# EGM08 Comparisons with GPS/Leveling and Limited Aerogravity over the United States of America and its Territories

D.R. Roman, J. Saleh, Y.M. Wang, V.A., Childers, X. Li, and D.A. Smith
National Geodetic Survey, NOAA, Silver Spring MD 20910 USA

**Abstract.** GPS-derived ellipsoidal heights on leveled bench marks (GPSBM's) have long been used as external data for testing gravimetric geoid models at regional and global scales. Ellipsoidal heights above the NAD 83 datum are available for all regions of the United States and its territories. Vertical datums are also available for all of the conterminous United States (NAVD 88), Alaska (NAVD 88), Puerto Rico (PRVD02), Guam (GUVD04), the Commonwealth of the Northern Marianas Islands (NMVD03), and American Samoa (ASVD04). Hence, it possible to provide estimates of the geoid undulation at a select few points scattered around the world. The more recent vertical datums provide coverage in remote regions and are more internally consistent and accurate. These data were compared to the Earth Gravity Model of 2008 (EGM08) in an effort to assess its quality and utility. Results indicated significant improvements for both the Conterminous United States (CONUS) and Outside CONUS (OCONUS) regions. In CONUS, a significant, meter-level trend was better defined than in EGM96. The remaining signal was also much smaller (under 7 cm SD). No significant trends were determined for OCONUS regions and most had dm-level agreement. Additionally, limited airborne gravity data over the northern Gulf of Mexico region were available. These data had very low cross-over errors (0.87 mgals RMSE) and compared favorably to EGM08 (1 mgal SD). Over all, the EGM08 model is deemed a definite improvement over the antecedent, EGM96, and it will be employed as a reference field in developing forthcoming national models for the United States.

**Keywords.** EGM, GPSBM, aerogravity, calibration/validation

## 1 Introduction

The National Geospatial-Intelligence Agency's (NGA) standard reference gravity field model for the past decade has been the venerable Earth Gravity Model of 1996, EGM96 (Lemoine et al. 1998). This model has served as a common reference field in the development of regional models, thereby ensuring high levels of international agreement between regions. NGA has now released an update to this in the form of the Earth Gravity Model of 2008, EGM08 (Pavlis et al. 2008). NGA formed an international working group under the auspices of the International Association of Geodesy to assess the quality and utility of this new model. This report provides that assessment from the national perspective of the United States.

The National Geodetic Survey (NGS) is the civilian counterpart to NGA and is responsible for maintaining the National Spatial Reference System (NSRS). The NSRS is composed of many elements including maintenance of bench marks and reference frames for GPS-derived ellipsoidal heights, orthometric heights, and gravity observations. These data were used here to evaluate EGM08.

The difference between the GPS-derived ellipsoidal heights and orthometric heights on leveled bench marks (GPSBM's) provides a point estimate of the separation between the ellipsoidal and vertical datums. It should be noted that there are several different vertical datums, primarily for geographically separated regions: conterminous United States (NAVD 88), Alaska (NAVD 88), Puerto Rico (PRVD02), Guam (GUVD04), the Commonwealth of the Northern Marianas Islands (NMVD03), and American Samoa (ASVD04). Hence, each of these regions was independently assessed to evaluate EGM08 worldwide.

## 2 CONUS GPSBM'S

One truth about the GPSBM's determined for conterminous United States (CONUS) is that their realization changes over time, even if the position on the ground doesn't move. Constant new observations on the existing bench marks as well as ongoing adjustments modify the ellipsoidal height for a given location. The net effect is that the apparent datum separation changes. Hence, comparisons with GPSBM data must be cautiously examined to ensure that an EGM with dm-level errors isn't compared to data with meter-level errors.

In an effort to reduce some of these known errors, NGS recently completed a national readjustment. The results in the shift of the ellipsoidal heights are shown in Figure 1. Note that many states experienced shifts in a mean value as well as increased variability. More significantly, some states show systematic effects (e.g., Minnesota).

