

# On the impact of airborne gravity data to fused gravity field models

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**Abstract** In gravity field modeling, fused models that utilize satellite, airborne and terrestrial gravity observations are often employed to deal with erroneous terrestrially derived gravity datasets. These terrestrial datasets may suffer from long-wavelength systematic errors and inhomogeneous data coverage, which are not prevalent in airborne and satellite datasets. Airborne gravity acquisition plays an essential role in gravity field modeling, providing valuable information of the Earth's gravity field at medium and short wavelengths. Thus, assessing the impact of airborne gravity data to fused gravity field models is important for identifying problematic regions. Six study regions that represent different gravity field variability and terrestrial data point-density characteristics are investigated to quantify the impact of airborne gravity data to fused gravity field models. The numerical assessments of these representative regions resulted in predictions of airborne gravity impact for individual states and provinces in the USA and Canada, respectively. Prediction results indicate that, depending on the terrestrial data point-density and gravity field variability, the expected impact of airborne gravity can reach up to 3mGal (in terms of standard deviation) in Canada and Alaska (over areas of  $1^\circ \times 1^\circ$ ). However, in the mainland US region, small changes are expected (0.2–0.4 mGal over areas of  $1^\circ \times 1^\circ$ ) due to the availability of high spatial resolution terrestrial data. These results can serve as a guideline for setting airborne gravity data acquisition priorities and for improving future planning of airborne gravity surveys.

**Keywords** Airborne gravity · Gravity field modeling · Data fusion · Wavelet decomposition

## 1 Introduction

Knowledge of the Earth's gravity field is vital for several applications in geodesy and geophysics, such as geoid modeling and modeling of the Earth's crust and lithosphere (e.g., Woollard 1959; Forsberg 1993; McKenzie and Fairhead 1997; Rummel et al. 2002; Fullea et al. 2007; Amjadiparvar et al. 2013; de Castro et al. 2014; Meijde et al. 2015). Gravity field information can be acquired from satellite, airborne and terrestrial means at different spatial resolutions and coverage. Terrestrial (land and marine) gravity data provide full-field gravity field information, but are often contaminated by systematic (long-wavelength) errors (Heck 1990; Saleh et al. 2013). Moreover, their data density is often heterogeneous, with data gaps in mountainous regions, dense vegetation and near shore or sea ice covered areas, which further degrades the quality of terrestrially derived gravity field models. For this reason, gravity data derived from satellite and airborne platforms are fused with terrestrial data to create fused gravity field models that exhibit improved long, medium and short wavelengths ( $>80$  km) of the Earth's gravity field (e.g., Pavlis et al. 2012; Smith et al. 2013). For example, satellite-only gravity field models with data obtained from the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission resulted in representing the long and medium wavelengths ( $>160$  km) of the gravity field with global and homogeneous coverage (Pail et al. 2011) and improved fused gravity field models in these wavelengths (Yi and Rummel 2014). Improvement of fused gravity field models in medium and short wavelengths (250–80 km) depends on the availability of airborne gravity data

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that provide regionally homogeneous coverage. Regional airborne gravity surveys provide gravity field information at wavelengths of 300 km to a few kilometers with an accuracy level of 1–2 mGal (e.g., Bruton 2000). For instance, airborne gravity data in the US from the Gravity for the Redefinition of the American Vertical Datum (GRAV-D) project resulted in improving our knowledge of the gravity field at wavelengths of 250–80 km (e.g., Smith et al. 2013). However, the impact of airborne gravity to fused gravity field models varies depending on the specific characteristics of each region, in terms of gravity field variability and terrestrial data point-density (e.g., Bolkas et al. 2015). Therefore, assessing the ‘impact’ of airborne gravity to fused gravity field models and identifying the regions that would benefit from airborne gravity is important for setting airborne gravity data acquisition priorities in the future. In terms of terminology, it is important at this point to identify the meaning of the term ‘impact’ as it pertains to the fused gravity field model. While airborne data can be used to ‘correct’ terrestrially derived gravity field models, we avoid using this term because of the lack of independent gravity information for validation. The term ‘contribution’ may also be used; however, this implies an ‘improvement’, which may not always be the case. In order to avoid confusion, the terms ‘impact’, ‘effect’ and ‘change’ are utilized throughout.

The objective of this study is to assess the impact of airborne gravity to fused gravity field models and identify the regions where changes are notable. Free-air gravity anomalies available from the latest satellite, airborne and terrestrial datasets are fused in six regions in the US, which exhibit variations in terrestrial gravity data point-density and gravity field variability. The study areas and datasets are described below, followed by the gravity data fusion methodology. Subsequent sections deal with the data analysis and discussion of results. In the last section, conclusions regarding the role of airborne gravity data culminating in maps and tables of potential impact of airborne data for individual states and provinces in the US and Canada, respectively, are presented. Of note is the possibility for this study to be extended in order to assess the impact of airborne gravity on other geodetic models such as the geoid, which was not evaluated herein. With several countries opting to adopt a geoid-based vertical datum, the continuation of this study should prove to be a valuable source of information.

