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AN ANALYSIS OF THE GRAVITY FIELD IN THE NORWEGIAN SEA AND MAPPING OF THE ICE CAP OF GREENLAND USING ERS-1 ALTIMETER MEASUREMENTS.

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ABSTRACT

New fast delivery 35 days repeat ERS-1 altimeter data have been used to recover the gravity field in the Norwegian-Iceland-Greenland Sea. Furthermore the spectral characteristics of the gravity field have been investigated from 18 arcs of 3 days repeat period data. The recovered gravity field correlates exclusively with the major geological structures, which clearly demonstrates the potential of these new ERS-1 altimeter data.

For land applications ERS-1 altimetry has completed a monitoring of the ice sheet in Greenland up to 82°. Hereby the first digital elevation model has been constructed from altimeter data with an almost complete coverage of the ice sheet.

Keywords: Altimetry, gravity field, surface topography.

INTRODUCTION

Five full 35 days repeat arcs of new fast delivery ERS-1 altimeter data are now available from ESA. The data are obtained as 1 second mean values on IGDR (Interim Geophysical Data Record) format for testing-purposes by the principal investigators only. The IGDR's are produced at NOAA/NOS and contain UTC time, latitude, longitude, orbit height, sea surface height, geophysical corrections (atmospherical effects and tides), and other quantities derived from the altimetric observation. The satellite orbits are provided by Delft University of Technology, Faculty of Aerospace Engineering, Netherlands.

In the following two separate subjects are treated. First the gravity field in the Norwegian-Iceland-Greenland Sea ($60° < \phi < 80°$, $-30° < \lambda < 20°$) is analyzed from the ERS-1 altimeter data. Of special interest is the area above 72 degree latitude, since this is the northern limit of Seasat and Geosat altimetry and associated gravity field recovery (Haxby, 1987, Balmino et al. 1987). Compared with the gravity map presented in Knudsen et al. (1992) the map presented in this paper has been updated using five 35 days repeat periods of data. Especially around Svalbard and in the Greenland Sea the data coverage has been improved.

Secondly, the ERS-1 altimeter data have been merged with other types of measurements of the ice surface elevation of Greenland and a digital elevation model has been constructed. Around the Greenland Ice Core Project (GRIP) site (located at the summit of the ice cap) a comparison of ERS-1 altimetry and GPS has been performed indicating the possibilities of using ice elevations for future support of gravity field mapping.

SPECTRAL CHARACTERISTICS OF THE GRAVITY FIELD

This detailed analysis of the spectral characteristics of the gravity field was performed using FFT techniques and altimeter data of pairs of collinear tracks (Marks and Sailor, 1986). The analysis was carried out using 3 days repeat data from 18 repeat periods covering January and March 1992 in a northern region and a southern region, in order to evaluate the gravimetric and time dependent content of the newly recovered gravity signal above 72 degrees latitude.

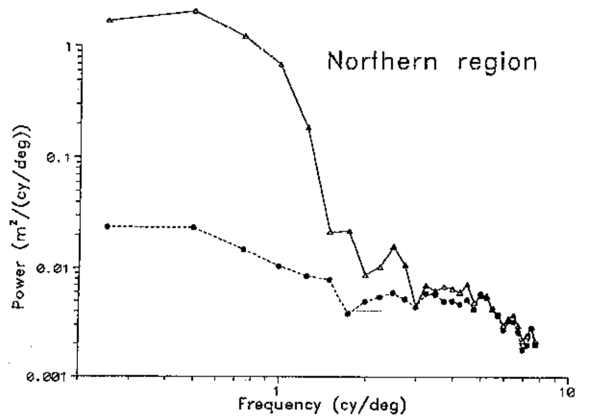

Figure 1a. Average power spectra of sea surface heights (solid line) and sea surface height differences (dashed line).