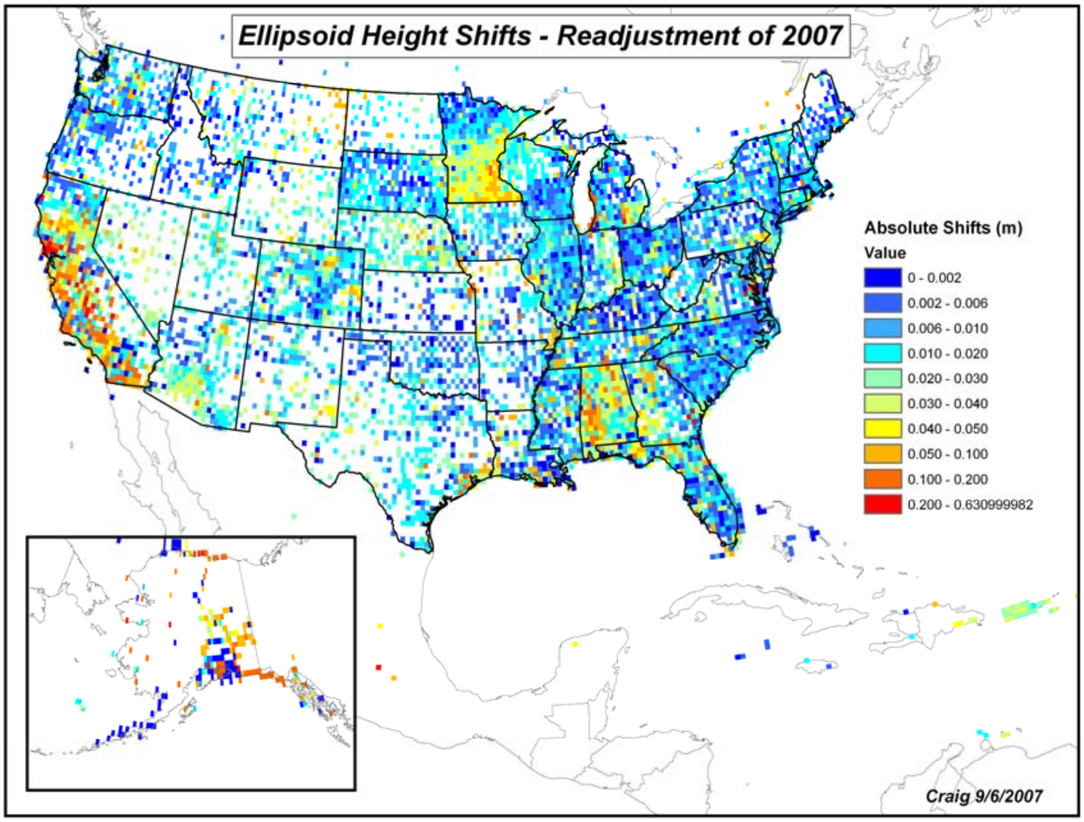


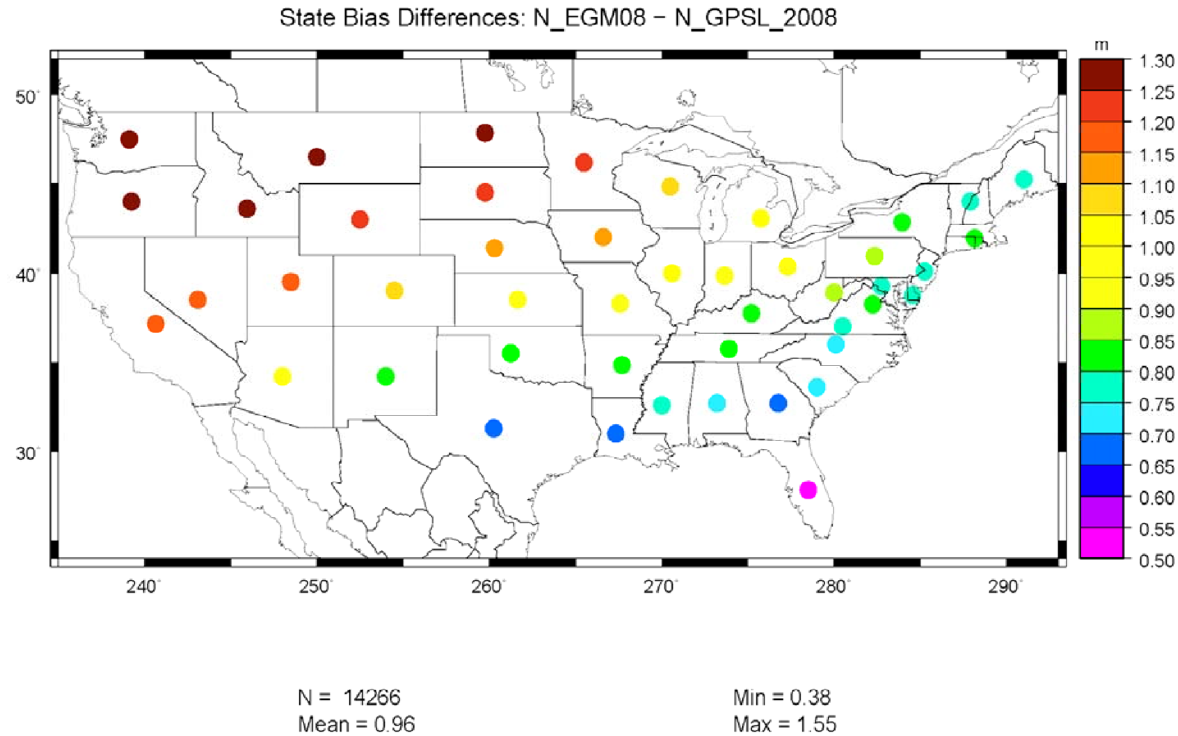

**Figure 1. Changes to ellipsoid height coordinates as a result of the National Readjustment of 2007 for CONUS and Alaska. Note dm-level biases, tilts, and standard deviations across numerous states.**

GPSBM's were then developed using these revised ellipsoidal heights for comparison to EGM08. Biases were removed state by state and then a standard deviation was determined. These results for CONUS are given in Figure 2. The biases are given on the top and the SD on the bottom. Note the trend in the state biases increases steadily westward. This is a significant feature thought to represent the propagated errors in the development of the North American Vertical Datum of 1988 (NAVD 88). The SD also shows increases westward into the mountainous western states, where a higher variability is not unexpected.

EGM96 and regional gravimetric geoid models developed from it were also compared. These models showed similar magnitude trends in the biases but were about 50% worse in the state SD comparisons. Nationally, EGM08 had about a 7 cm SD, while EGM96 was closer to 11 cm.

These improvements show that adopting EGM08 as a reference field significantly reduced the residual signal. This is highly desirable given amount of variability seen in the residuals across the CONUS region. Fortunately, other U.S. regions outside CONUS do not see such great variability in the systematic errors associated with the respective GPSBM's.

EGM08 was also compared at sites in Alaska, American Samoa, Guam, the Commonwealth of the Northern Marianas Islands, and Puerto Rico where similar improvements were seen (Table 1).