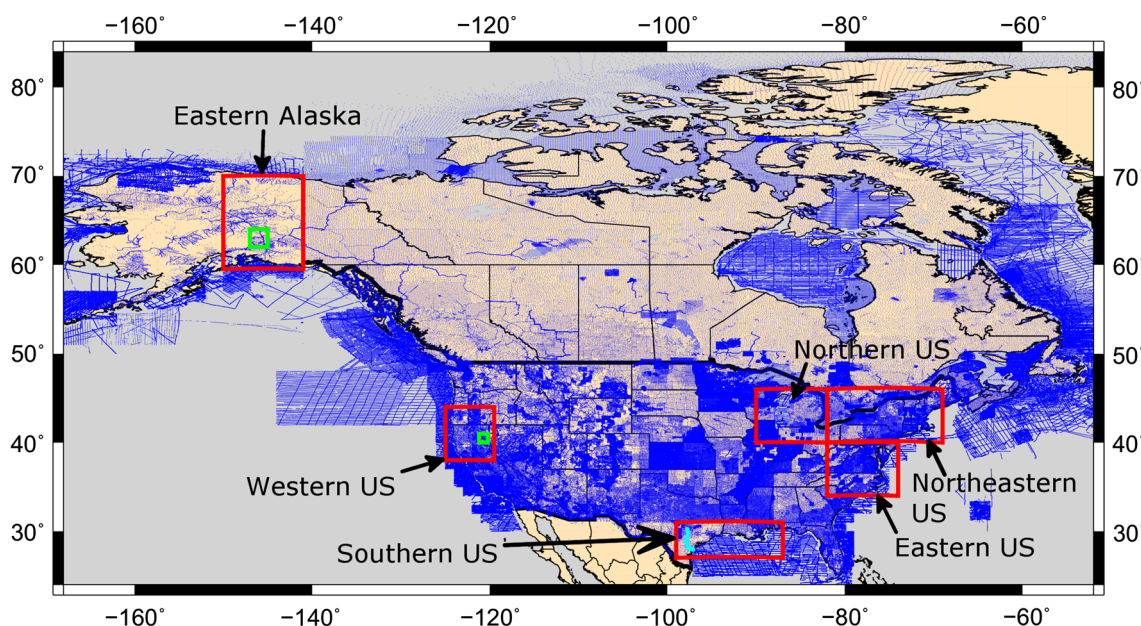
## 2 Study areas and datasets

Six regions with co-located satellite, airborne and terrestrial gravity datasets are evaluated for this study. Specifically, these are (see red boxes in Fig. 1): (1) the northern US, (2) northeastern US (3) eastern US, (4) western US, (5) southern US and (6) eastern Alaska. The airborne gravity datasets are

part of the GRAV-D project (Smith 2007) and were acquired with 10 km spacing at flight altitudes of 6–11 km. The original data provided at flight level were downward continued to the geoid using a 2nd order free-air correction (Heiskanen and Moritz 1967). This method was found to provide sufficient results for the analysis conducted in this study. Terrestrial free-air anomalies (land and marine) are retrieved from the National Geodetic Survey (NGS) database (see Fig. 1). Figure 1 also shows the Canadian terrestrial gravity datasets, retrieved from the Natural Resources Canada (NRCan) database. Long wavelength information for this study is derived from the fifth generation satellite model DIRR5 (Bruinsma et al. 2014) of the GOCE mission. DIRR5 is a result of the so-called direct approach of Level 2 GOCE data processing, and is based on a full combination of GOCE-satellite gravity gradient data with GRACE and LAGEOS data (Bruinsma et al. 2014).

EGM08 is used for full-field comparisons of the fused gravity field models (Pavlis et al. 2012). EGM08 incorporates the same terrestrial dataset (Pavlis et al. 2012), hence comparisons on land will be relative to EGM08. In the southern US, the satellite altimetry-based gravity model DTU10 is used (Andersen et al. 2010) for comparisons in ocean areas in the northern Gulf of Mexico. Comparisons in the remaining study areas are restricted to land, as airborne gravity data are mostly located over land. Moreover, in the southern US, free-air gravity anomalies are estimated from the absolute gravity values of the Geoid Slope Validation Survey of 2011 (GSVS11) (cyan line in Fig. 1), which provide an independent validation for the fused models. The GSVS11 line consists of 218 control marks with absolute gravity values between Austin and Rockpoint (Texas, USA) (for details see Smith et al. 2013).

Table 1 shows the variability of the gravity field (defined in this study as the standard deviation of the terrestrial free-air anomalies), terrestrial data density (defined in this study as the number of terrestrial data points per km<sup>2</sup>) and spatial extent (in km) of the study areas and sub-areas. For this study, a gravity field variability of ~20 mGal is considered low, while a variability of ~40 mGal is considered high. We assume that the gravity field variability is proportional to the terrain variability in the areas. Also, terrestrial data density of less than 0.04 points/km<sup>2</sup> is considered low, while data density of 0.10 points/km<sup>2</sup> is high. Terrestrial data density in eastern Alaska is only 0.02 points/km<sup>2</sup> and several data gaps exist. Hence, a sub-area with higher data density (i.e., 0.06 points/km<sup>2</sup>) is also selected (green box in Fig. 1). Furthermore, in the western US, a sub-area is selected (green box in Fig. 1) with a gravity field variability of 31 mGal (Table 1). This sub-area serves as an area of intermediate gravity field variability with respect to the northeastern US (variability of 24 mGal) and the western US (variability of 38 mGal).



**Fig. 1** Terrestrial gravity datasets in the US and Canada; red boxes show areas with co-located satellite, airborne and terrestrial data; green boxes show selected sub-areas

**Table 1** Regional and data characteristics of the six study areas

Region	Variability of gravity field (mGal)	Terrestrial data density (points/km <sup>2</sup> )	Extent (km)
Northern US	18	0.12	550 × 450
Northeastern US	24	0.10	660 × 960
Eastern US	22	0.17	660 × 450
Western US	38	0.14	600 × 400
Western US sub-area	31	0.11	110 × 80
Southern US	21	0.17	600 × 1100
Eastern Alaska	44	0.02	900 × 300
Eastern Alaska sub-area	46	0.06	220 × 100