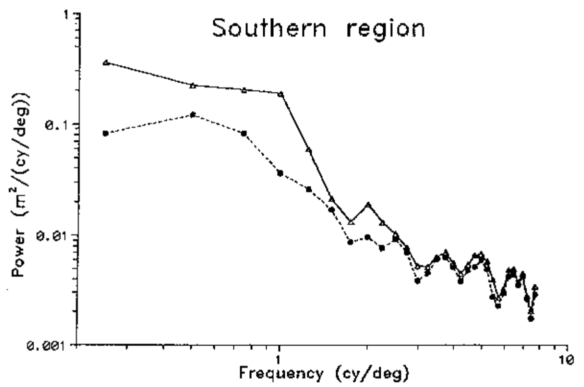

Figure 1b. Average power spectra of sea surface heights (solid line) and sea surface height differences (dashed line).

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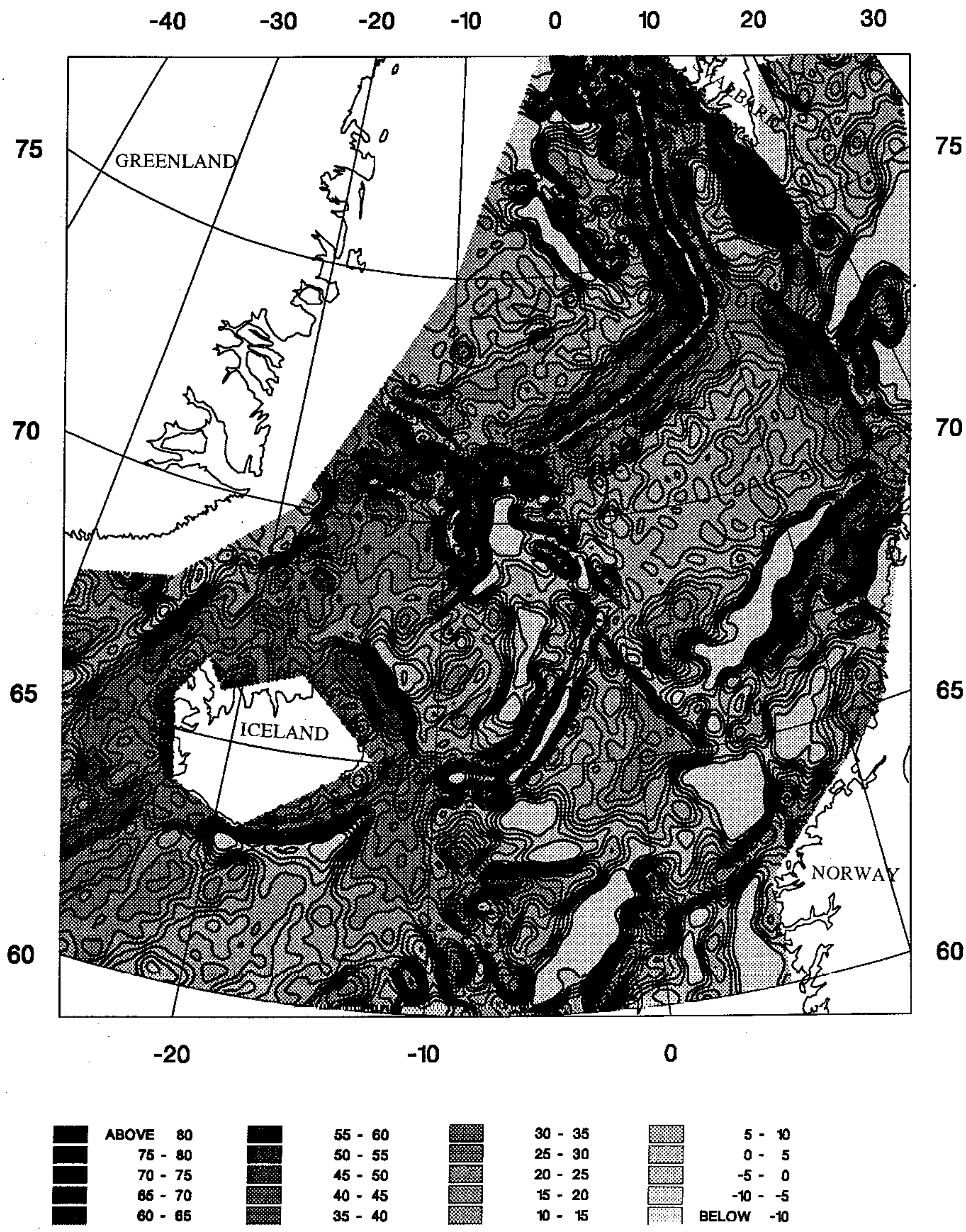

