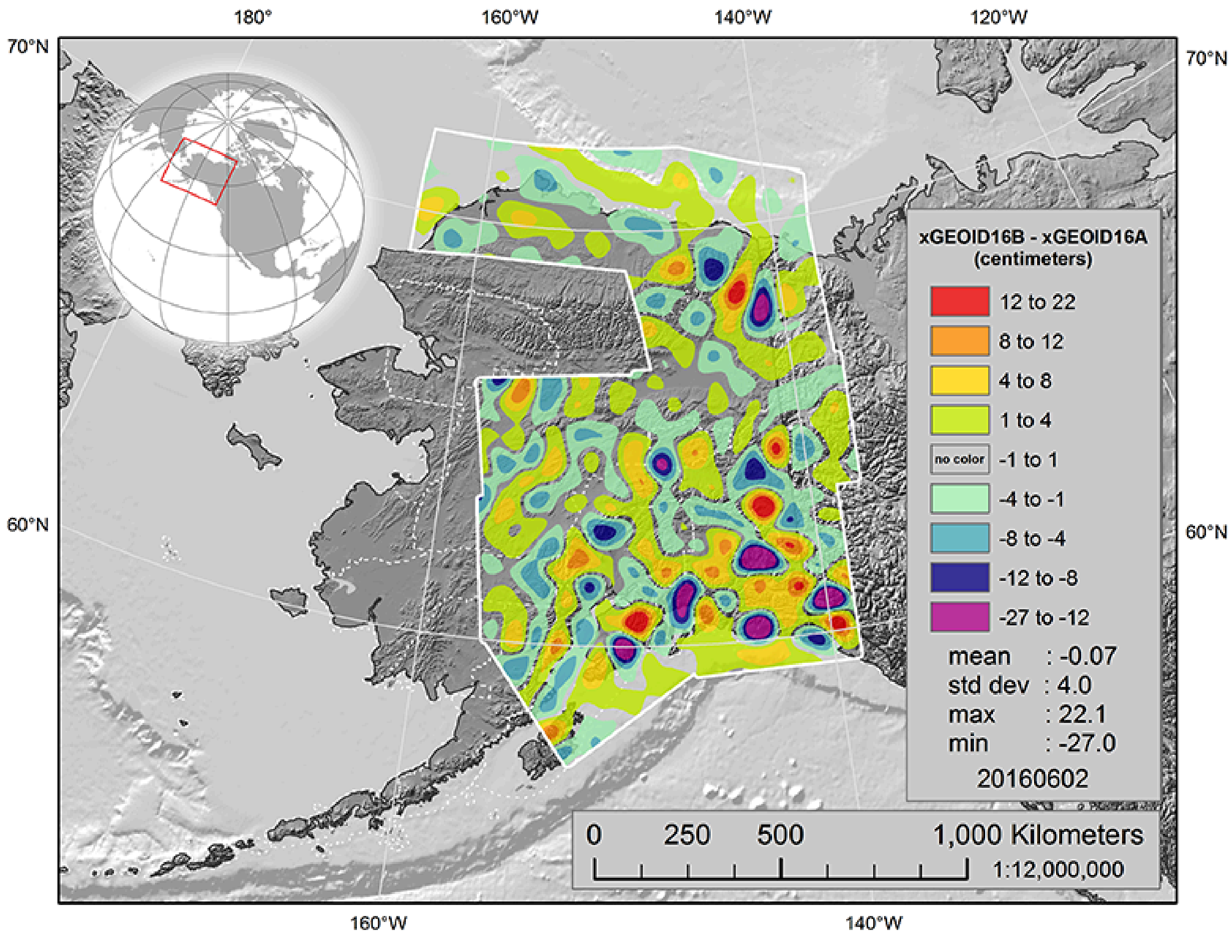
