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Improved Free-air Gravity Anomalies by Satellite Altimetry

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Abstract : Ocean satellite altimetry-implied free-air gravity anomalies have had the shortest wavelengths removed during the processing to generate the optimal solution between multiple radar altimeter missions. ERS-1 168day mission altimetry was residualized to a reference geoid surface generated by integrating Anderson & Knudsen's free-air gravity anomalies for the Barents Sea. The altimetry tracks were reduced and filtered to extract the shortest wavelengths (between 4 and 111 km) from both ascending and descending tracks, respectively. These data were recombined using existing quadrant-swapping techniques in the wavenumber domain to generate a correlated, high frequency gravity field related to the local geologic sources. This added-value surface adjusted the reference free-air gravity anomalies to better reflect features in the gravity field at a wavelength related to the distance between altimetry ground tracks.

Key Words : Radar Altimetry, Free-air gravity anomalies, Barents Sea.

1. Introduction

Satellite radar altimetry has been widely used to extract free-air gravity anomalies (FAGA) for all ice-free ocean areas (Anderson and Knudsen, 1998; Kim, 1996; Rapp and Yi, 1997). Each author has his own technique that has resulted in different FAGA estimations using the same altimeter data sets. Some criteria that authors use may eliminate or greatly reduce the weighting for altimeter measurements obtained near the coastal areas or in shallower seas. This is based on quality assessment of the altimetry under those conditions. In addition, all available data sets have been incorporated into many of these analyses employing various weighting schemes to account for varying quality between data collected during different missions (Geosat, ERS-1, Topex/Poseidon, etc.).

These schemes often do not take into account the geologic sources that generate the FAGA signal. Primarily, the data are reduced based entirely upon a numerical approach. Therefore, an approach is offered here that assesses geographically adjacent profiles to determine the similar static components, which are assumed to

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be from geological sources. To that end, profiles that have the closest spacing between tracks are desired, because they generate the best between track resolution i.e., they could contain FAGA signals at double the spacing). Geosat altimetry from Geodetic Mission(GM) has a much better between track spacing (3-4 km at the equator) than the combined ERS-1 168-day missions (8 km at the equator). It is usually desirable, therefore, to use Geosat to estimate the shorter wavelengths of the Earth's gravity field and all available data for the longer wavelengths.

To eliminate long wavelength orbit errors inherent in the satellite radar altimetry, a remove-and-restore technique (Bašić and Rapp, 1992) is used to reduce the altimetry to a reference geoid surface determined from available global FAGA data sets. The reduced profiles may then be filtered to remove remaining long wavelength aspects. Although the assumed reference FAGA will likely have an unknown bias and trend with respect to the geoid, these will be assumed negligible with respect to the determination of the higher frequency gravity field. Additionally, quadrant-swapping techniques (Kim *et al.*, 1998) were used to eliminate long wavelength errors.

In general, it is assumed that the geologic sources that have a spatial anomaly 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 Earth's gravity field. The original reference FAGA is enhanced by the re-addition of this residual field. As a result, we are better able to define geologic features as small as 10 km in wavelength for some regions.

2. Altimetry-Implied Free-air Gravity Anomalies

There are two primary approaches to the generation of FAGA from altimeter data. Both rely upon the fact that the ocean surface is a relatively good proxy indicator of the geoid undulation surface.

The first approach involves taking the along track derivative and interpolating this to intersection points to estimate the deflection of the vertical, that can be directly created to the desired FAGA (Sandwell and Smith, 1997). The advantage to taking the along track derivative is that the long wavelength orbit errors are de-emphasized.

Another approach (Kim, 1996) uses the altimetry to directly calculate a geoid undulation and then determine the FAGA from the geoid surface. The inherent problem of orbit errors is reduced in the following two ways. The residual profiles are geographically ordered and compared to extract the most correlative static elements, which are assumed to have common crustal sources (Kim, 1996). This process is repeated for all pairs within each track mode (ascending and descending). The final two grids reflect residual orbit errors, as well as track noise.

The second means of reducing track noise is discussed in Kim *et al.* (1998). In each grid, two quadrants will have minimal noise. Due to orthogonality, the quadrants with minimal noise for the grids derived from different modes will be opposite. Therefore, it is possible to retain the two least noisy quadrants from each grid's spectral amplitude plot and combine them into one spectrum. This may be inversely transformed to generate a merged geoid undulation that has minimal errors, which have been referred to as a corrugated Anderson and Knudsen (1997) effect.

