1739

MERGING OF AIRBORNE GRAVITY AND GRAVITY DERIVED FROM SATELLITE ALTIMETRY: TEST CASES ALONG THE COAST OF GREENLAND

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ABSTRACT

The National Survey and Cadastre - Denmark (KMS) has for several years produced gravity anomaly maps over the oceans derived from satellite altimetry. During the last four years, KMS has also conducted airborne gravity surveys along the coast of Greenland dedicated to complement the existing onshore gravity coverage and fill in new data in the very-near coastal area, where altimetry data may contain gross errors. The airborne surveys extend from the coastline to approximately 100 km offshore, along 6000 km of coastline. An adequate merging of these different data sources is important for the use of gravity data especially, when computing geoid models in coastal regions.

The presence of reliable marine gravity data for independent control offers an opportunity to study procedures for the merging of airborne and satellite data around Greenland. Two different merging techniques, both based on collocation, are investigated in this paper. Collocation offers a way of combining the individual airborne gravity observation with either the residual geoid observations derived from satellite altimetry or with gravity derived from these data using the inverse Stokes method implemented by Fast Fourier Transform (FFT).

Keywords: airborne gravimetry, satellite altimetry, merging techniques, collocation, FFT

1. INTRODUCTION

Airborne gravimetry is a fast and economic method for local to regional scale gravity mapping. Some of the biggest advantages are the uniform and seamless coverage of land and sea, and the ability to cover remote and otherwise inaccessible areas. The bias free property of airborne gravity data obtained by spring type gravimeters is also an important point for geodetic applications, see *Childers et al. (2001)* and *Olesen et al. (2000)*.

Altimetric gravity fields are unique in the sense that they provide estimates of global uniform gravity information at high resolution. These global marine gravity fields are in the KMS99 solution (*Andersen et al., 1999*) given on a grid corresponding to 4 by 4

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kilometers at the equator for all marine regions within the 82-degree parallels. In near coastal regions, the accuracy of the altimetric gravity field is known to degrade, due to the coastal sea state variability (*Andersen and Knudsen, 2000*). The processing of the satellite altimetry data is based on the EGM96 geoid (*Andersen and Knudsen, 1998*), and possible deficiencies in the EGM96 geoid of wavelength longer than 200 km will not be improved from the altimetric observations. This may lead to long wavelength errors in the altimetry derived gravity field.

Two different approaches based on collocation (*Moritz, 1980*) are used to merge airborne gravity data with satellite altimetry. These are:

- collocation using sea surface height observations from satellite altimetry and airborne gravity
- collocation based interpolation of Fast Fourier Transform (FFT) derived gravity (KMS99) and airborne gravity (hereafter FFT+interpolation).

The same set of satellite altimetry observations is used for both methods. Data are the GEOSAT and ERS-1 geodetic and repeat mission data processed as described by *Andersen and Knudsen (1998)*. Since all three test areas are located further north than latitude of 66° North, there are no TOPEX/Poseidon data available. For the first merging method, the sea surface height observations are used whereas, in the second method, gravity anomalies from the KMS99 gravity field are used. The KMS99 gravity anomalies are derived using the inverse Stokes method, implemented by using FFT, but otherwise based on the same sea surface height data, which was used in the first merging method.

The three areas, chosen as test cases, are shown in Figure 1. They are characterized by having different ice conditions and sufficient data coverage. The first area is Disko Bay. It is located on Greenland's west coast at latitude of 69° North. This area has seasonal ice cover and ice drift. The second area is the Blosseville Coast, it is located at the same latitude as Disko Bay, but on the east coast. Due to the more severe ice conditions on this coast, the satellite altimetry data for this area are expected to be noisier than those for the Disko Bay area. Finally, the third area, Shannon Island, is located at latitude of 75° North on the east coast. It has the most severe ice conditions of the three test areas and is virtually permanently ice covered.

2. MERGING METHODS EMPLOYED

In the first collocation approach, where the satellite sea surface height observations and airborne gravity are merged, the solutions are obtained using the program GEOCOL from the GRAVSOFT package (*Tscherning et al., 1992*). A covariance function based on airborne gravity residuals is estimated for each area and an analytic expression is determined (*Knudsen 1987*), see Figure 2. A system of normal equations, including auto and cross covariance for gravity and height residuals, is set up and solved. An error model, which takes into account the correlated noise, is used for the airborne gravity. However, the effect of incorporating this feature was found to be insignificant. This implies, that even though the airborne data are filtered along track, they may be considered as point values for our use. Predicted gravity anomalies, as well as their associated error estimates, are finally derived from the normal equation solution.

