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Altimetry Enhanced Free-Air Gravity Anomalies in the High Latitude Region

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ABSTRACT

Available marine free-air gravity anomalies (FAGA) derived from multiple satellite altimetry missions have had geologically useful, short wavelength features removed during processing. An approach is described for augmenting these FAGA in the high latitude region with coherent higher frequency data. This added-value approach is demonstrated over the Barents Sea in the Arctic using existing FAGA predictions from the Danish National Cadastre (KMS98) as a reference. Short wavelength components between 4 and 111 km were added from reduced and correlation-filtered ERS1 168-day mission altimetry that had been sorted into ascending and descending datasets for separate processing. The processed data were then recombined by spectral quadrant swapping to generate a correlated, high frequency gravity field related to the local geologic sources. This added-value surface adjusted the reference FAGA to better reflect features at wavelengths related to the distances between altimetry tracks.

Key words: Altimetry-derived gravity anomaly, Barents Sea, ERS-1

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1. INTRODUCTION

Satellite altimetry has been used extensively to derive free-air gravity anomalies (FAGA) for ice-free, ocean areas (Kim 1996; Rapp and Yi 1997; Sandwell and Smith 1997; Anderson and Knudsen 1998; Anderson et al. 2003). Various techniques are available for estimating FAGA from altimetry. However, the minimum spectral resolution of these derivations is generally greater than 20 km (Sandwell and Smith 1997, 2001, 2002). Given the quality of available data, it is desirable to explore techniques for estimating features smaller than 20 km that may be represented in the Earth's gravity field.

Here, we offer an approach that assesses geographically adjacent profiles to determine transversely correlative components in the gravity field, which are assumed to reflect geological sources. Our approach pre-selects the most closely spaced profiles, because they will generate the best between-track resolution. Geosat GM altimetry data with 3 - 4 km track spacing at the equator, for example, are more desirable than the combined ERS1 168-day mission data with 8-km spacing at the equator. We can better estimate the shorter wavelengths of the Earth's gravity field using altimetry, while retaining all available data for the longer wavelengths to maximize spatial coverage.

To minimize track-line noise in the high latitude region and long wavelength orbit errors inherent in altimetry, spectral quadrant swapping (Kim et al. 1998) and a remove-and-restore technique (Bašić and Rapp 1992) are used to reduce altimetry to a reference geoid surface determined from available ocean FAGA datasets. The reduced profiles may then be filtered to remove remaining long wavelength distortions. Although the assumed reference FAGA will likely have an unknown bias and trend with respect to the geoid, they are negligible in the determination of the higher frequency gravity field.

We assume that geologic sources with spatial anomalies larger than the track spacing will be detected in the residual altimetry along adjacent tracks. We use this signal to determine the high frequency component of the ocean

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gravity field. The original reference FAGA is enhanced by the addition of this residual field. As a result, we are able to define geologic features as small as 10 km in wavelength for some regions.

2. FREE-AIR GRAVITY ANOMALY ENHANCEMENT

Figure 1 shows the approach adapted in this study to generate FAGA from ocean altimeter measurements. It is adapted after Kim (1996) and uses altimetry directly to calculate geoid undulations from which the FAGA are determined.

For a region where enhanced FAGA are desired, an altimeter dataset and reference FAGA must be selected. Considerations for the altimetry data selection include quality and coverage of the measurements. To extract the most correlated signal with highest spatial resolution, the tracks should be sub-parallel and as closely spaced as possible. Figure 2 shows the ascending (upper panel) and descending (lower panel) ground tracks of ERS1 168-day mission data selected for this study.

With the altimetry data selected, the reference FAGA are integrated for a reference geoid using an inversion of the fundamental equation of geodesy (Schwarz et al. 1990; Kim 1996). A collection of FORTRAN programs for performing this inversion based on the 2-D FFT of the Stokes Equation (Heiskanen and Moritz 1967; Schwarz et al. 1990) is available from the National Geodetic Survey. The mean value of this surface is removed as the intent is to use the high frequency components to modify the reference FAGA. This relative, regional geoid surface can then be interpolated to sea surface points along the altimetry profiles to calculate reference profiles. Removing the reference profiles from altimetry produces residual profiles that can be analyzed for common, static, and short wavelength components.