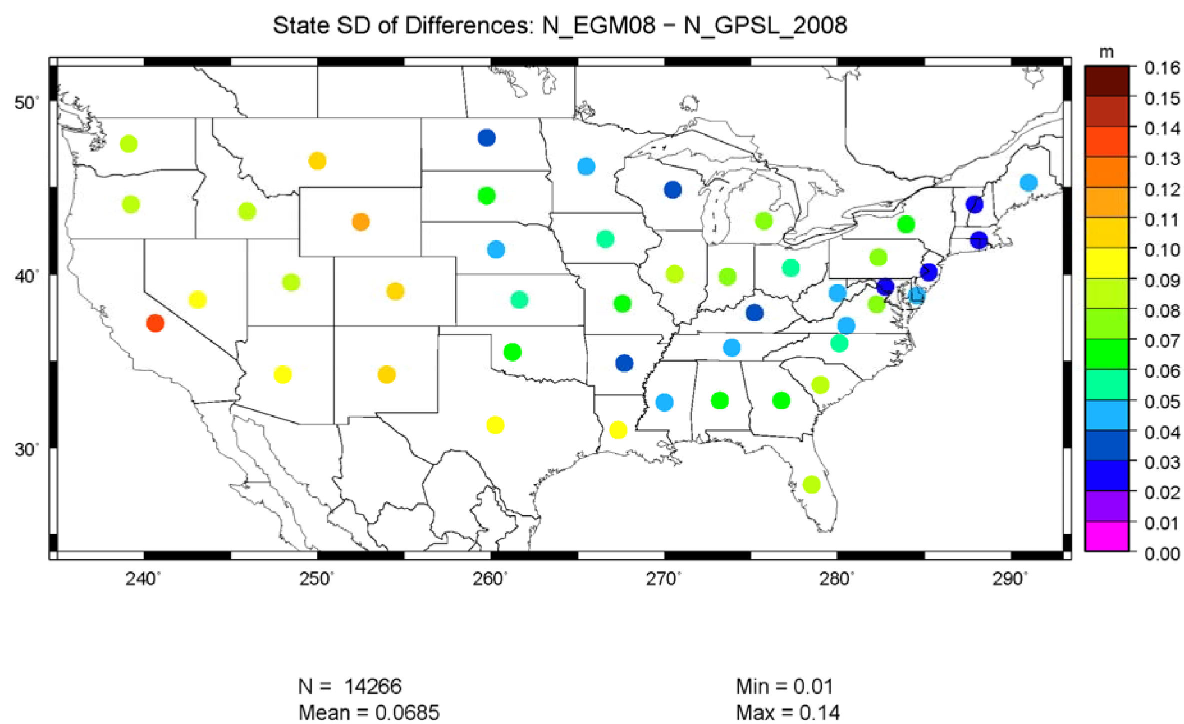




**Figure 2. Biases developed from comparisons on a statewide basis between EGM08 and GPSBM's are shown in the top figure, while the SD's are shown in the bottom figure.**

**Table 1. Comparisons between EGM08 and GPSBM's for U.S. states and territories. Biases largely reflect the tide gage selected as the datum. SD is the significant statsistic and is very good throughout the Pacific.**

| Region | # Pts | Min (m) | Max (m) | Ave (m) | SD (m) |
|---|---|---|---|---|---|
| CON -US | 14266 | 0.229 | 1.793 | 0.960 | 0.069 |
| Alaska | 239 | 0.761 | 2.551 | 1.744 | 0.254 |
| Puerto Rico | 29 | 0.030 | 0.128 | 0.078 | 0.029 |
| Guam | 16 | -0.773 | -0.563 | -0.645 | 0.066 |
| CNMI | 54 | -0.744 | -0.489 | -0.570 | 0.072 |
| Am. Samoa | 22 | -0.853 | -0.514 | -0.696 | 0.110 |

For most regions, significant biases occurred. This largely reflects the selection of the tide gage used as the datum point. The SD is most relevant and demonstrates that EGM08 generally provides dm-level or better agreement.

Alaska represents an exception for both the bias and the SD for a number of reasons. The tide gage is the same as for CONUS, Father Point/Rimouski in the St. Lawrence Seaway - thousands of kilometers away. Also, errors in NAVD 88 were propagated to the end of the network, which is Alaska. These factors contribute to the significant bias. Frost heave and other factors also contribute high variability in the GPSBM's and create a significant SD. EGM96 and other models based on it have proportional biases and SD's.