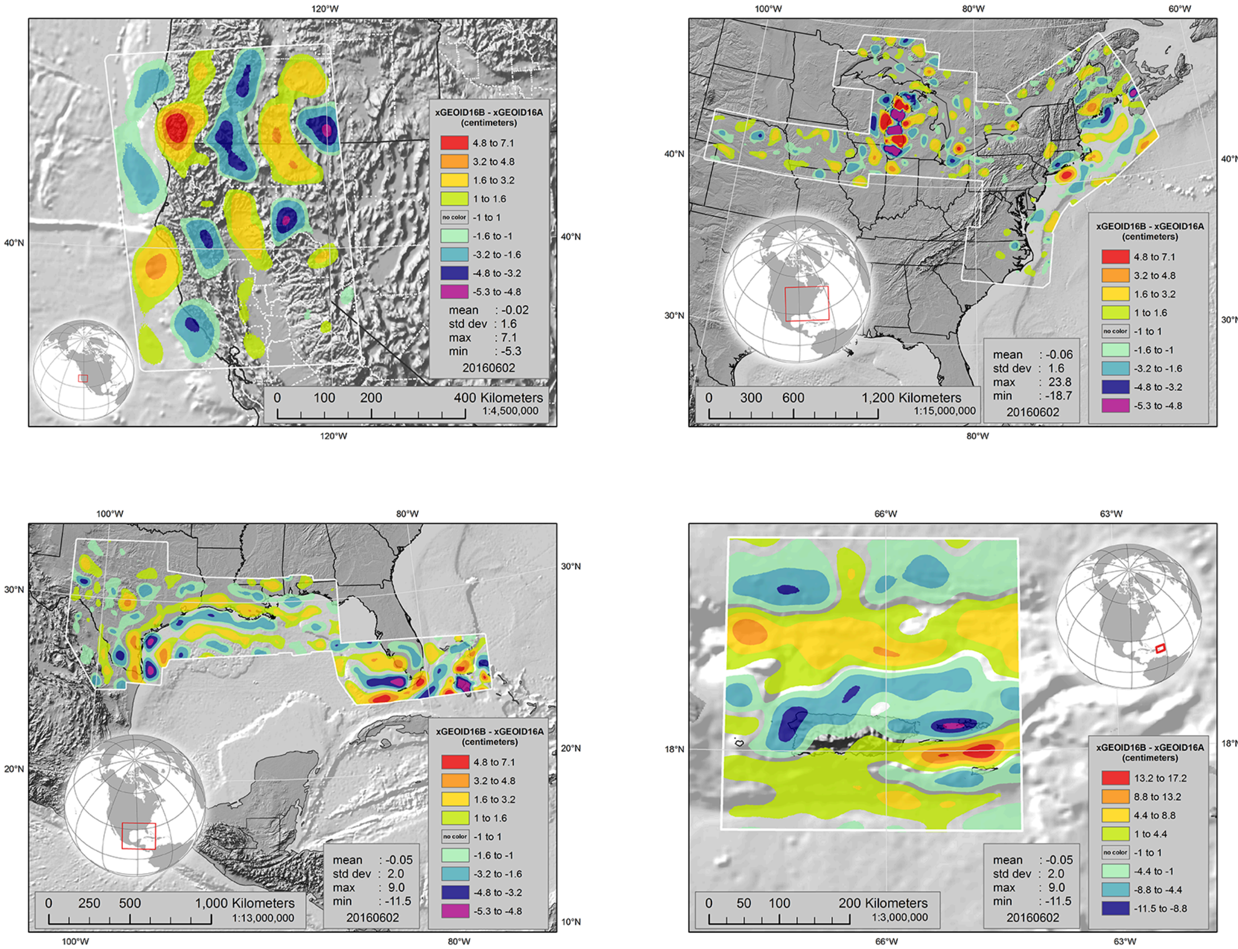
Technical Details for xGEOID16 Models