### 3 Gravity field modeling

Modeling of the Earth’s gravity field is often performed through spherical harmonic expansion and Fourier transform (e.g., Pavlis et al. 2012; Schwarz et al. 1990). However, in these methods, errors associated with the gravity data will not only cause local errors in the frequency domain, but also affect adjacent areas (noted as spectral leakage). In the spatial domain this means that areas where gravity data are of poor quality may affect areas where gravity data are of high quality. Least squares collocation is another tool often employed in gravity field modeling, which provides estimates of the error of the fused gravity field model (e.g., Kern et al. 2003). However, this method is computationally intensive when large datasets are involved (as in this study) due to the construction of covariance matrices for the input gravity datasets (Schwarz et al. 1990). The wavelet transform is a powerful data fusion tool employed in a number

of fields (e.g., medical diagnostics, remote sensing, geodesy, etc.) due to its ability to localize in both space and spectral domains (e.g., Pajares and Cruz 2004) and efficiently handle large datasets (Panet et al. 2004, 2011). The wavelet localization properties are exploited herein for an improved understanding of how each individual gravity field dataset impacts/changes the fused gravity field models. In order to assess the impact of airborne gravity data on fused models, a fusion methodology based on wavelet decomposition in a 2D approximation is followed, which was found to facilitate the fusion of satellite, airborne and terrestrial gridded datasets (for details see Bolkas et al. 2015).

Satellite, airborne and terrestrial free-air gravity anomalies are gridded with a grid spacing of 20'' × 20'' (~0.5 km × 0.5 km) and decomposed up to level 10 (560 km in this study) using the 4th order Daubechies wavelet (Daubechies 1992). This grid spacing was selected in order to exploit the high spatial resolution of the terrestrial gravity datasets and does not

reflect the actual resolution of the fused models, which varies within the study areas (see also Fig. 1). Furthermore, several wavelet families were investigated including Symlets (orders from 1 to 16), Coiflets (orders from 1 to 5) and Daubechies (orders from 1 to 16). Results, in terms of first-order statistics, showed that the 4th order Daubechies wavelet performed the best. Since the wavelet functions were only used in a forward and inverse transform, their spectral sensitivities did not play an important role because the wavelengths were not interpreted in the wavelet domain.

A set of approximation and detail coefficients are derived from the decomposition of each input gridded dataset, through the 2D discrete wavelet transform (DWT); for detailed formulations see Burrus et al. (1998), Mallat (1998). The representation of the gridded gravity free-air anomalies ( $\Delta g_{FA}$ ) in the wavelet domain is given as follows (for a decomposition up to wavelet level 10):

$$\Delta g_{FA} = \sum_{k_x \in Z} \sum_{k_y \in Z} cA_{k_x, k_y}^{10} \varphi_{10, k_x, k_y}(x, y) + \sum_{i=H, V, D} \sum_{j=0}^{10} \sum_{k_x \in Z} \sum_{k_y \in Z} cD_{k_x, k_y}^{j, i} \psi_{j, k_x, k_y}^i(x, y) \quad (1)$$

where  $\varphi_{j, k_x, k_y}(x, y)$  and  $\psi_{j, k_x, k_y}^i(x, y)$  are the 2D scaling and wavelet basis functions, respectively;  $cA_{k_x, k_y}^{10}$  are the approximation coefficients of the input free-air gravity anomalies at level 10;  $cD_{k_x, k_y}^{j, i}$  are the detail coefficients in the horizontal, vertical, and diagonal direction ( $i = H, V, D$ ) of the input free-air gravity anomalies at level  $j$ ;  $k_x$ , and  $k_y$  are integer indices for the shift of the scaling and wavelet basis functions; and  $j$  is the wavelet level.

The scaling and wavelet basis functions perform a low-pass and high-pass filtering to the free-air gravity anomalies. The result of these filtering operations are the approximation and detail coefficients of Eq. (1), which represent low- and high-resolution information of the free-air gravity anomalies. Small numerical values for the wavelet scale (e.g.,  $j = 0$ ) mean high-frequency information of the free-air gravity anomalies, while large numerical values (e.g.,  $j = 10$ ), mean low-frequency information. Note that the grid spacing of the gravity anomalies at a wavelet level changes according to the dyadic sequence of the DWT. The correspondence of the wavelet levels with wavelength of the gravity field is discussed in the next paragraphs along with the data fusion scheme.

The wavelet-based data fusion takes into account the error contribution of the three input datasets in the various wavelet bands. Analysis of the DIRR5 model shows the error is  $\sim 1$  mGal at wavelengths of  $\sim 200$  km (Bruinsma et al. 2014). Thus, in order to model the long-wavelength gravity field information DIRR5 is used in wavelet levels 10 and 9 ( $> 280$

km). Airborne gravity data from the GRAV-D project present their strongest spectral information at wavelengths of  $\sim 250$ – $85$  km (Smith et al. 2013), while crossover analysis of the airborne gravity data has shown that their quality is about  $2$ – $3$  mGal (Smith et al. 2013). Therefore, their impact in the fused models is explored at wavelet levels 7 and 8 (70 and 140 km, respectively). Terrestrial gravity data in N. America are precise, but contain systematic errors that range from hundreds to thousands of kilometers with magnitudes of a few mGal (Huang et al. 2008; Saleh et al. 2013). Therefore, their inclusion is limited to wavelet levels  $< 8$  (i.e., medium and short wavelengths,  $< 140$  km). For the wavelet levels where there is an overlap between the various datasets (i.e., levels 7 and 8) the detail wavelet coefficients of the fused model are derived via a weighted average of the gridded datasets (DIRR5, GRAV-D, and NGS database). The weighted average of the detail wavelet coefficients at wavelet scale is implemented as:

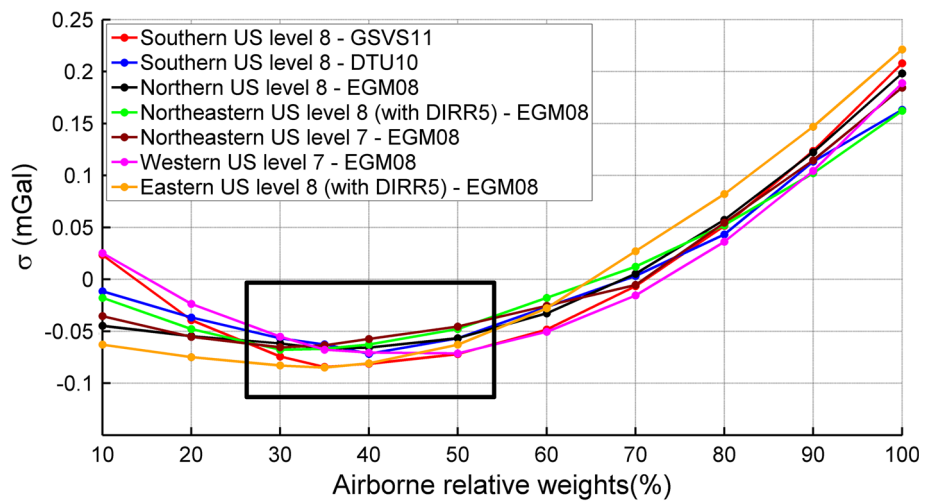
$$cD_{\text{fused}}^{j, (H, V, D)} = \frac{cW_{\text{Sat}} cD_{\text{Sat}}^{j, (H, V, D)} + cW_{\text{Air}} cD_{\text{Air}}^{j, (H, V, D)} + cW_{\text{Ter}} cD_{\text{Ter}}^{j, (H, V, D)}}{cW_{\text{Sat}} + cW_{\text{Air}} + cW_{\text{Ter}}}, \quad (2)$$

where  $cD_{\text{fused}}^{j, (H, V, D)}$  are the fused horizontal, vertical and diagonal sets of the detail wavelet coefficients at scale  $j$ ,  $cD_{(\cdot)}^{j, (H, V, D)}$  are horizontal, vertical and diagonal sets of detail wavelet coefficients of the input gridded datasets (i.e., satellite, airborne and terrestrial) at scale  $j$ ,  $cW_{(\cdot)}$  are the weights of the detail wavelet coefficients of the input gridded datasets (i.e., satellite, airborne and terrestrial), with values from 0 to 100 and sum of 100. Note that a weight of 100 for a single dataset means that only this dataset is used in the respective wavelet level.

The fused gravity field model is derived by applying the inverse DWT, which performs the synthesis of the input gravity field signals. To derive the relative weights of the airborne gravity data with respect to the satellite and terrestrial data at wavelet levels 7 and 8, several weight scenarios for the airborne gravity data are tested. The fused models are then compared with EGM08, DTU10 and GSVS11, and the standard deviations of these comparisons are calculated (see Fig. 2). Table 2 summarizes the fusion scenarios applied herein. For most regions, the minimum point (black box in Fig. 2) is located for relative weights of 30–35 %, while for the western US it is located at 50 %. In eastern Alaska, the airborne dataset is used in levels 8 and 7 at 100 % contribution, as it improves the fused model at these levels compared to EGM08. Fused models without airborne data are also estimated to show the impact of airborne data. In these models, the airborne data are replaced by DIRR5 or the terrestrial gridded data. Conclusions regarding the impact of airborne gravity data to fused gravity-field models are specific to the



**Fig. 2** Change in standard deviation ( $\sigma$ ) for various airborne relative weights at levels 7 and 8 for the study areas; the  $\sigma$  values are reduced by their means to enable the comparison



**Table 2** Fusion scenarios of satellite, airborne and terrestrial gravity data for the study areas

Region	Satellite	Airborne	Terrestrial
Northern US	Levels 10–9	30 % at level 8	70 % at level 8, levels <7
Northeastern US	Levels 10–9, 70 % level 8	30 % at level 8, 30 % at level 7	70 % at level 7, levels <6
Eastern US	Levels 10–9, 65 % level 8	35 % at level 8	Levels <7
Western US	Levels 10–8	50 % at level 7	50 % at level 7, levels <6
Southern US	Levels 10–9	35 % at level 8	65 % at level 8, levels <7
Eastern Alaska	Levels 10–9	Levels 8–7	Levels <6

weighting scheme applied herein, and results may change depending on the chosen weighting strategy. We selected the weighting scheme based on first-order statistics from the comparison of fused models and EGM08, DTU10 and GSVS11, and selected the weights based on the greatest impact of airborne data to the fused model.

## 4 Discussion of results

### 4.1 Impact of terrestrial data density and gravity field variability

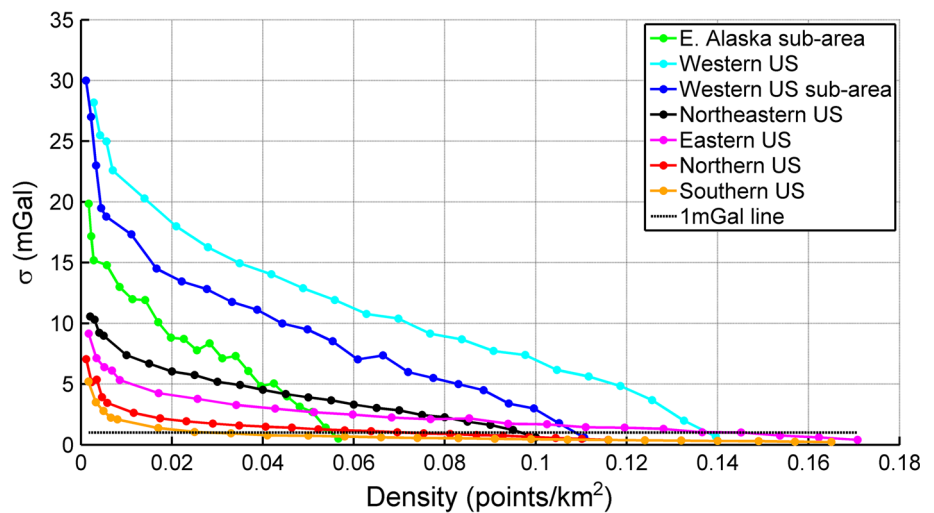
To assess the impact of terrestrial data density on fused gravity field models several terrestrial gridded datasets are created using successively fewer data points, referred to herein as “thinned” gridded datasets. The thinned gridded terrestrial datasets are compared with the original terrestrial dataset, revealing the level (in terms of standard deviation— $\sigma$ , in mGal) and rate [ratio of  $\sigma$  change to the point-density change with units of mGal/(points/km<sup>2</sup>)] of deterioration in the six study areas (Fig. 3). Results show that in areas of high gravity field variability (eastern Alaska, western US), the deterioration rate of gridded terrestrial datasets is higher than in areas of low gravity field variability (northeastern, eastern, northern and southern US). For instance, in northern US thinned