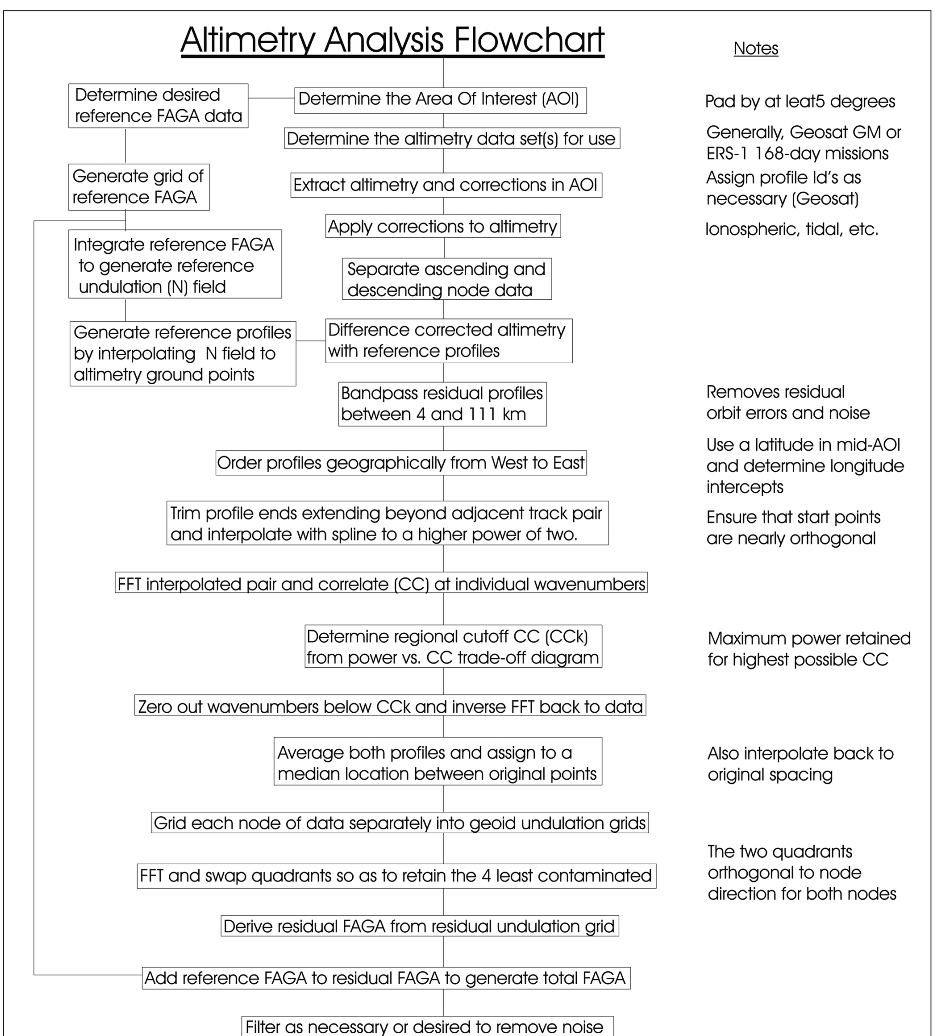


Fig. 1. Flowchart of satellite altimeter data analysis for combining the longer wavelength components of the reference free-air gravity anomaly data with the shorter wavelength data from the altimetry.