Figure 2. Free air gravity anomalies from ERS-1 35 days altimeter data. C.I. 5 mgal.

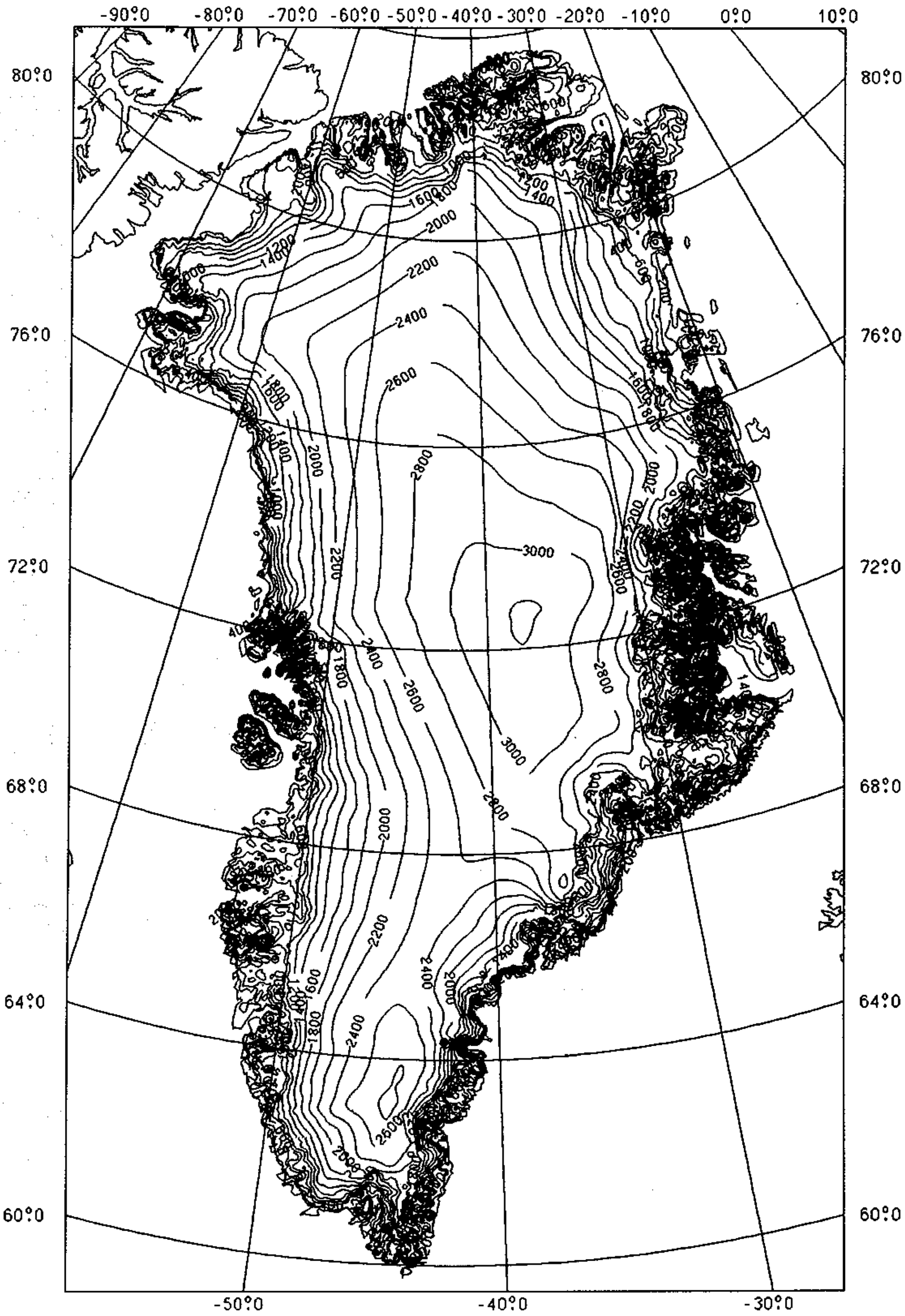

Figure 3. Digital elevation model of Greenland. C.I. 200 m.

For all tracks in each region power spectra of the sea surface heights were calculated and subsequently averaged. In order to evaluate the time varying parts of the sea surface heights, power spectra of sea surface height differences along pairs of collinear tracks were calculated and averaged (all possible combinations were used). The tracks have a length of 64 seconds or 448 km. Linear trends were removed and the tracks were cosine tapered in order to avoid spectral leakage due to non-periodicity. The averaged power spectra are shown in Figure 1a (Northern region) and Figure 1b (Southern region).

In the northern as well as the southern region the power spectra of both the heights and height differences exhibit patterns of decay. From a frequency of 3 cycles per degree (3 cy/deg ~ 35 km), which have a magnitude of about 7 cm, the spectra of the sea surface heights coincide with the spectra of the time varying parts of the sea surface heights. All spectra decrease to about (0.05 m)^2/cy/deg around 10 cy/deg.

In the northern region the spectrum at the lower frequencies of the stationary parts of the signal (defined as the differences between the two spectra) is nearly 100 times larger than the spectrum of the time varying parts of the sea surface heights (Figure 1a). In the southern region this ratio is only around 3 (Figure 1b). The difference is caused by two factors: The gravimetric signal is much more prominent in the northern region, and the time varying signal is more prominent in the southern region. The increasing magnitude of the gravimetric signal in the northern region is partly caused by inaccuracies in the OSU91A model that occur north of 72 degrees latitude, where a detailed recovery of the gravity field previously has been hampered by lack of altimetry.