gridded datasets remain around the 1-mGal level even when the terrestrial data are thinned by 50 %, i.e., from 0.12 to 0.06 points/km<sup>2</sup>. On the contrary, in the western US, any reduction in terrestrial data densities creates large deviations in the terrestrial gridded datasets. For example, the 1-mGal level is exceeded when the terrestrial data is thinned by only 5 %. Figure 3 reveals EGM08 outperforming the thinned gridded terrestrial datasets and therefore provides a reasonable means for comparison.

### 4.2 Impact of airborne and satellite gravity data to fused models

In order to evaluate the impact of airborne and satellite gravity data to fused gravity field models, the various ‘thinned’ gridded terrestrial datasets (see previous section) are fused with the airborne and satellite models, and the results are compared with EGM08. Figure 4 shows the change in  $\sigma$  of the fused models when DIRR5 is fused with the thinned gridded terrestrial datasets. Including DIRR5 in the fused model in low gravity field variability areas does not change with the terrestrial data densities (northern, southern, eastern and northeastern US). In contrast, in areas of higher gravity field variability, such as the western US and eastern Alaska, the inclusion of DIRR5 in the fused models creates higher rates of  $\sigma$ -differences for densities less than 0.04 points/km<sup>2</sup>.

**Fig. 3** Terrestrial gravity gridded datasets deterioration in standard deviation ( $\sigma$ ) based on various densities of terrestrial data used



**Fig. 4** Change of standard deviation ( $\sigma$ ) in fused gravity field models due to the inclusion of DIRR5 for various terrestrial data densities

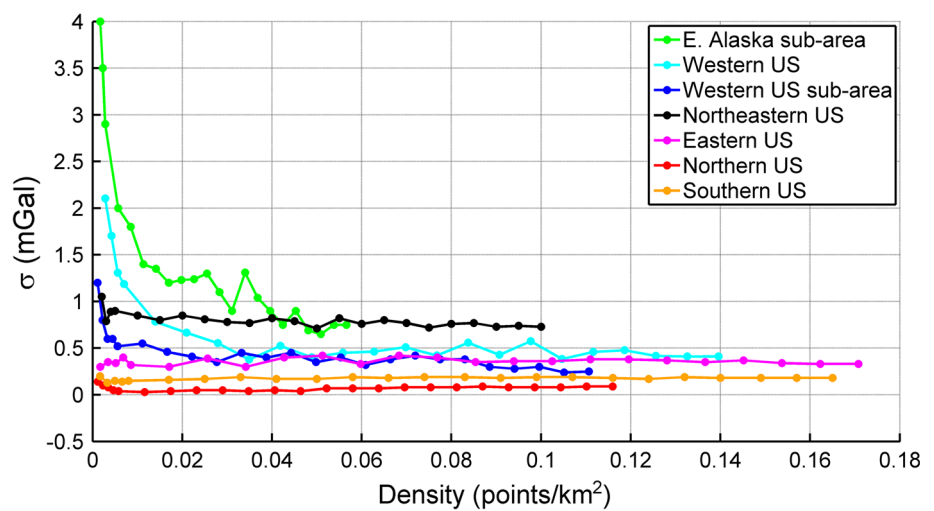


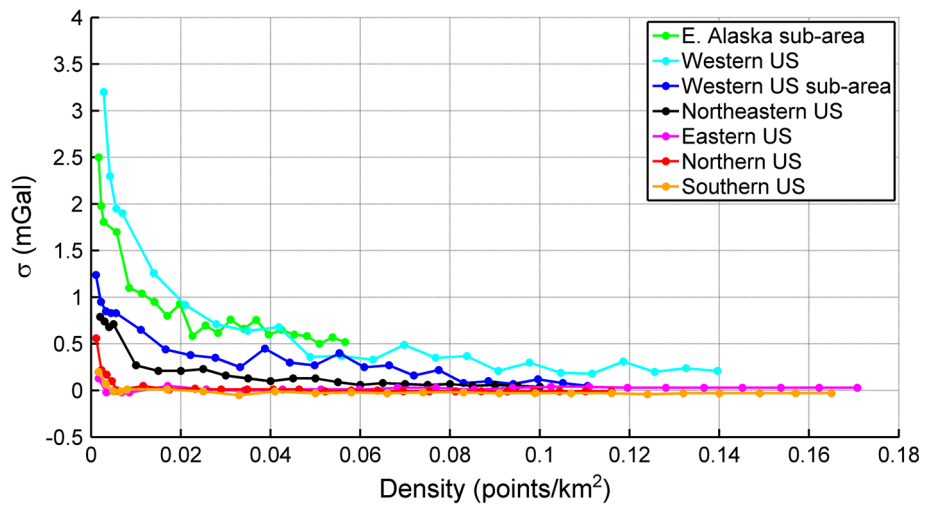
Figure 5 reveals the additional change in  $\sigma$  that airborne gravity brings to the fused models, when airborne data are fused with DIRR5 and the thinned gridded terrestrial datasets. Airborne data have limited impact (0.2–0.3 mGal level) in areas of low gravity field variability such as the northern, eastern, and southern US. For the northeastern US, where gravity field variability is slightly ( $\sim 2$ –6 mGal) larger, differences in  $\sigma$  reach the 0.6–0.7 mGal level for densities of less than 0.01 points/km<sup>2</sup>. The sub-area in the western US shows that in regions with gravity field variability of  $< 31$  mGal, airborne data, in general, will have sub-mGal level impact to fused models. However, in regions with higher gravity field variability, such as the western US and eastern Alaska (gravity field variability of 38 and 46 mGal, respectively), the airborne data impact starts at the  $\sim 0.5$  mGal level and increases up to  $\sim 3$  mGal at low terrestrial data densities ( $< 0.01$  points/km<sup>2</sup>). Therefore, airborne gravity data will have a greater effect in regions exhibiting large gravity variability. Results from this numerical assessment are utilized in the next section to identify areas in the US and Canada