GRAV-D Airborne Gravity Contribution

The xGEOID16A and xGEOID16B models are identical except that xGEOID16B includes the available GRAV-D airborne gravity data. So, the difference between the two models shows the important contribution of the airborne gravity data to the accuracy of our geoid models. Since the differences are only in areas where the GRAV-D airborne gravity data have been used, examining the regional plots given below will illustrate the varying levels of improvement in, due to GRAV-D, seen indifferent parts of the country.





Panels (clockwise, double click to zoom in) show the contribution of GRAV-D airborne gravity in Alaska, Gulf of Mexico region, states in the Northeast and Puerto Rico/Virgin Islands. The contribution of airborne gravity can reach decimeters in areas where there is no terrestrial gravity data or terrestrial data of low quality, such as in Alaska and Lake Michigan. In areas with good gravity coverage and quality, the addition of the GRAV-D airborne gravity data causes changes that are at the centimeters level.

Creation of xGEOID16A

xGEOID16A was computed using the following data inputs:

- GOCO05S satellite gravity model (Mayer-Gürr et al. 2015)
- EGM2008 (Pavlis et al. 2012)
- NGS Terrestrial gravity data
- 3" digital elevation model (Li et al. 2008)

The methodology for computing xGEOID16A follows very closely the methodology for computing it's predecessor, xGEOID15A. Firstly, combining the GOCO05S (Mayer-Gürr T., et al. 2015) satellite gravity model with EGM2008 (Pavlis et al 2012), yields the global spherical harmonic reference model, 'REF16A'. REF16A replicates exactly the format and spectral resolution of EGM2008. Once again, this year's procedure experimented with space-domain combinations of EGM2008 and GOCO05S. This procedure operated on global 5'x5' grids of gravity disturbances that had been generated from each of the two models. For this approach, application of non-stationary, local error models to these two 5'x5' grids of disturbances allowed them to be combined into one, composite 5'x5' grid. Harmonic analysis of this composite grid yielded a combination spherical harmonic gravitational model (Nmax=2190). Such local, space-domain combinations are suited for resolving harmonics in the spectral band n > 100. For harmonic coefficients below this band, GOCO05S values were used, yielding the final reference model, REF16A. Additionally, a 1'x1' reference gravitational geoid was computed from the REF16A model, using the same procedure as was used for the EGM2008 gravimetric geoid (Pavlis et. al., 2012).

The REF16A reference model was then combined with the NGS terrestrial data, in a classic remove-restore approach (Wang et al. 2012). In this particular case, the REF16A gravity anomalies were subtracted from the NGS terrestrial gravity anomaly station values, yielding residual gravity anomalies. Additionally, high frequency terrain effects beyond the resolution the REF16A resolution were also computed from a Residual Terrain Model (RTM, Forsberg 1984), and subtracted from the residual gravity anomalies. Combined digital elevation from the Shuttle Radar Topography Mission (SRTM, Farr et al. 2007), as well as from the digital elevation version 2 in section of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, Tachikawa et al. 2011), both served as DEM input for the RTM computations. The final residual gravity anomalies were then gridded onto a 1'x1' grid, and then simultaneously filtered and converted to residual geoid heights using a spherically-banded (n > 280) Stokes kernel applied in the space domain. Both the REF16A reference 1'x1' geoid and the RTM geoid effects were then restored to the residual geoid heights. The result was xGEOID16A.

Creation of xGEOID16B

The xGEOID16B model was created with the intention that it should be identical to xGEOID16A, except that it also includes NGS GRAV-D airborne gravimetry. Thus xGeoid16B was computed using the following data inputs:

- GOCO05S satellite gravity model
- EGM2008
- NGS Terrestrial gravimetry
- 3" digital elevation model
- GRAV-D airborne gravity data

The general approach for computing xGEOID16B was the same as for xGEOID16A. The only difference between these two models is that global spherical harmonic gravitational model that supports xGEOID16B, 'REF16B', incorporates the GRAV-D airborne data, whereas REF16A does not. The xGEOID16B and xGEOID16A models are almost identical otherwise. REF16B has identical format and spectral resolution to REF16A, and to EGM2008. The general recipe for generating REF16B generally follows that of its predecessor, 'REF15B', except that for REF16B the data treatment is much more consistent across different regions than was the case for REF15B. For REF16B, we still divide the United States into three separate regions, **but the differences in the treatment of these regions are minimal.** The three regions were:

- 'CONUS' included surveys in:
    - the Great Lakes (EN01, EN02, EN03, EN04 and EN05),
    - the East Coast (EN06, EN07, EN08, EN09, EN10, ES03, ES04),
    - the Gulf of Mexico (CS01, CS02, CS03, CS04, CS05, CS06, **CS08**),

    - the South East (ES01, ES02),
    - the Midwest (CN02, CN03),
    - and California (PN01).
- 'Alaska' (AS01, AS02, AS03, AS04, AN01, AN02, AN03, AN04, AN05, AN06)
- 'Puerto Rico and the Virgin Islands' (TS01).