ALTIMETRIC GRAVITY FIELD MAPPING

The gravity field in the Norwegian-Iceland-Greenland Sea displays many geological features related to continental spreading along the extension of the Mid-atlantic Ridge. North of Iceland the Mid-Atlantic Ridge is divided into three main segments: The Kolbeinsey, the Mohns, and the Knipovich ridges (Eldholm et al., 1990). These features have been seen in earlier gravity field maps compiled from marine gravimetry (e.g. Talwani & Grønlie, 1976).

The 35 days repeat period ERS-1 altimeter data provides a dense coverage of data. Hence, a valuable source of new information about the gravity field has become available.

The mapping of the gravity field from the altimetry was carried out relative to the OSU91A model complete to degree and order 360 (Rapp et al., 1991). Within the region around 126,000 altimetric values were found. In order to reduce the time varying signals the five repeat arcs were averaged in a collinear analysis. This procedure resulted in 32,065 mean sea surface heights.

To reduce effects of orbit errors and sea surface topography a crossover adjustment was carried out that simultaneously fitted the tracks to the OSU91A geoid model. This procedure (described in Knudsen & Brovelli, 1991) resulted in a reduction of the 2951 crossover discrepancies from 2.03 m to 7 cm. Relative to the geoid model the 32,065 adjusted sea surface heights have a RMS value of 0.41 m. The conversion of geoid heights into gravity anomalies was done using FFT techniques (e.g. Schwarz et al., 1990). Subsequently, the OSU91A gravity anomaly model was added in order to obtain the free air gravity anomalies (Figure 2).

Figure 2 clearly displays the geological features described above. South-west of Iceland the Mid-atlantic Ridge is seen. North of Iceland this ridge continues into the Kolbeinsey, the Mohns, and the Knipovich ridges.