where airborne gravity data provide notable changes to the gravity field model. It should be noted that the terms ‘high’ and ‘low’ impact are relatively used in this study and the significance of these values depends on the specific application. For instance sub-mGal changes in the gravity field can have a great impact for applications such as geoid modeling (e.g., [Smith et al. 2013](#)), but this can have limited effect in geological modeling and interpretation (e.g., [Pal et al. 2015](#)).

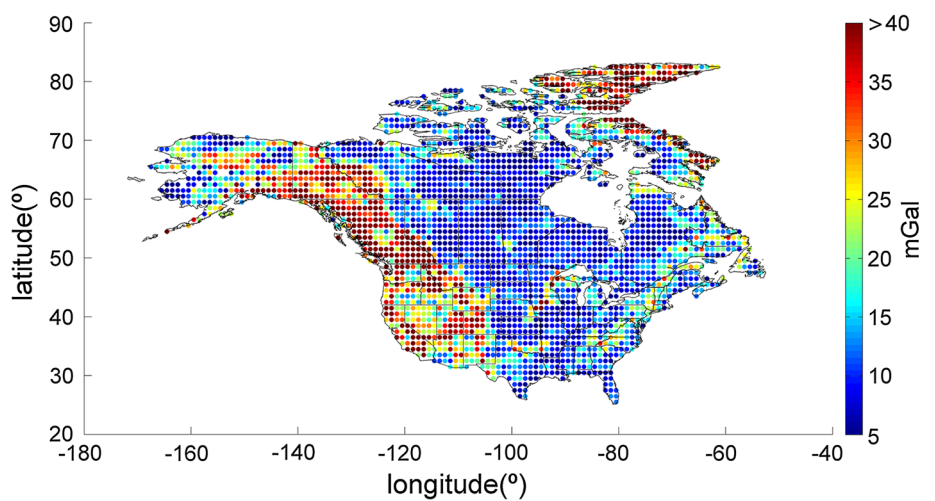
#### 4.3 Prediction of the impact of airborne gravity to fused gravity field models

In order to identify areas where airborne gravity significantly impacts fused models, gravity field variability and terrestrial data densities are computed in cells of  $1^\circ \times 1^\circ$  in Canada and the US, using the existing and available terrestrial gravity field information. Resulting gravity field variability and terrestrial data density are shown in Figs. 6 and 7, respectively. Utilizing this information and the results from the previous section, the prediction of airborne gravity impact to the grav-

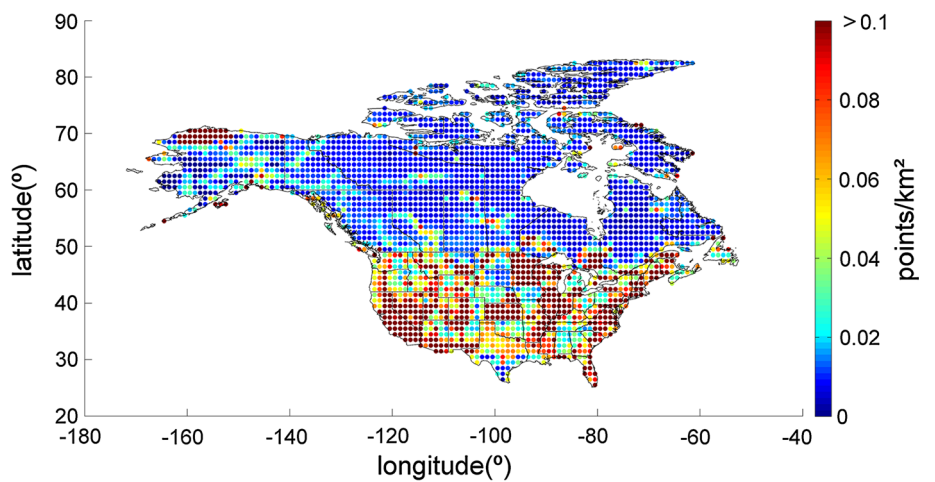
**Fig. 5** Change of standard deviation ( $\sigma$ ) in fused gravity field models due to the inclusion of airborne data for various terrestrial data densities



**Fig. 6** Gravity field variability in the US and Canada; *dark-red areas* depict gravity field variabilities of >40 mGal



