. The degree range for the model covariance is chosen such that it matches best with ECF. Here, the degree ranges 455 to 2000 show the best results for the empirical data. There is not much change in the covariance function for the degrees above 2000. Figure 4 shows quite good agreement of MCF and ECF for distances of less than 20km. Also, the model covariance function oscillates around zero with increasing distance. Thus, determined MCF was used as the covariance function to proceed to Least-Squares Collocation.

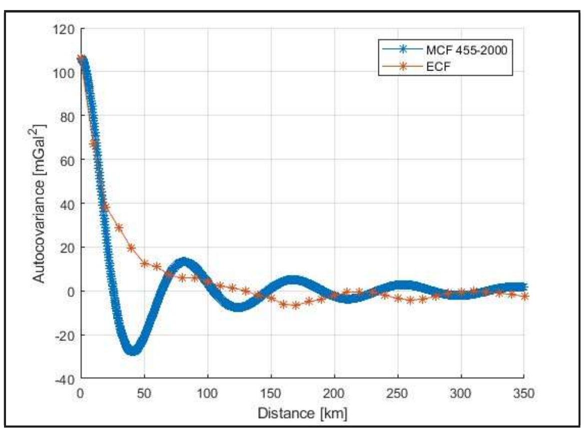

Figure 2. Comparison ECF (Computed from input gravity anomaly) and MCF (Computed from XGM2019e) for degree range 455-2000

The output gravity anomalies were estimated/predicted using the input gravity anomalies at the same stations. The input and output gravity quantities were made the same in order to test if the model that we used fits the input. The geoid residuals in Figure 6 show that the geoid residuals obtained from LSC are quite reasonable. The residual range is between 2.5 meters. Inside the country's boundaries, the residual is even smaller. Higher values are seen in the major mountainous regions of the country. The lack of terrestrial data at the border and outside the country's border has resulted in higher residuals.

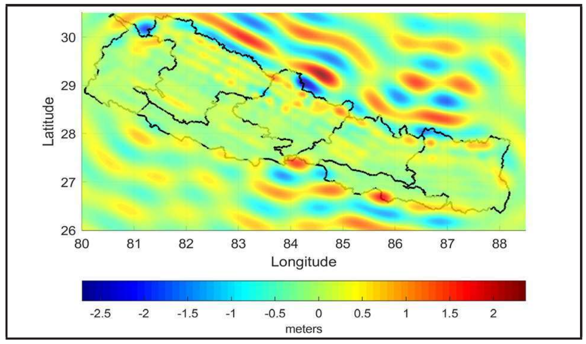

Figure 3. Geoid Residuals computed from LSC

3.3 RESTORE

Restoring is the part where we restore back the long and medium wavelength component that was reduced in the reduction process. The restoring of geoid height is done as following:

$$N = N_{res} + N_{GGM} \quad (3)$$

where N is the final geoid value obtained after adding the N_{GGM} computed from the XGM2019e to the geoid residuals N_{res} computed using LSC. The final geoid is presented in Figure 4. The geoid value ranges between -60 to -10 meters which means the ellipsoid height and orthometric height differs from around -60 to -10 meters.

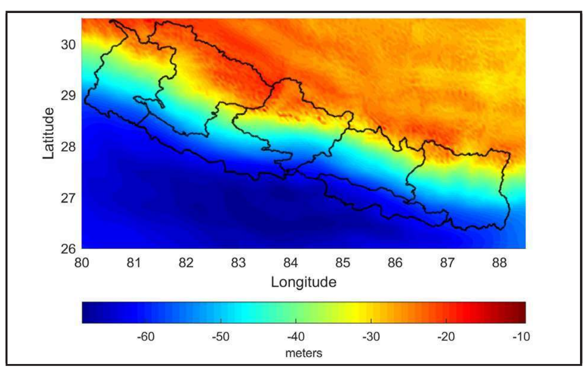

Figure 4. Final Geoid

4. CONCLUSION AND OUTLOOK

This study successfully demonstrated the use of airborne gravity data for geoid determination over Nepal, which is characterized by complex topography and limited terrestrial gravity coverage. By employing the Remove-Compute-Restore method within a Least-Squares Collocation framework, and using the XGM2019e global gravity model for long- and medium-wavelength signal reduction, a regional geoid model was developed with reasonable accuracy. The comparison between empirical and model covariance functions showed good agreement, validating the statistical approach adopted in the LSC process. Although residuals were generally small within Nepals boundaries, higher discrepancies in mountainous and border areas highlight the limitations imposed by sparse or absent ground data. The determination of geoid using airborne gravity can be done. The high frequency signal for the determination of a complete geoid signal would be possible with the availability of high-quality terrestrial observations or denser airborne data with rather low flight altitudes above ground, which in this case is not available. It is helpful in covering areas where ground gravity data is missing with rapid data collection over large areas, typically with larger spatial resolution, in a cost-effective manner.

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