The resulting geoid undulation grid is then used to generate the desired FAGA, essentially by taking the first vertical derivative. The advantage of this approach is that long wavelength errors are reduced first, and then minimized further by taking the vertical derivative. In addition, Kim (1996) removed the OSU91A geoid undulation values from the altimetry and later restored the OSU91A FAGA to the final grid of residual FAGA data that were derived from the residual altimetry. It has been previously shown by Rapp *et al.* (1991) that use of this remove-and-restore technique generates a valid solution.

The enhancement techniques discussed next are a variant on the second approach and are outlined in the flowchart in Fig. 1. The principle difference is that reference geoid and FAGA data are utilized, which have information at shorter wavelengths (down to 20 km) than those from 360o coefficient models.

3. A Case Study of Barents Sea

The approach outlined in Fig. 1 was implemented with altimetry from the ERS-1 168-day mission and a reference FAGA grid from Andersen and Knudsen (1998) (KAFAGA). There are some bias/tilt differences between KAFAGA data and other data sets (Sandwell and Smith, 1997). However, they do provide an excellent reference for FAGA data for the shorter wavelengths that are of primary interest here. KAFAGA were derived from multiple altimetry data sets, which have been shown to be reliable down to a range of 20-50 km wavelengths depending on location (Yale *et al.*, 1995).

KAFAGA were used to generate a reference geoid undulation grid by use of a 2D FFT transform provided by Dru Smith of the National Geodetic Survey. Reference undulation profiles were generated by interpolating the reference undulation grid to the 1/10 second altimeter ground point locations. The top diagram in Fig. 2 shows a reference undulation profile (dashed) and an observed altimeter profile (solid) over the same ground points. It can clearly be seen that there are long wavelength discrepancies between these two profiles, which may be attributed to residual orbit errors and tilt errors in the reference model. The bottom diagram in Fig. 2 shows that the differences are primarily long wavelength, along with spikes and very high frequency features. The latter may contain both observation noise and real signal, but features containing signals at wavelengths shorter than the Nyquist frequency of the track spacing will appear only as noise. A band pass filter of the residual profile between 4 and 111 km was applied to remove the apparent orbit errors in the altimetry and unresolvable features. The lower end (4 km) is dependent on the track spacing of the altimetry data being used (ERS-1 or GEOSAT), while the upper end (111 km) was selected to pick a level where the signal present in the reference FAGA (KAFAGA) is deemed reliable. When the long wavelength differences and spikes were removed by filtering, the two profiles compared at roughly 100%. These profiles are separated into two groups according to whether they were collected during the ascending or descending modes of the altimeter passes. Within each such grouping, the tracks are ordered geographically to place them in west to east order.

Adjacent track pairs are then interpolated into a power of two and Fourier transformed into the wavenumber domain. The individual