GREENLAND SURFACE TOPOGRAPHY: A DIGITAL ELEVATION MODEL.

The model is made utilizing most existing digital elevation data, and as opposed to previous models it covers Greenland totally. The launch of ERS-1, enabled a very significant expansion compared to existing models, due to the fact that the ERS-1 orbit provides coverage to $\pm 82°$, thus, for the first time, monitoring the ice sheet completely. In addition, data from maps were extracted, so that the coastal part could be incorporated in the model as well. A very brief description of the data types and of the computation is given below.

Data from five sources have been included in the modelling:

Geosat - geodetic mission - altimetry ($\phi \leq 72.1°$): Roughly 1.5 mio. observations were collected during the initial 18 months of non-repeat operation. Data are corrected for slope induced errors (Brenner et.al., 1983), retracked (Martin et al.,

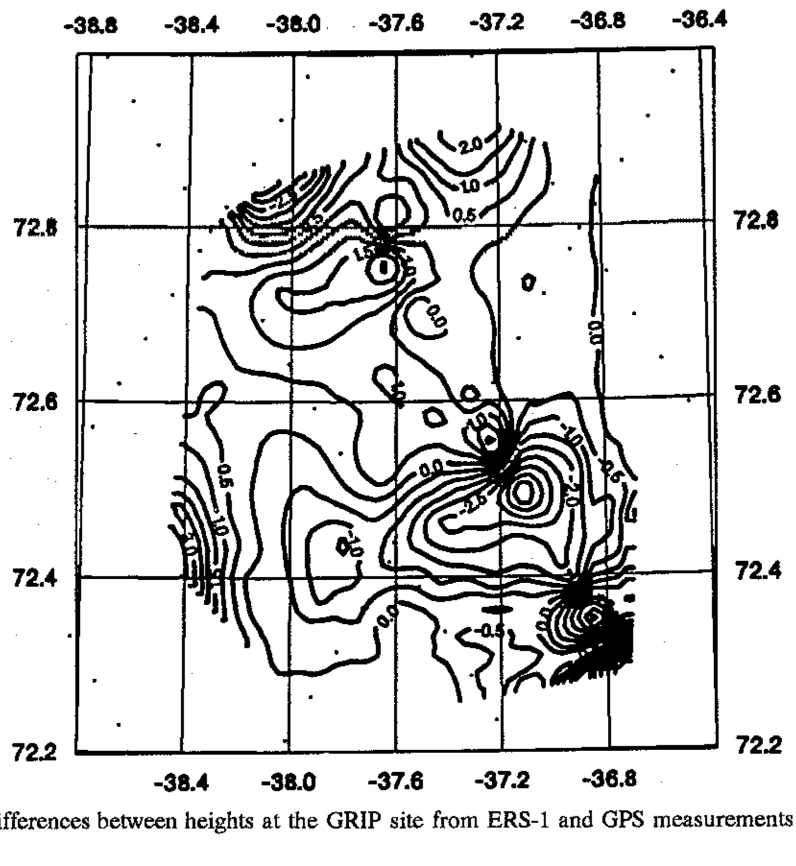

Figure 4. Differences between heights at the GRIP site from ERS-1 and GPS measurements. C.I. 0.5 m.

1983), and radial orbit errors are reduced by applying a least squares crossover correction.

ERS-1 - altimetry: Data from the first 35 days period have been used. North of 72.1° 14.000 datapoints were found and subsequently a crossover analysis has been performed. Neither re-tracking nor slope correction have yet been applied.

Digitized maps: Information from the International Civil Aviation Organization mapseries (scale 1:1 000 000) was extracted manually and converted into a number of grids, completely covering the coastal area.

Airborne altimetry: The Greenland Aerogeophysical Project was carried out during the summers of 1991 and 1992 as a cooperation between Naval Research Laboratory and Defense Mapping Agency (both Washington D.C.). It was primarily an airborne gravity survey, but elevation data were collected simultaneously. Only data from the first half (south of 73°) is processed and released yet, and in this application only coastal measurements are included in the modelling.

