Using High-Low Flight Gravity Data to Improve Geoid Model Precision: A case study in U.S. Virgin Islands (July 2021)

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Abstract— **The Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project collected airborne gravity data over Puerto Rico (PR) and the U.S. Virgin Islands (VI). There was one large N-S/E-W survey at about 11km altitude running from N17 to N21 latitude and E291 to E297 longitude. Considering the very limited surface gravity coverage on VI, only about 500 points, additional flights were conducted at lower altitudes (1.5 km to 1.8 km). By adding these additional low altitude aerial gravity data, the geoid model precision is improved from 6.55 cm with no airborne data to 2.55 cm with both the high and low altitude data. Using only the high altitude flights achieves only 4.99 cm geoid model precision. The ~500 surface gravity data points in the target area do not improve the model precision significantly, which justifies the rationale of carrying out these lower altitude flights. Noticing the nearly 3 times geoid model precision improvements from the low flight data, we suggest to fly in low altitudes in future airborne gravimetric survey for geoid modeling in the areas that have limited surface gravity coverage and/or small topographic features like islands that are not well-sampled in high-altitude, wider-spaced data.**

Index Terms— **Airborne Gravimetric, Gravity, Geoid**

I. Introduction

DUE to high frequency attenuations of the Earth's gravity field in high flight altitudes, the spectrum content of airborne gravity becomes smoother (or attenuated) as flight altitude increases. As well, the airborne gravimetric system will experience less air turbulence at higher altitudes. Thus, it is easier to obtain accurate gravity signals at higher altitudes than lower altitudes in airborne gravimetry. For an extreme case, if the observation system is moved far enough away from the Earth, the Earth's gravitational effect can be treated as a point mass and can be determined very accurately. But from these values, approximately a constant, one cannot obtain any spatial resolution of the geoid from these perfect gravity data. Therefore, flying high will be, of course, at the cost of losing spatial resolution but is sometimes necessary when surveying large spatial areas as with the goals of the GRAV-D program. The GRAV-D program at the National Geodetic Survey (NGS) has been collecting mainly high altitude airborne gravity data across the entire U.S. and its holding since 2008, to support the creation of a cm-level accuracy geoid-based vertical datum for the United States.

This paper provides a case study to demonstrate the benefits of using low flight altitudes for local geoid modeling. The study area selected is in the U.S. Virgin Islands, where limited high quality dual-altitude data is available from GRAV-D. There are also some high-low dual altitude flights in the Gulf of Mexico (Li 2011) but that area has some land subsidence that causes uncertainties in the measured orthometric heights. Thus, the Gulf of Mexico airborne survey cannot be reasonably assessed for its impact to the modeled geoid because of unreliable surface validation data. The relatively isolated and independent island chain in the U.S. Virgin Islands enables more confidence in result validation. It is also an interesting study location because the island chain is not well-sampled in the higher altitude data due to the islands' small sizes.

In low altitude flights, it is true that some heavy filtering approaches (Childers et al., 1999) have to be applied to effectively reduce the noise caused by the presumed stronger air turbulences, especially when flying in stable weather conditions is not possible. After filtering, the along track spatial resolution is usually more than 10 km in typical airborne gravimetric systems (Forsberg et al., 2000). However, the signal in this low altitude data is also much stronger. Downward continuation from these low flight levels to the reference ellipsoid is much easier to handle in these scenarios as well (Li et al., 2021). Therefore, we expect that the addition of the low altitude flight data will improve the calculated geoid model over the Virgin Islands.

Section II describes the procedures used in data processing and geoid modeling. The geoid model validations are given in Section III. Finally, the conclusion is given in Section IV.