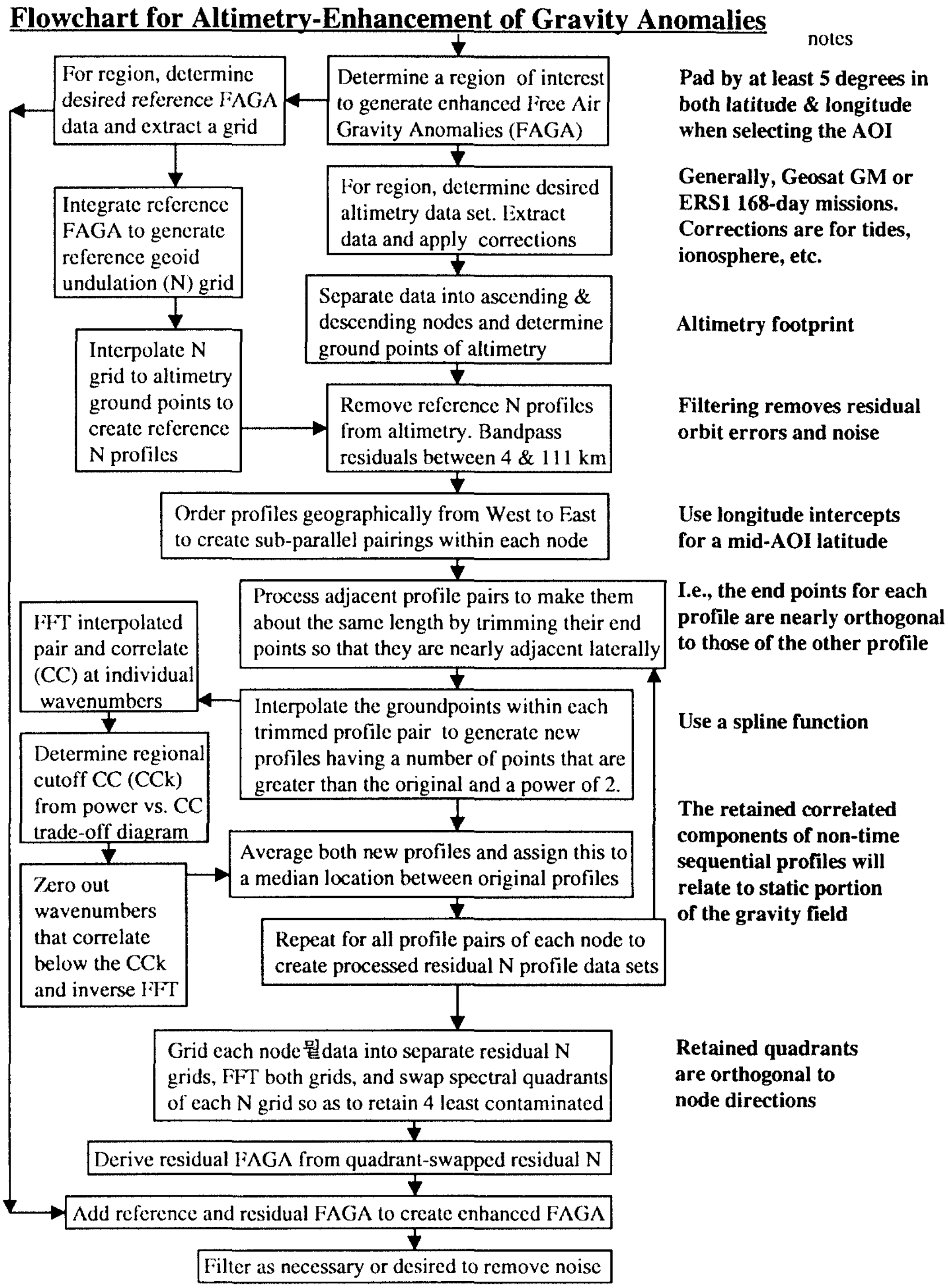


Fig. 1. Flowchart of the satellite radar altimeter data analysis. Various processing steps are necessary to generate enhanced free-air gravity anomalies. Ultimately, the long wavelength component of the reference FAGA data is combined with the short wavelength data from the altimetry.

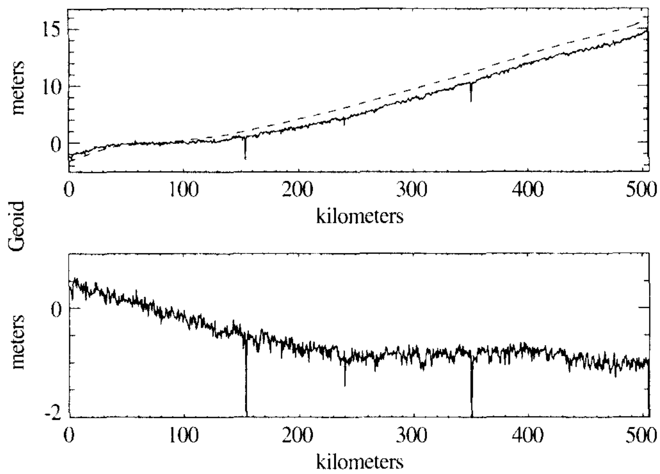
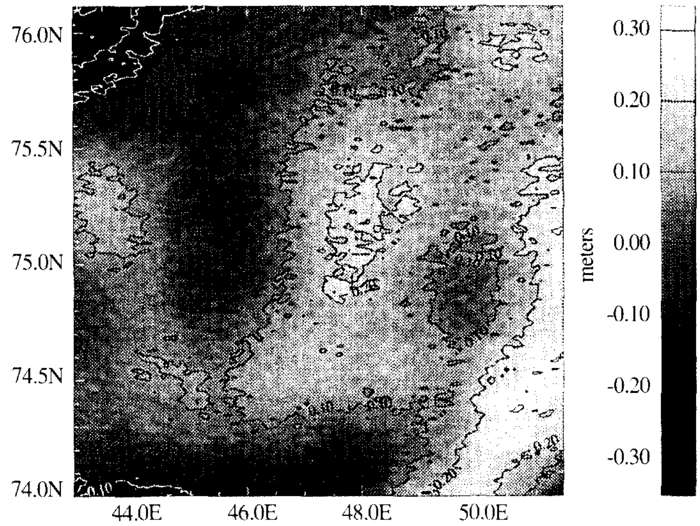


Fig. 2. Comparison of altimeter (solid) and reference geoid (dashed) derived profiles (top) and the difference between them (bottom). Differences are primarily due to long wavelength (111+ km) errors, spikes, and higher frequency features that represent both noise and crustal signals. Profile shown is ERS-1 168-day mission track 24168 and is sampled roughly every 660 meters.