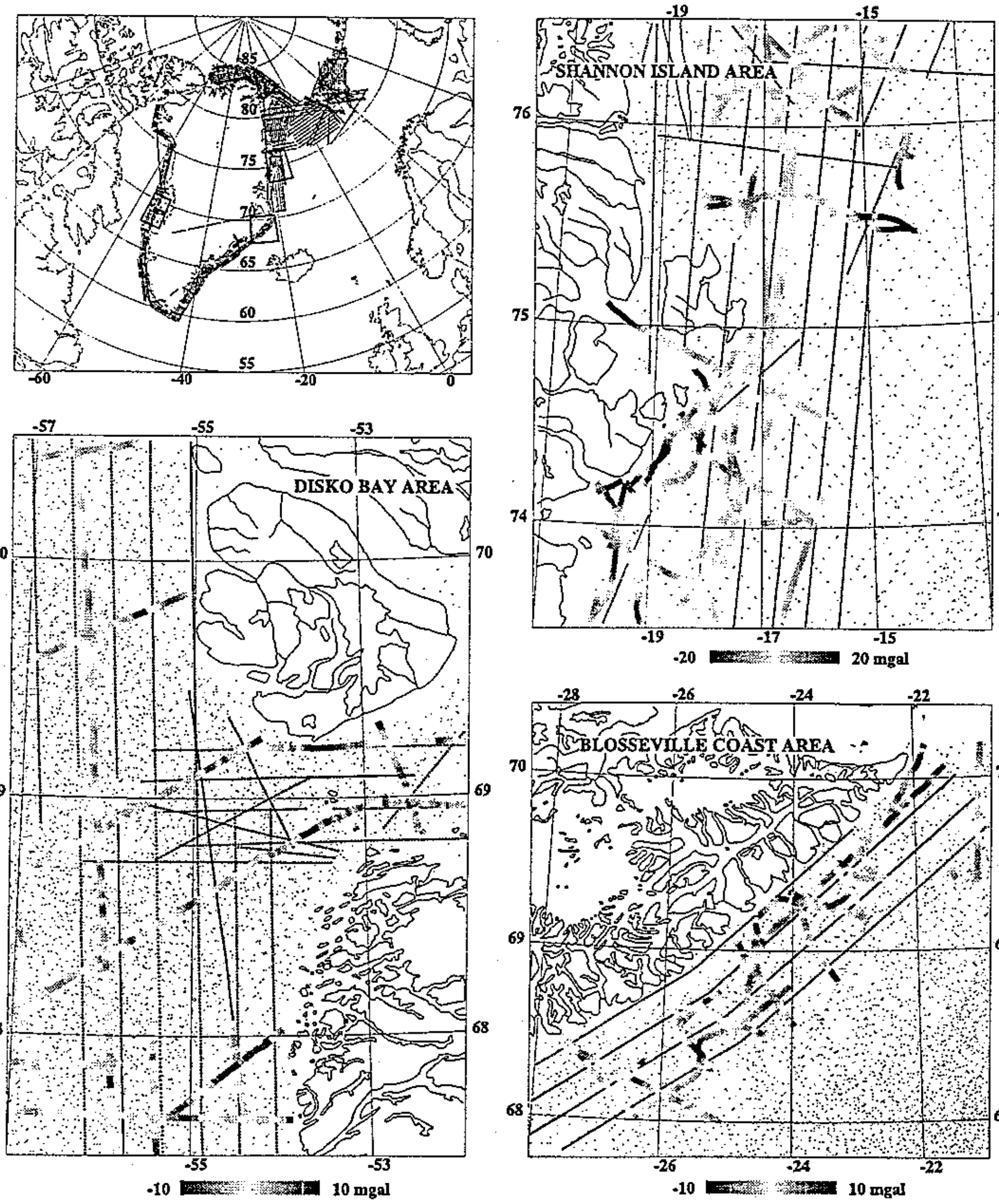

Fig. 1. Overview and detailed maps for the three test areas. The overview map of Greenland shows the tracks of the airborne surveys and the location of the three test areas. The detailed maps show the data distribution for satellite altimetry (gray dots) and airborne gravity (black dots) together with the difference between marine gravity and collocation results based on sea surface heights observations and airborne gravity. This difference is shown as a gray scale band along the marine tracks.