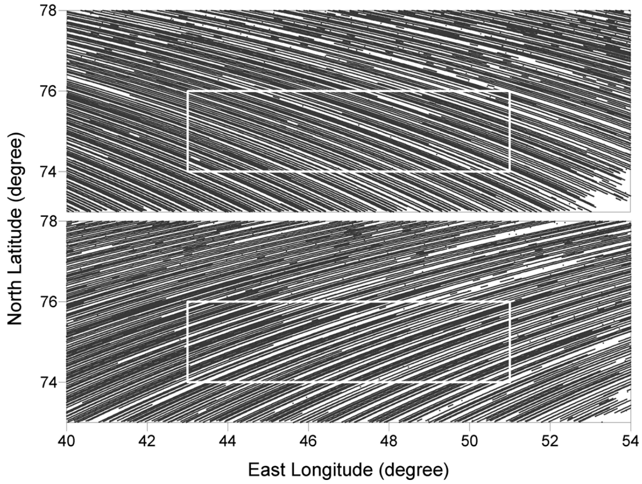


Fig. 2. ERS1 168-day mission orbit distributions with the study area highlighted. Ascending (upper) orbits have a SE to NW trend, whereas descending (lower) orbits have a NE to SW trend.

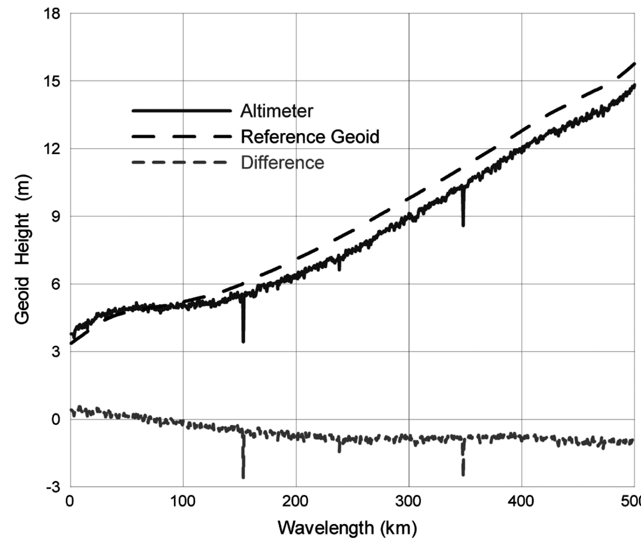


Fig. 3. Comparison of altimeter (solid), reference geoid (dotted), and their differenced (altimeter - reference geoid) (dashed) profiles. Track profile shown in the figure is track # 24168 from the ERS1 168-day mission sampled roughly every 660 meters.

Figure 3 shows an interpolated reference undulation profile (dashed) coincident with an observed altimeter profile (solid) over the Barents Sea region. The difference (dotted at the bottom) highlights discrepancies in both the long and short wavelength components.

To make the residual profiles sub-parallel, the orbital tracks are separated into ascending and descending datasets and geographically ordered from West to East. The profiles are then band-pass filtered to remove both long (usually greater than 111 km) and short wavelength (dependent on the spacing between profiles) signal. The long wavelength signal may be related to errors in the reference FAGA or residual orbit errors, while the short wavelength signal may represent both noise and crustal signals. Since a common surface is desired for comparing the residual profiles, the long wavelengths are removed to emphasize the shorter wavelengths. Wavelengths shorter than twice the spacing between profiles are also removed.

Altimetry profile pairs are spectrally compared to extract the correlative static elements where the effects of common crustal sources are enhanced (Kim 1996; von Frese et al. 1997). They are trimmed to approximately the same length, resampled to track-perpendicular coordinates (Kim 1996), and transformed using a 1-D FFT. The individual components at each wavenumber, k, are then compared for the cosine of their phase difference to determine their correlation coefficient CC_k. Inversely transforming the positively correlated components for each track yields two profiles that may be averaged for a track where the coherent effects of common geologic sources are enhanced (Kim 1996; von Frese et al. 1997).