wavenumber components between each pair of neighboring tracks are correlated based upon their phase difference. Small phase differences imply wavenumber components that are strongly correlated and which may be derived from the same geologic features. The cosine of the phase difference gives the coefficient of correlation (CC) of each wavenumber pair. The effect on the overall power of selectively removing those wavenumbers that have progressively higher correlations is plotted, and a critical cutoff point is established where the power drop off of the passed wavenumber components becomes very steep. This cutoff CC (CC_k) is used to pass maximum power while removing those wavenumbers that correlate the least. The elimination of these wavenumbers occurs independently depending on whether they correlate better or worse than the cutoff CC (notch filtering). The remaining wavenumbers are then inversely transformed to reconstruct the track pair. The two profiles are averaged to produce a least squares estimate of the common signals and assigned to the median locations of the original two profiles.

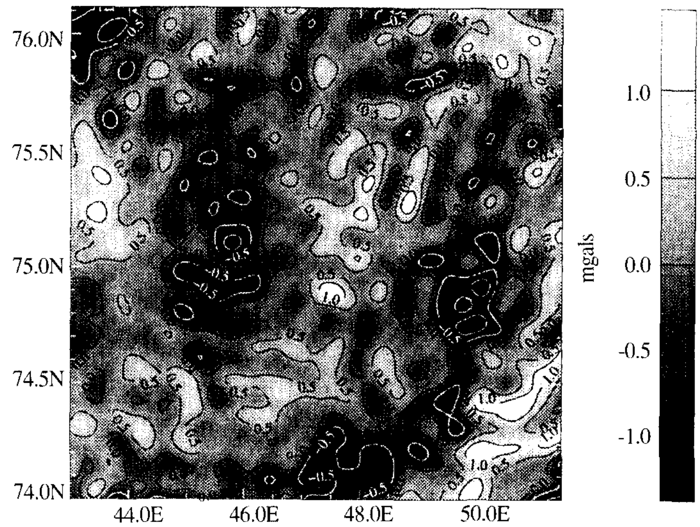
These averaged profiles then most nearly represent residual geoid undulation profiles for an ascending or descending direction. To remove directional effects a quadrant swapping method (Kim, 1996; Kim *et al.*, 1998) is utilized instead of a crossover adjustment. This method helps to reduce the corrugated effect associated with residual track line bias when gridding. The two separate data modes are gridded and inversely transformed to generate Fourier spectra. The effects of the individual track directions are apparent as a band in the quadrants orthogonal to the mode directions (e.g., a band would appear in the upper-left and lower-right quadrants of the amplitude spectrum for descending data, which would pass through the upper-right and lower-left quadrants in the data domain). By retaining the two relatively uncontaminated quadrants from each data mode, a composite Fourier spectrum may be generated. This composite spectrum is then inversely transformed to generate a final residual geoid undulation grid (Fig. 3). The residual geoid undulation may now be transformed into a residual FAGA grid (Fig. 4) through application of the fundamental equation of geodesy as expressed in a Fourier transform (Kim, 1997; Schwarz *et al.*, 1990).

This final residual FAGA grid contains information nominally between the 4 and 111 km



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

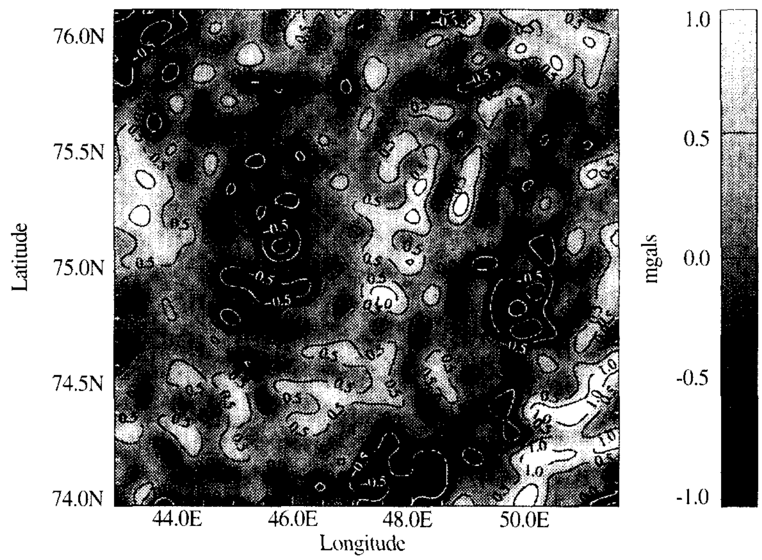
Fig. 3. Residual geoid undulations for the Barents Sea test area derived from processed satellite radar altimetry. Attributes listed for the map include the amplitude range AR of minimum, maximum, the amplitude mean AM, the amplitude standard deviation ASD, the amplitude unit AU, and grid interval GI.