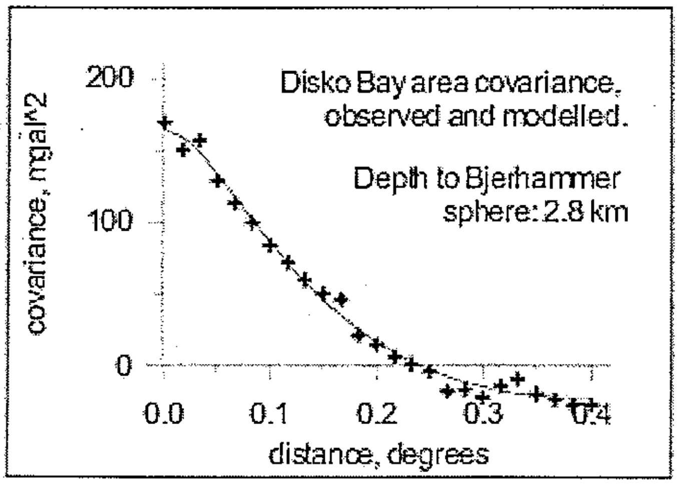

Fig. 2. Observed and modeled covariance functions for the Disko Bay area.

The second merging method (FFT+interpolation) uses airborne gravity and the KMS99 satellite gravity anomalies, which where derived by using FFT. The KMS99 satellite altimetry gravity data are merged with the airborne gravity data using least squares collocation. A second order Markov covariance function with a correlation length of 12 km is used in the least squares collocation. We assign a noise equal to 2 mgal to the airborne data. A smooth noise model reflecting the misfit between satellite and marine gravity is assigned to the satellite gravity data. For each test region, the noise values range between roughly 5 and 20 mgal.

3. DATA

The airborne gravity surveys around Greenland were performed during four field campaigns during the summers of 1998 to 2001 (*Forsberg et al., 1999; Olesen et al., 2000*). The US National Imagery and Mapping Agency (NIMA) provided most of the funding for this work. The purpose of the surveys was to complement the existing on-shore gravity coverage, mainly established by KMS by helicopter-based conventional gravimetry in the years of 1991-1997 (*Forsberg and Rubek, 1998*). Refined algorithms for airborne gravity processing, together with a careful readings at base stations, have proven to give virtually unbiased gravity estimates (*Olesen et al., 2000*). The bias free nature of the airborne gravity data is underlined by the fact that no track crossover adjustment had to be applied in the processing of the data.

The airborne gravity observations were converted from gravity disturbances to gravity anomalies using a geoid based on the EGM96 spherical harmonic coefficients (*Lemoine et al., 1998*). (This conversion is only needed when merging with the KMS99 gravity anomaly data, and the conversion error is judged to be below 0.3 mgal).

The marine gravity data were collected in the 1990s by NUNAOIL, the national oil company of Greenland. The marine data is considered to be of the highest quality, with an

Table 1. Differences between airborne gravity and nearby marine data points (in mgal)

Max. distance	Number of points	Mean diff.	Std. dev.	Abs. max
1 km	1212	0.4	2.5	13.1
2 km	2455	0.5	2.7	14.7

error standard deviation of less than 1 mgal. A special effort was made to ensure that the marine data were properly connected to IGSN71 (*Strykowski and Forsberg, 1995*).

Table 1 shows a comparison of the airborne gravity with nearby marine gravity data, which also include data points outside the test areas. The mean difference of 0.4 mgal indicates that one or both of the two data sets contain minor systematic errors. The harbor gravity ties are a possible source for this error, since the harbor ties are referred to the mean sea level rather than to the geoid. Also, the EGM96 geoid model incorporated in the airborne data set may be a source for minor systematic errors. The standard deviation of 2.5 mgal agrees well with the errors assigned to the two data sets. The error assigned to the airborne and marine data is 2 mgal and 1 mgal, respectively.

The satellite altimetry data are the GEOSAT and ERS-1 geodetic and repeat mission data, which were also used by *Andersen and Knudsen (1998)*. For Disko Bay and Blosseville Coast areas, both ERS and GEOSAT geodetic mission data are available, whereas for the Shannon area only sparse data from the ERS-1 exact repeat mission are available. Global comparisons with marine observations indicate a noise level of 4 mgal in the open ocean for the KMS99 gravity field. (*Andersen et al., 1999*). This noise estimate seems to be rather optimistic for the coastal regions around Greenland, mainly due to the presence of sea ice.

4. COMPARISONS WITH MARINE DATA

The methods and data combinations listed in Table 3 are used for gravity predictions at the marine data points. The results of comparisons for each area are summarized in Table 4.

For Disko Bay and Blosseville Coast areas, Table 4 shows that the gravity estimates derived from satellite altimetry fit the marine data at the 5 to 6 mgal standard deviation level, with the collocation solution performing slightly better than the FFT one.