This process is repeated for all nearest-neighbor track pairs in the ascending and descending data sets. For each data set, a residual geoid undulation grid is generated from the correlation-filtered data. In addition to geological signals, the resultant two undulation grids may also reflect coherent orbit errors, as well as track-line noise (Kim et al. 1998) that sometimes is also called a corrugated effect (Anderson and Knudsen 1998). For each residual geoid grid, the strong along-track errors are predominantly limited to only two of the corresponding spectral quadrants (Kim et al. 1998). Because the ascending and descending orbits cross each other, the most strongly corrupted quadrants are mutually exclusive between the two datasets. Hence, the two cleaner quadrants from each dataset may be recombined into a single spectrum that, when inversely transformed, yields a residual geoid with greatly reduced along-track errors.

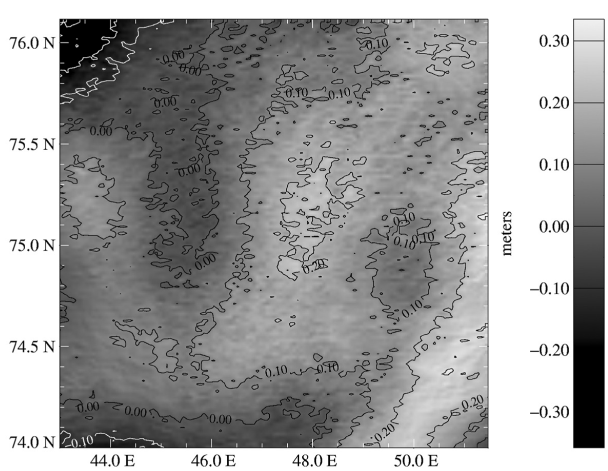
The corresponding residual FAGA may be derived from this residual geoid grid using the fundamental equation of geodesy (Schwarz et al. 1990; Kim 1996). Merging the regional reference FAGA with these residual FAGA restores the long wavelength signal. Because spectral overlap is likely, it is commonly necessary to high-pass filter the residual FAGA and low-pass filter the reference FAGA. Combining these results yields an enhanced FAGA where the long wavelength components controlled by the reference FAGA have been supplemented with the higher frequency features implied by correlation-filtered altimetry.

3. A CASE STUDY: THE BARENTS SEA OF THE RUSSIAN ARCTIC

We used this added-value approach outlined in Fig. 1 to compute geologically enhanced FAGA over the Barents Sea. The basic data were the ERS1 168-day mission altimetry and a reference FAGA grid (KAFAGA) from Andersen and Knudsen (1998). The KAFAGA were derived from multiple altimetry datasets, which are reliable to 20 - 50 km wavelengths depending on location (Yale et al. 1995). Some bias and tilt differences between the KAFAGA and other datasets have been noted (Smith 1997). However, experience suggests that the KAFAGA provide an excellent reference field for estimating the shorter wavelength components in FAGA. The KAFAGA and ERS1 altimetry were used to generate the residual geoid grid shown in Fig. 4.

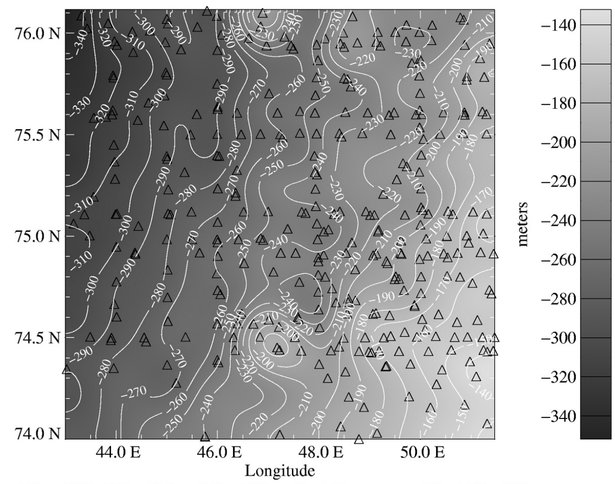
These residual undulations should correlate with the bathymetry if they represent geologic components. For this test, 327 bathymetric measurements were gridded as shown in Fig. 5 using a minimum curvature spline function. These data were digitized by the Naval Research Laboratory from USSR and Norwegian Polar Institute charts (Robin Warnken, personal communication, 1997). The data have an average spacing of about 10 km, and hence a 20-km low-pass filter was applied to smooth the resulting grid. Both Figs. 4 and 5 exhibit common North-South and Northwest-Southeast regional trends, as well as the East-West extending feature in the South-central portion of the study region. The two grids correlate at 0.668, which is statistically significant at the 99.9% confidence level and supports the hypothesis that the residual geoid is a function of the static, geologic sources.