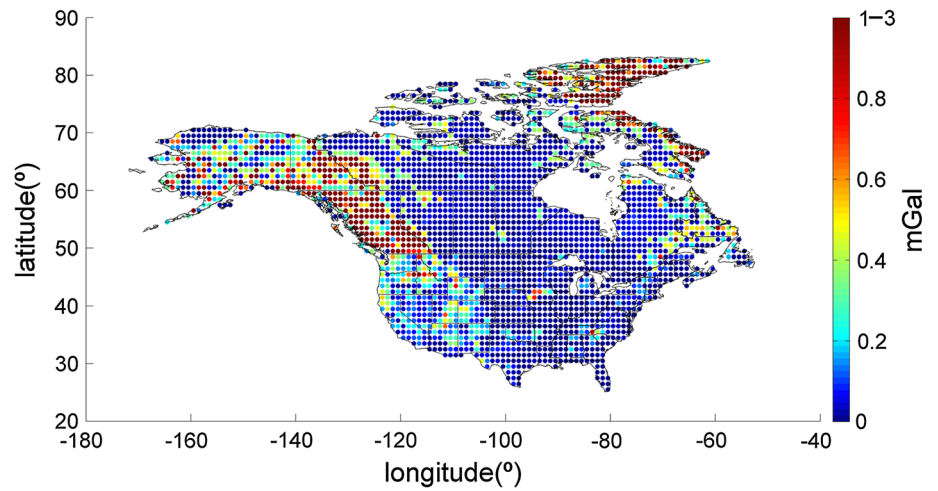
**Fig. 7** Terrestrial data density in the US and Canada; *dark-red areas* depict terrestrial data densities of >0.1 points/km<sup>2</sup>



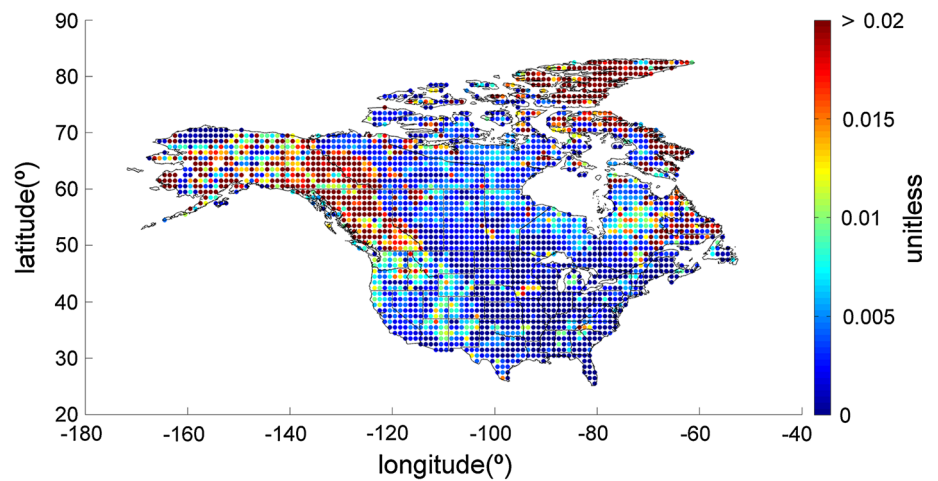
ity field is possible (Fig. 8). It is recognized that due to the lack of independent terrestrial gravity information, prediction outcomes may underestimate the actual effect of airborne gravity data to the fused gravity field model. The correlation coefficients are 0.7 for gravity variability and airborne data, and

−0.4 for terrestrial data density and airborne data. The central and eastern US regions present low gravity field variability (<20 mGal) and high terrestrial data densities of about 0.10 points/km<sup>2</sup> (see Figs. 6, 7). Therefore, the impact of airborne data to the fused gravity field models will be limited to <0.3

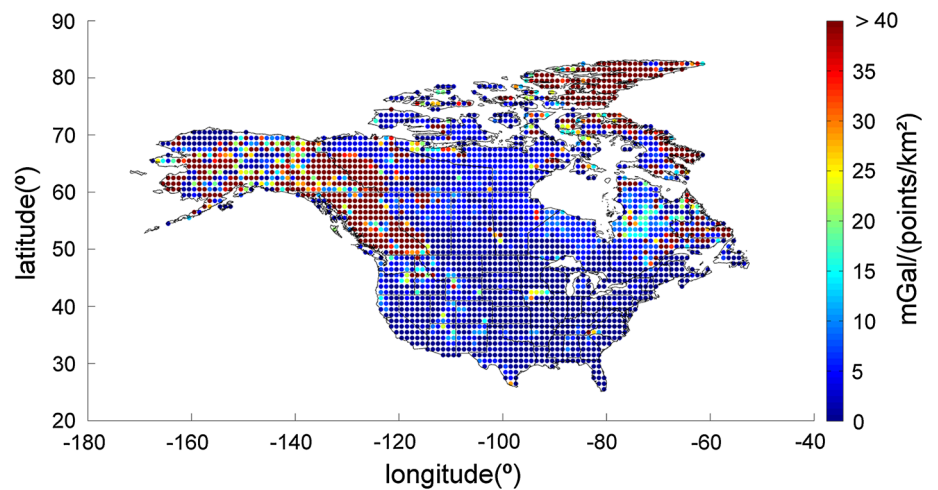
**Fig. 8** Prediction of airborne data impact on the gravity field based on terrestrial data density and gravity field variability



**Fig. 9** Cell-by-cell ratios of airborne gravity data impact/gravity field variability



**Fig. 10** Cell-by-cell ratios of airborne gravity data impact (mGal)/terrestrial data point density (points/km<sup>2</sup>)



mGal (Fig. 8). Similar effects are expected in western Alaska and central Canada (see Fig. 8). In eastern Canada and Baffin Island, larger changes of  $\sim 0.7$  mGal are expected due to the higher gravity field variability ( $\sim 25$ – $35$  mGal) and low terrestrial data density ( $0.01$ – $0.02$  points/km<sup>2</sup>). In the western US, both gravity field variability and terrestrial data densities

are high ( $> 30$  mGal and  $0.08$ – $0.10$  points/km<sup>2</sup>, respectively) and the assessment predicts that the airborne data impact will be slightly higher ( $< 0.4$  mGal). In eastern Alaska, western Canada and Ellesmere Island, where gravity field variability is high ( $> 30$ – $40$  mGal) and terrestrial data densities are very low ( $0.01$ – $0.02$  points/km<sup>2</sup>), airborne gravity data are