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

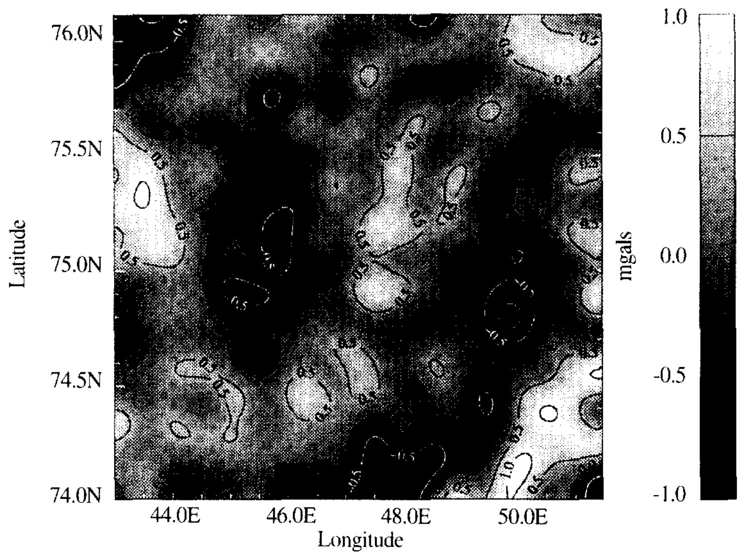
Fig. 4. Residual free-air gravity anomalies for Barents Sea test area derived from the geoid undulations in Fig. 3.

wavelengths. However, the radial power spectrum of the residual FAGA in Fig. 4 reveals a significant drop at a 13 km wavelength. When a low pass filter of 13 km is applied to the residual FAGA, the resulting 13 km filtered grid (Fig. 5) correlated with a CC of 0.999 with the original. This suggests the data have an actual resolution of 13 km and seem to support the analysis of features of that size and larger. For comparison, the radial power spectrum of KAFAGA suggests that the data have been filtered to about 27 km. To exemplify the features that are re-captured from



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

Fig. 5. Residual free-air gravity anomalies from Fig. 4 with a 13-km low pass filter applied.



AR = −1.661,1.186 Am = 0.129 ASD = 0.372 AU = mgals GI = 1'N x 4'E

Fig. 6. Residual free-air gravity anomalies from Fig. 4 with a 27-km low pass filter applied.

the ERS-1 altimetry for incorporation in the enhanced FAGA, low pass filters were also applied at 27 km (Fig. 6) wavelength. These grids correlated with the original at 0.864. The grid shown Fig. 6, which has a similar spectral character to KAFAGA, appears much smoother than that of the original residual FAGA. While features present in Fig. 4 may represent unwanted noise, it is now possible to filter the results to levels that may highlight existing signal and minimize the noise short of the original filtering level.

Similar results were obtained using proprietary data for other regions (Roman 1996; Roman and von Frese, 1998). A known 12-km feature in the Gulf of Mexico was highlighted using these techniques. The feature was obscured by the noise when the processed FAGA were low pass filtered below about 10 km and removed completely when filtered at more than 18 km.

4. Conclusions

Available global Free-air gravity anomaly (FAGA) data sets can be enhanced using altimetry data. The long wavelengths of the resulting enhanced FAGA will take on the same character as the selected global FAGA data, while the shorter wavelengths will be enhanced by the incorporative geologic signal implied by geographically adjacent altimeter profiles. This added-value approach permits the user to highlight smaller features that may only be decipherable at limited wavelengths due to noise and filtering. Because it uses existing data sets to build upon, it does not require the regeneration of an entire grid and simplifies the requirements for updating a region for recent observations.

Additionally, this approach could be adapted for use with airborne FAGA profiles. These data are being collected in numerous regions along sub-parallel tracks with tracks spacings that may be sufficient for this approach (e.g. 3 km). These data could be reduced with respect to a reference FAGA data set and geographically adjacent profiles correlated to extract the component related to the static geologic signal. The benefits to this type of application would be that orbital and tidal problems would be eliminated, and the FAGA signal could be directly determined instead of using the sea surface as a proxy indicator of the gravity field (i.e., the geoid). Difficulties may arise around the near simultaneity of the observations (modeling of dynamic effects would have to be better to remove these) and the observation noise and elevation levels of the airborne survey.

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