II. Data processing and geoid modeling methods

In the target area, VI, there are two sets of airborne gravity data (GRAV-D team 2014, 2017). One is at the expected flight height for the Cessna Citation II that was in use by GRAV-D from 2008-2009, i.e., 11 km. This nominal value is determined by a simple of rule of thumb that is used to resolve the crustal

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signals (GRAV-D team 2017). The other set of flight data is from customized flights along the islands, whose altitudes range from 1.5 km to 1.8 km, about 5 times lower. In addition to this significant reduction in flight heights, the aircraft was also flying at a relatively slow speed, ~200kts. In general, the VI-only flights were low and slow for the Cessna Citation jet. The statistics of the residual gravity disturbances with respect to xGeoid20refA (Geoid team 2021), which is an internal model developed at NGS by spectrum weighting between GOCO06s (Kvas et al, 2021, 2019) and EGM2008 (Pavils et al., 2012, 2008), are given in Table I.

Due to the huge flight height differences, there are clear gravity field attenuation effects in Table I. By comparison, the gravity data from the higher altitudes are more "quiet" than the ones from the lower altitudes. The high altitude gravity data has a standard deviation of about 1.4 mGal, ranging from -5 mGal to 9 mGal. The low altitude gravity data shows about 6 mGal standard deviation and a range from -14 mGal to 30 mGal. A closer examination of the lower altitude data shows some unexpectedly high frequency variations with respect to the reference field. A conservative Gaussian low pass filter with $f_c = \frac{1}{20} hz$ is used to further smooth the data to remove any residual data noise.

To demonstrate the improvement to the geoid model by adding these airborne gravity data from the two altitudes, the data are incorporated into the geoid model step by step in a careful method detailed below. First, we only add the gravity data from the higher altitude to our usual other sources of gravity data and gravity estimates (satellite gravity, laser altimetry, high-resolution DEM, etc.). The resulting gravity model is the downward continued residual gravity disturbances on the reference ellipsoid; see Li et al. (2021) for the details of the downward continuation computation. Then both the high and low altitude gravity data are combined and downward continued on to the reference ellipsoid by using the same downward continuation procedure.

A space domain comparison, Fig. 1, of the downward continuation results with and without low altitude data suggests that after adding the low altitude data, the gravity signal is stronger and the spatial resolution is better in the target area (VI), as expected. Because of the harmonic nature of the method, the lower altitude gravity data have impacts not only directly in the area of VI, but also helps to improve the downward continuation process in Puerto Rico and over the ocean around the islands. These effects will be justified in the following section.

To further characterize the impact on the downward continued gravity grids before and after adding the low altitude flight data, both of them are transformed into the frequency domain. Their corresponding power spectrum densities (PSD) are plotted in Fig. 2. The green curve is for the high flight data. The red one represents the high and low altitude combined data. From the PSD plots in Fig. 2, it is clear that the magnitude of power is amplified in all frequencies after adding the data from low flight altitudes. In general, the amplification becomes stronger in higher frequency bands. In the highest frequency, the improvement is more than an order in magnitude. This plot underscores the importance of the high-frequency contribution of the low altitude flight gravity data to the local gravity field around the target area.

The downward continued residual grids on the reference ellipsoid (GRS 80) are then used to update the local geoid models in the classical remove-compute-restore scheme (Smith et al 2013, and Li et al., 2021). Three models are computed by progressively adding: 1. high flight airborne gravity data, 2. low flight airborne gravity data, and 3. local surface gravity data.

III. Validation on local GPS/Leveling bench marks

Starting from the xGeoid20refA model as a reference model, we constructed three geoid models by gradually adding only high altitude data, the combined data form both the higher and the lower altitude, and the surface gravity data in the target area, which is named as B1, B2, and B3, respectively. Twenty GPS/Leveling points in the U.S. Virgin Islands and 107 bench marks in Puerto Rico (PR) are used to validate these geoid models. These newly collected bench marks in the islands provide reliable ground checks of the geoid models. The corresponding model precisions are summarized in Table II.

Table II shows about 1.5 cm geoid model improvement by only using high altitude airborne gravity data for both the U.S. Virgin Islands and Puerto Rico. After adding the low flight data above the U.S. Virgin Islands, we see an extra 2.5 cm model precision improvement in the U.S. Virgin Island. Some marginal improvements are also found in the Puerto Rico Island, which proves that the lower flight data is helpful not only directly in VI, but also in PR, the postulation that we have in Section II. As expected, after adding the surface gravity data, the model precision only improves 3.1% by adding the land gravity in VI, which is understandable considering the Virgin Islands are small in size and their surface gravity data are limited.