Note that the CS08 block is bolded, as it is the only new block that was not available for inclusion into the xGeoid15B.

General Processing of GRAV-D Data

All 35 GRAV-D data blocks were processed according to the general method applied to 'Area 1' in 2015. For 2016, adjoining or overlapping surveys were processed together as a single survey. Then, EGM2008 reference gravity values were subtracted from all the published airborne survey values, yielding residual gravity disturbances. Residuals were crossover adjusted, solving for line biases only (not tilts). For overlapping surveys, this was performed as a single adjustment, allowing survey lines from many of the surveys to contribute to the adjustment of adjacent and overlapping surveys. In this way, all surveys from the Great Lakes, the Mid West and the East Coast were adjusted together. All surveys from the Gulf of Mexico and the South West were adjusted together. All surveys from Alaska were adjusted together. Note that, for xGEOID15B, many cross-tracks in Alaska were not published for blocks AN02, AN04 and AS03, and so no cross-over adjustment was performed in Alaska for 2015. Similar to xGEOID15B, a rudimentary error model was applied to all adjustments. Here the 'sigma error' applied to each crossover value was computed by first adjusting each trackline to give a zero median residual, and then using the resulting cross-over discrepancies as the 'sigma error' value. For each survey, crossover adjusted residuals were compared against unadjusted residuals in terms of inter-line variability, and those few adjustments that were clear outliers were abandoned in favor of their unadjusted counterparts. The remaining residuals were cleaned by:

- removing extreme outliers, and
- removing residuals corresponding to large prediction errors from gridding.

For the latter approach, the residuals were gridded by least-squares collocation. A simple data error model was applied within the collocation procedure, which set the error variance of each 'scattered' residual point equal to the signal variance computed for residuals local (within 30') to that point. Input 'scattered' residuals that differ by more than some arbitrary threshold from the gridded values are discarded. This threshold was determined empirically for each survey.

Cleaned residuals for each of the 35 GRAV-D blocks were aggregated together. These composite residuals were then interpolated to a 1'x1' equiangular grid, and captured in a spherical harmonic model (Nmax = 2190), very much according to Smith et al. (2013). The resulting spherical harmonic model of the residuals was then arithmetically added to EGM2008, yielding a final spherical harmonic model (Nmax = 2190) that reproduced EGM2008 gravity disturbances away from the airborne survey areas, and reproduced a 'cleaned' counterpart for the airborne data inside the survey areas. This airborne-supported model was then compared to EGM2008 in terms of relative match to NGS GPS on Bench Marks data (GPS/L). Local error covariances for each of the two models were approximated for overlapping 2-degree regions, based on their relative match to the GPS/L. These local error models were used to spatially combine the airborne-supported model and EGM2008 into a single, spatially filtered model (Nmax = 2190). Note that, for Puerto Rico, the Virgin Islands and Alaska, the lack of even GPS/L coverage precluded such spatial filtering in these areas. Also, it is here acknowledged that using the GPS/L to combine the two solutions in this way is really only a half-measure. A more optimal combination strategy requires reliable error models for the various data sets. The development of such error models is a high priority for future xGeoids.

Finally, a general, degree-wise (n), low pass filter was selected for each of the three regions, based on a priori estimates of airborne survey error vs. EGM2008 terrestrial error in each region. This low-pass filter was applied to the spatially filtered model above, thereby limiting the maximum harmonic degree (n) to which GRAV-D data was permitted to augment the EGM2008 model.

Combining Into a Composite Model

The GRAV-D-augmented version of EGM2008 was then combined with GOCO05S, using the same procedure as that were used to combine EGM2008 and GOCO05S to yield the REF16A reference model supporting xGEOID16A. This final model, designated REF16B, served as the reference (global spherical harmonic) gravitational model for xGEOID16B.

In the final step of creating the xGEOID16B, the REF16B reference model was combined with the NGS terrestrial data, yielding xGEOID16B. This was done very nearly identically to the final combination of REF16A with the NGS terrestrial data. The primary exception to this was over Lake Michigan. For xGEOID16B, the REF16B model was used to identify and mitigate egregious biases in a few of the ship-track surveys over Lake Michigan. The 'de-biased' ship-track data was then used as NGS terrestrial data input for xGEOID16B over Lake Michigan.

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