GRIP-survey: This GPS-survey out of the GRIP icecore drilling camp on the summit of the ice cap was included (as opposed to other groundtruth observations) to be able to monitor the top of the ice as precisely as possible in the model. It consists of 240 measurements spanning an area of about 10 000 km^2.

All data discussed in the first paragraph were merged in a common direct access database in such a fashion that satellite remote sensing were included only if considered located on the icecap (data of this nature are normally regarded as non-valid if the general surface slope is above 1°), while digitized data plus GAP-observations were included only if considered to be coastal. This separation was done by examining each datapoint with respect to an ice/land/sea scanning, and a narrow zone around the land/ice boundary was in addition kept free of data in order to reduce effects from data inconsistencies and to smooth the transition. In the process of gridding the data, two prediction methods were used:

a) A standard weighted means scheme, where the weight of a data point is reversely proportional to the squared distance to the current prediction point.

b) A least squares collocation approach based on a second order Markov model, where the prediction is primarily governed by the covariance of the field and the estimated standard variance of the data.

The weighted means procedure was applied on the part of ice sheet covered by Geosat. The data density of this region is so large, that sophisticated (and time consuming) methods do not give any improvements compared to the straightforward one. The collocation approach proved, on the other hand, to be very successful on the northern half due to the relative sparsity of the ERS-1 altimetry, and on the coast, where the very variable terrain is not easily modelled by simple averaging. To improve accuracy, a biquadratic surface were fitted locally to data after every input operation. Points considered too distant to this surface were regarded as outliers and rejected in the prediction (this procedure was applied on the icecap only; a similar analysis does not work on the coast, again due to the variation of surface).

The result of the prediction was a 5'x10' geographical grid model. Finally, this grid was smoothed using a standard averaging filter, thus eliminating some predicting noise and a few modelling blunders. The result is displayed by a contour plot in Figure 3.

Comparisons with GPS

The digital elevation model of Greenland has been evaluated by comparing the obtained heights with groundtruth observations. This indicate that the mean accuracy over the ice is in the order of 5-7 m. This error is partly due to slope introduced errors and is not due to the altimeter performance. A measure of the accuracy in coastal regions have not been obtained, but it is definitely much poorer, and this is primarily where the model can be significantly improved.

Around the GRIP site a detailed comparison between the GPS height measurements and the altimetric heights from ERS-1 has been performed. This resulted in a nice agreement with differences around one meter (see Figure 4). Notice that this nice agreement has been obtained in a flat and smooth region, where re-tracking and slope correction are of minor importance.

Conclusion

In this paper new preliminary ERS-1 altimeter data have been analyzed, and a free air gravity anomaly map has been produced. The spectral analysis displays that the time varying parts of the sea surface heights dominate the signal at a level of about 7 cm at frequencies higher than 3 cy/deg. At lower frequencies a prominent stationary signal in the northern region shows up. The recovered gravity field correlates very well with major geological structures.

The results clearly demonstrate the potential of these new ERS-1 altimeter data. First of all, the 35 days repeat period provides altimetry with a significantly improved coverage compared with Geosat 17 days ERM data, moreover, data above 72 degrees latitude have become available even with a superior coverage. Hereby, valuable areas can be investigated: e.g. the Southern ocean around the Antarctic, the Barents Sea, and the Greenland Sea. Furthermore, determinations of the sea surface topography (e.g. Knudsen, 1992) can now be carried out in these regions.

In the future, when the satellite enters its 176 days repeat orbit (approx. April 1994), the coverage will be 5 times denser, superior mean sea surface heights can be computed and more fine structure gravity anomalies can be exposed.

The new ERS-1 ice cap data are extremely valuable, since a digital elevation model can be constructed for all of Greenland. When the altimeter data have been re-processed the elevation model of Greenland will be updated. Furthermore, when a model of the seasonal and annual height changes will be established, the known ice surface may be utilized in a reduction of the orbit error.

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