IV. Conclusion

There are two sets of GRAV-D airborne gravity data collected by NGS on quite different flight altitudes above the U.S. Virgin Islands. One is ~11 km above the reference ellipsoid. The other set of data is on customized flight heights according to the local topography, which yields a changing flight altitude from 1.5 km to 1.8 km above the reference ellipsoid. We utilized both the higher and the lower altitude gravity data for local geoid modeling. First, only the higher altitude data are downward continued and used to generate a geoid model. Validation tests show about 1.5 cm geoid model improvements on the local GPS/Leveling bench marks. Then, both the higher and lower data are combined together and downward continued on to the reference ellipsoid. The downward continued gravity data show stronger power and higher spatial resolution in the target area. The PSD plot shows at least an order of power amplification in high frequency bands. Considering this significant signal improvements, we determined that it was critical to use all data (high and low altitude airborne data as well as surface gravity data) for precise local geoid modeling. The resulting geoid model shows an additional 2.5 cm improvement after incorporating the data from the lower flight altitude. This underscores that lowering the fight heights indeed helps to improve the geoid model precisions, though an extra along-track low pass filter reduced its along track spatial resolution. Adding the very limited surface gravity data on the islands does not further improve the precision.

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Fig. 1. Differences of the downward continued airborne gravity data on the reference ellipsoid (Thin dotted lines are high altitude flight trajectories; Thick solid lines are low altitude flight trajectories; black squares are surface gravity spots).

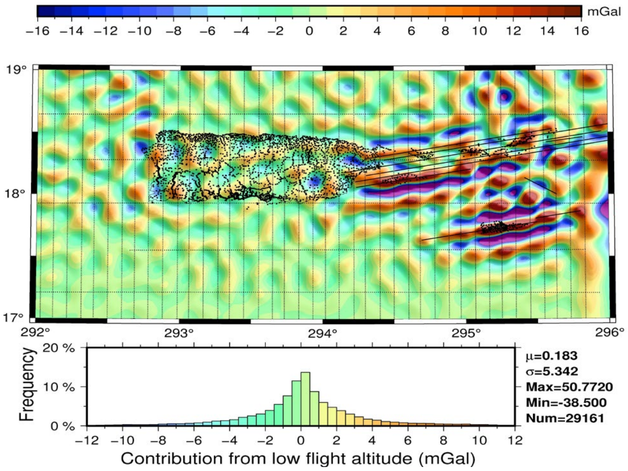

TABLE I
Statistics of the residual gravity disturbances w.r.t. the full field of xGeoid20refA (in mGal)

	mean	Standard Dev.	min	max
High	0.13	1.39	-5.45	9.32
Low	0.65	5.93	-14.10	29.66

Fig. 2. Power spectrum densities of the downward continued airborne gravity data on the reference ellipsoid.

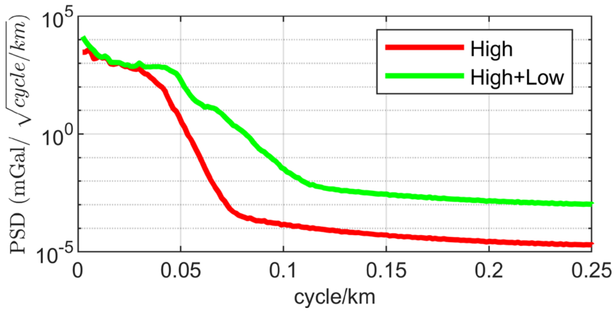

TABLE II

Geoid model precisions in the target areas

Model/ Precision (cm)	PR	VI
xGeoid20refA	5.48	6.55
B1 (High)	3.95	4.99
B2 (High-low)	3.69	2.55
B3(High-low and surface data)	2.60	2.47