## 3 Aerogravity

Aerogravity profiles have been collected by NGS to validate existing terrestrial data holdings and served a similar purpose for EGM08. Figure 3, 4, and 5 show the differences between EGM08 and aerogravity profiles for over Florida in 2005 and the northern Gulf of Mexico in 2006 and 2008. These data were collected at 35,000 ft (approximately 10 km) at speeds of about 500 kmh. Track spacing was at 10 km and intended to capture a 20 km full wavelength signal – commensurate with along track signal after filtering. Comparisons are made at flight altitude. Note that none of these three data sets were incorporated into EGM08, so they provide independent assessments of the quality of EGM08.

In Figure 3, the profiles over Florida are rougher and track spacing is closer to 20-40 km. A significant bias exists and seems largely due to the features off of Cuba and the Bay of Florida. This may derive from significant issues with ocean topography in the altimetric anomalies used in EGM08. These data were not gridded due to the sparseness and irregular nature of the profiles.

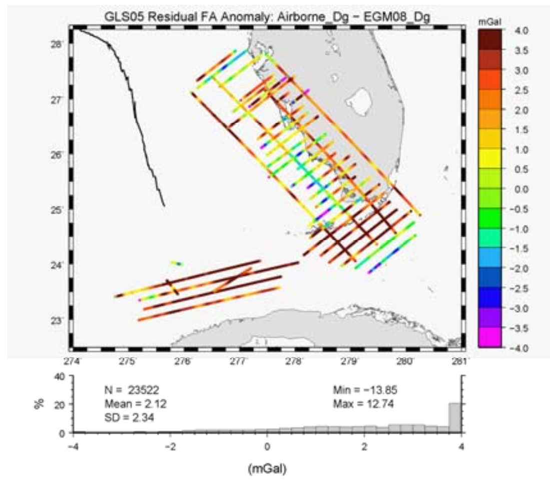



**Figure 3. Differences between EGM08 and aerogravity data collected over Florida in 2005 at 35,000 ft.**

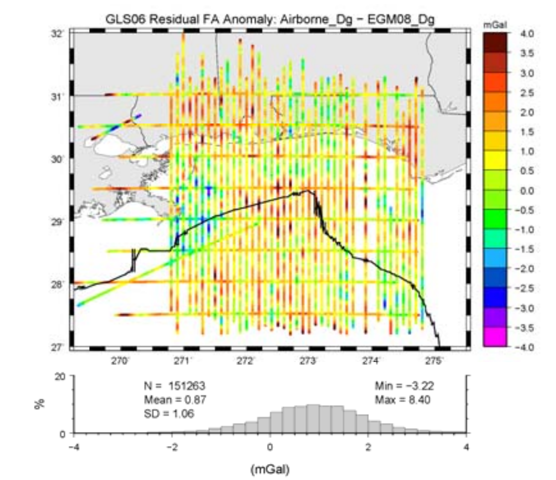



**Figure 4. Differences between EGM08 and aerogravity data collected over coastal regions of the northern Gulf of Mexico in 2006 at 35,000 ft.**

A more comprehensive and consistent collection occurred in 2006 for the northern Gulf of Mexico. This survey had a very low crossover error (0.87 mgal) and provides an excellent comparison. Figure 4 shows that EGM08 agrees closely with the aerogravity data. (1 mgal SD).

The central portion of this area was re-flown in early 2008 as a means of calibrating a new aerogravimeter purchased by NGS. The earlier surveys were flown by NOAA using the Naval Research Laboratory's instruments. The 2008 survey used the

NGS instrument and yielded a more typical cross-over comparison (2 mgal SD). Track spacing was at 5 km to evaluate omission errors in the collection scheme. The comparison with EGM08 was, likewise, 2 mgal SD and highlights many of the same features seen in the 2006 survey.