**Table 3** Predicted airborne gravity impact on the gravity field by US state, and Canadian province; states/provinces highlighted in italics show impacts greater than 0.3 mGal

States/province	Terrestrial data point density (points/km <sup>2</sup> )	Gravity field variability (mGal)	Predicted airborne impact (mGal)
Alabama	0.039	17	0.1
<i>Alaska</i>	<i>0.044</i>	25	<i>0.3</i>
Arizona	0.123	28	0.1
Arkansas	0.158	11	0.0
California	0.190	45	0.2
<i>Colorado</i>	<i>0.115</i>	<i>40</i>	<i>0.3</i>
Connecticut	0.119	20	0.1
Delaware	0.105	16	0.1
Florida	0.084	14	0.0
Georgia	0.063	15	0.0
<i>Hawaii</i>	<i>0.024</i>	<i>60</i>	<i>0.8</i>
Idaho	0.059	33	0.2
Illinois	0.286	11	0.0
Indiana	0.155	12	0.0
<i>Iowa</i>	<i>0.019</i>	<i>34</i>	<i>0.9</i>
Kansas	0.160	12	0.0
Kentucky	0.072	18	0.1
Louisiana	0.049	13	0.0
Maine	0.112	13	0.0
Maryland	0.112	25	0.1
Massachusetts	0.164	16	0.0
Michigan	0.079	22	0.1
Minnesota	0.244	20	0.0
Mississippi	0.070	16	0.1
Missouri	0.087	16	0.1
Montana	0.078	33	0.2
Nebraska	0.084	23	0.1
Nevada	0.136	29	0.1
New Hampshire	0.195	18	0.0
New Jersey	0.091	22	0.1
New Mexico	0.117	28	0.1
New York	0.087	22	0.1
North Carolina	0.109	28	0.1
North Dakota	0.058	15	0.1
Ohio	0.063	18	0.1
Oklahoma	0.039	28	0.2
Oregon	0.060	32	0.2
Pennsylvania	0.073	25	0.2
Rhode Island	0.020	6	0.0
South Carolina	0.097	15	0.0
<i>South Dakota</i>	<i>0.032</i>	<i>26</i>	<i>0.3</i>
Tennessee	0.060	17	0.1
Texas	0.046	22	0.1
<i>Utah</i>	<i>0.118</i>	<i>34</i>	<i>0.3</i>
Vermont	0.101	23	0.1
Virginia	0.200	22	0.0

**Table 3** continued

States/province	Terrestrial data point density (points/km <sup>2</sup> )	Gravity field variability (mGal)	Predicted airborne impact (mGal)
<i>Washington</i>	0.068	42	0.4
West Virginia	0.067	23	0.1
Wisconsin	0.175	34	0.2
<i>Wyoming</i>	0.064	38	0.4
District of Columbia	0.537	4	0.0
Alberta	0.017	20	0.2
Saskatchewan	0.017	15	0.2
Manitoba	0.016	20	0.2
<i>Newfoundland &amp; Labrador</i>	0.017	31	0.4
Prince Edward Island	0.049	7	0.0
Nova Scotia	0.042	19	0.1
<i>Northwest Territories</i>	0.011	31	0.5
Nunavut	0.011	34	1.3
Ontario	0.054	14	0.0
New Brunswick	0.173	18	0.0
<i>Yukon Territory</i>	0.016	41	1.0
<i>British Columbia</i>	0.019	55	0.9
Quebec	0.023	24	0.2

expected to have the largest effect and could lead to improved gravity field models by 1–3 mGal.

The spatial distribution of the cell-by-cell ratios (airborne gravity data impact/gravity field variability and airborne gravity data impact/terrestrial data point density) is shown in Figs. 9 and 10, respectively. Figure 9 demonstrates where the airborne impact would be significant due to gravity field variability and Fig. 10 demonstrates where the airborne impact would be significant due to terrestrial data points density. Gravity variability, primarily caused by increased terrain variability, is more relevant than terrestrial data density with respect to the predicted impact of airborne data.

Table 3 lists the three key parameters, namely terrestrial data density, gravity field variability, and airborne impact for each state and province/territory in the US and Canada, respectively. States/provinces highlighted by italics are those in which airborne campaigns could contribute significantly towards a better gravity field model indicating the regions that should perhaps be prioritized in future airborne campaigns. The table also reveals the areas where airborne campaigns will have a smaller impact on fused gravity field models, i.e., the central and eastern US as well as central Canada.

## 5 Conclusions

Six study areas in the US with co-located satellite, airborne and terrestrial gravity data were used to numerically assess

the impact of airborne gravity data on fused gravity field models. Results indicate that gravity field variability and terrestrial data density are important factors controlling the improvements which airborne data yield when used in fused gravity field models. The numerical results from the aforementioned study areas were used to predict airborne impact on all states and provinces in the US and Canada, respectively. Prediction results show that the Alaskan territories and Canadian Rockies present highly variable gravity field and low terrestrial data densities; hence, significant impacts are expected in these regions (1–3 mGal). In general, in the US, small changes are expected (<0.3 mGal) due to the existing high terrestrial data density. However, terrestrial data biases, that are not fully assessed in this study, may increase prediction results. The methodology presented can aid with setting airborne data collection priorities and improve overall planning of upcoming airborne gravity surveys. Future work should focus on assessing the impact of airborne gravity to other geodetic parameters such as the geoid, which was not evaluated as part of this study. This will further enhance our understanding of impact of airborne gravity in view of developing geoid-based vertical datums.

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