The residual geoid undulations were used to derive the residual FAGA grid in Fig. 6 that contains information nominally between 4- and 111-km wavelengths. The radial power spectrum of these residual FAGA drops significantly at 13-km and shorter wavelengths. However, the longer wavelength components shown in Fig. 7 correlate at 0.999 with the original data. This suggests that the unfiltered data have an effective resolution of about 13-km for analysis. Statistical comparison between the residual and 13- and 27-km low-pass filtered FAGA was summarized in Table 1.



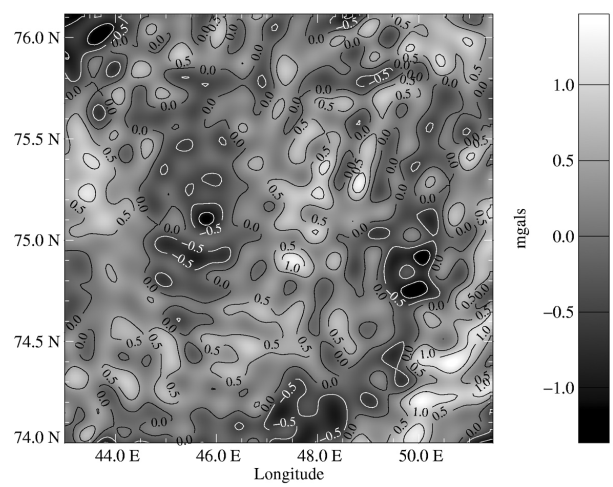
AR = −0.358,0.335 AM = 0.085 ASD = 0.095 AU = meters GI = 1'N x 4'E

Fig. 4. Residual geoid undulations for the Barents Sea test area derived from correlation filtered ERS1 altimetry. Map parameters listed for this and subsequent figures include the amplitude range (AR) of (min, max), mean (AM), standard deviation (ASD), units (AU), and grid interval (GI).



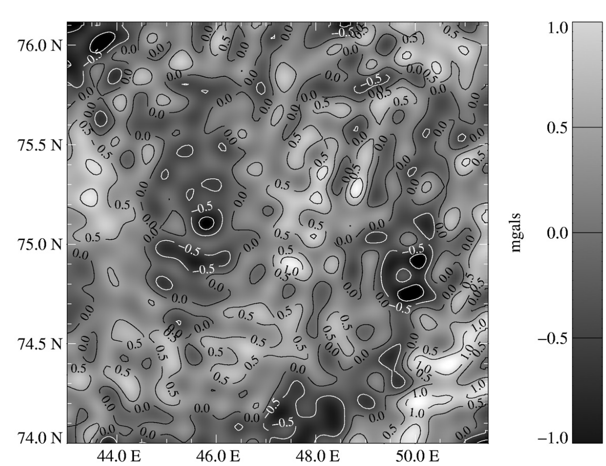
AR = −352,−132 AM = −242 ASD = 48 AU = meters GI = 1'N x 4'E

Fig. 5. Bathymetry generated from 327 observations (diamonds) using a minimum curvature cubic spline and low-pass filter at about a 20-km wavelength cut-off.



AR = −1.365,1.471 AM = 0.129 ASD = 0.431 AU = mgals GI = 1'N x 4'E

Fig. 6. Residual free-air gravity anomalies for the Barents Sea test area derived from the geoid undulations in Fig. 4.