Table 2. The local marine gravity field and its residuals relative to EGM96 (in mgal)

	Disko Bay 1217 marine observations		Blosseville Coast 1506 marine observations		Shannon Island 2997 marine observations	
	Observed	Residual	Observed	Residual	Observed	Residual
Mean	3.6	−4.6	26.6	2.8	11.9	0.9
Std. dev.	57.7	14.7	18.0	16.6	35.6	14.3
Abs. max.	120.1	42.1	67.4	46.1	71.2	53.3

Table 3. Methods and data combinations

Method \ Data	Airborne gravity	Satellite altimetry	Satellite altimetry + airborne gravity
Collocation	X	X	X
FFT + interpolation		X	X

Both solutions suffer from a bias problem. Inclusion of the airborne data reduces this bias problem and improves the fit. The standard deviation of the error is now 3.6 to 3.9 mgal in the Disko Bay area and 4.2 to 4.7 mgal in the Blosseville Coast area. The collocation solution again performs best in both areas. The difference in the quality of the satellite data in the two areas is mainly due to ice conditions (ice drift and seasonal ice cover). Results from one of the marine tracks in the Blosseville Coast area are shown in Figure 3. The figure illustrates a good concurrence between the formal error estimates and the misfit. It also shows an excellent agreement between airborne and marine data at the crossing points. A closer examination of Figure 1 depicts that this is the case almost everywhere in the three test areas.

There is hardly any additional gravity information contained in the pure altimetry based gravity field in the Shannon Island area when compared to the EGM96 field, see Table 2 and 4. This is partly due to a more severe ice conditions than in the other areas and partly due to an error in the preprocessing procedure of the altimetry data used in the derivation of the KMS99 gravity field. Consequently, the results based only on the airborne data fit the marine data as well or even better than results obtained with the merged data.

Table 4. Comparisons to marine gravity data (in mgal).

Area	Input data	Method	Mean	Std. dev.	Abs. max.
Disko Bay	Airborne gravity	Collocation	−0.5	6.9	26
	Satellite altimetry	Collocation	−2.5	5.4	24
		FFT + interp.	−2.5	5.6	26
	Satellite altimetry + airborne gravity	Collocation	−0.7	3.6	18
		FFT + interp.	−1.5	3.9	23
Blosseville Coast	Airborne gravity	Collocation	−0.3	7.8	33
	Satellite altimetry	Collocation	2.4	5.8	27
		FFT + interp.	1.0	5.9	29
	Satellite altimetry + airborne gravity	Collocation	−0.1	4.2	17
		FFT + interp.	0.2	4.7	25
Shannon Island	Airborne gravity	Collocation	−1.6	7.0	31
	Satellite altimetry	Collocation	−4.1	12.8	50
		FFT + interp.	1.8	21.0	70
	Satellite altimetry + airborne gravity	Collocation	−0.9	7.6	46
		FFT + interp.	1.6	13.0	51

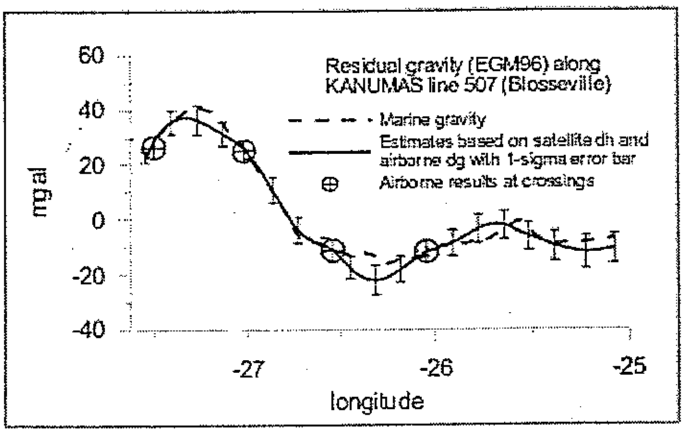

Fig. 3. Marine gravity and collocation estimates based on sea surface height anomalies and airborne gravity along one of the marine gravity tracks in the Blosseville Coast area. Airborne results at the crossing points are shown as well.

5. CONCLUSIONS

The prediction of coastal gravity data using a combination of the two data types, i.e. airborne gravity and satellite altimetry, improves the fit to precise marine gravity observations in all three areas compared with the cases where only the altimetry data are used. However, the inverse is not always true, when altimetry is used to improve the airborne data. Hence, the quality of an altimetry derived gravity map will be improved by adding airborne data and a map derived from airborne data may be improved by adding the altimeter data. The latter is somewhat depending on the airborne line spacing and the quality of the altimeter data.

Gravity models derived from satellite altimetry may be biased due to, e.g., sea surface topography or un-modeled tides (*Shum et al., 1997; Andersen, 1999*). It was shown that high quality airborne or marine gravity data can be used to reduce these problems.

The collocation approach performs slightly better in the three test areas than the FFT+interpolation approach, most likely due to the use of a locally determined signal to noise ratio in collocation. A collocation drawback is the intensive computations needed. However, the collocation technique may be used with randomly distributed data at or very close to the coast, while the FFT based method requires regularly gridded data.

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