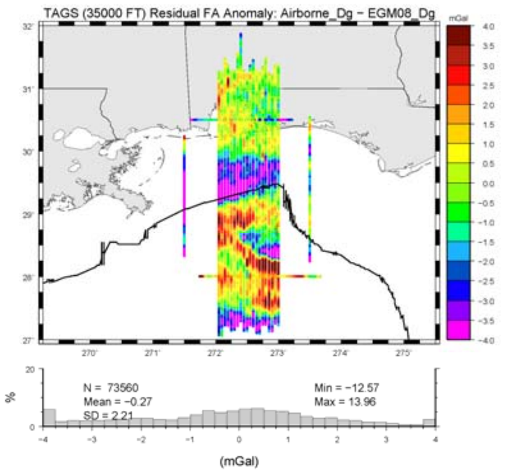



**Figure 5. Differences between EGM08 and aerogravity data collected over coastal Alabama in 2008 at 35,000 ft.**

In Figures 3, 4, and 5, prominent features exist that seem to point to inconsistencies with features at scales at hundreds of kilometers. These features have relatively low signal (3-4 mgals) but they are seen to span multiple profiles. This supports a supposition that real differences exist and that the features are not just random track noise or derived from filtering. Their spatial extents create dm-level differences in derived geoid models and are the subject of ongoing study at NGS. Similar features are seen in comparison to upward continued terrestrial data held by NGS in the historical database.

A recent terrestrial campaign was completed to test the terrestrial data for the Mobile Bay, Alabama region. The preliminary results of that survey show that the errors lie with the historical, terrestrial data that underlie EGM08.

## 4 Summary and Conclusions

GPSBM's & aerogravity were compared to EGM08 in an effort evaluate the quality of the model in U.S. states and territories around the world.

EGM2008 performed better than EGM96 in comparison to existing GPSBM data everywhere except in the western Pacific. This improved behavior supports the modifications by NGA to the weighting scheme between GRACE (Tapley et al. 2004) and surface gravity in creating EGM2008. Additionally, the effect of NGS' National Readjustment of 2007 on GPSBM data further improved the comparisons with EGM2008. Differences with recent, internally consistent, high-altitude aerogravity were not conclusive. This possibly due to along-track filtering of the aerogravity but may also be due to potential systematic errors in the historical terrestrial data used to develop the higher degree harmonics in EGM2008.

Previous studies and recent terrestrial surveys support the possibility that these systematic differences exist. Incorporation of these data into the EGM2008 model means that the errors are now embedded into the model. Comparison with the same data will not reveal this weakness, because they reinforce each other in comparisons. The merging techniques used to mitigate the longer wavelength differences cannot be applied at signals to which GRACE is not sensitive.

Instead of further weighting schemes, a more appropriate approach would be to eliminate any remaining systematic errors through refinement and cleansing of the surface gravity data.

If the surface gravity data do not agree with GRACE data as it appears, then this may be resolved by implementing an internally consistent airborne gravity campaign (e.g., GRAV-D) tied to GRACE and GOCE and designed to bridge surface gravity to satellite gravity. This would eventually eliminate or reduce the need for further weighting schemes or modified kernels.

EGM2008 still represents a significant step forward and will remain useful as a unifying reference model. It is consistent with existing data quality and is likely adequate for most applications. Particularly when used in a remove-compute-restore approach.

Using R-C-R and a partially modified kernel would allow adoption of the lower degree harmonics and modification of the higher degree harmonics. It is a mark of how much this model represents an improvement to note that many recent regional models now adopt the "low" degree value to be 360. In deed, recent efforts for the U.S. model have focused on using EGM2008 completely through that level incorporating a modification to the Stokes kernel to affect this. The full signal of EGM2008 (through degree 2160) is removed and the differences between 360 and 2160 and passed through the kernel to restore to the regional model. This approach builds on the EGM2008 model to address those shorter wavelength signals where some discrepancy remains.

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