AR = −1.374,1.468 AM = 0.130 ASD = 0.427 AU = mgals GI = 1'N x 4'E

Fig. 7. Residual free-air gravity anomalies from Fig. 6 with a 13-km low-pass filter applied.

Table 1. Statistical comparison of the residual and low-passed filtered free-air gravity anomalies in Figs. 6, 7, and 8 (Unit: mgals).

FAGA	(Min, Max)	Mean	STD	CC with Residual
Residual (Fig. 6)	(-1.365, 1.471)	0.129	0.431	-
13-km LPF (Fig. 7)	(-1.374, 1.468)	0.130	0.427	0.999
27-km LPF (Fig. 8)	(-1.166, 1.186)	0.129	0.372	0.864

For comparison, the radial power spectrum of the KAFAGA indicates an effective resolution of about 27-km. Figure 8 highlights the 27-km and larger features in the original residual FAGA. Clearly, these features at the poorer spectral resolution of the KAFAGA are quite smooth and lack the detail captured from the ERS1 altimetry in Fig. 6.

Similar results were obtained using proprietary data for the Gulf of Mexico where a 12-km anomaly feature was mapped with this technique for a known geological structure (Roman 1996). In this case, the regional reference FAGA of Sandwell and Smith (1997) were updated with geologically significant shorter wavelength information from Geosat GM altimetry.

4. CONCLUSIONS

In the high latitude region, spectral correlation analysis of altimetry may update available marine free-air gravity anomaly (FAGA) datasets with higher frequency components for enhanced geological analysis. The updating will be particularly effective for areas where altimetry data are available that offer improved track coverage and measurement statistics relative to the regional altimetry properties reflected by the reference FAGA. This added-value approach simplifies the requirements for updating a region with recent observations. It builds on the effective regional components from available reference FAGA estimates by incorporating shorter wavelength geologic signals derived from geographically adjacent altimeter profiles.

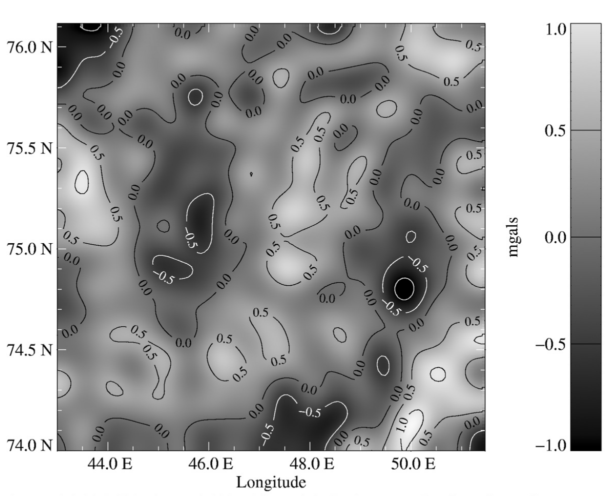


Fig. 8. Residual free-air gravity anomalies from Fig. 6 with a 27-km low-pass filter applied.

Aerogravity surveys of continental platform areas are becoming increasingly important sources of higher frequency data for augmenting regional altimetry-derived FAGA predictions. This approach may be adapted for extracting the geologic components from the airborne profiles and merging them with a reference FAGA dataset. Aerogravity data are commonly collected along parallel, closely spaced (e.g., 3 - 5 km) flight lines that can be spectrally correlated for their static geologic signals. Relative to altimetry predictions, this application avoids orbital and tidal problems and the use of the sea surface as a proxy indicator of the gravity field (i.e., the geoid). Reducing aerogravity data for the extreme noise level of the observations due to aircraft dynamics can be a difficult but surmountable problem (e.g., Bell et al. 1999). Further enhancement of the signal-to-noise ratio of these data can result from correlation filtering to improve the across-track coherency of the geological signals (e.g., Foster and Guinzy 1967; Kim 1996).

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