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Geodetic GPS-Based Evaluation of Present-Day Geodynamical Movements and Geoid in the Nares Strait Region

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Abstract: The Nares Strait region between Ellesmere Island and Greenland has for many years been of significant geological interest, since the details of the plate tectonic evolution of the region is still being debated. Even though the region is currently seismically inactive, it is still relevant to investigate whether the area is presently affected by movements, and if so, how large these movements are. Movements of interest are both the horizontal changes (if any) and – especially – the vertical uplift (the Nares Strait region is a major uplift anomaly in current glacio-isostatic rebound models). With the development in GPS, monitoring of geodynamical changes are a major focus point for geodesy – the traditional geodetic discipline that describes the size and the shape of the Earth. Repeated measurements in high-accuracy satellite geodetic reference networks are used for this, and any movements of the reference points, caused by geodynamic activity, must be considered in defining the reference systems.

This paper describes two geodetic GPS survey campaigns carried out in the Nares Strait region in 1995 and 2001, repeating observations in selected points from the classical joint Danish-Canadian triangulation along the Nares Strait completed in the early 1970's. Both recent GPS surveys were "opportunity missions" relying on logistics provided either by gravity survey activities (1995) or the research vessel "Louie S. St Laurent" (2001). Approximately ten geodetic markers were surveyed during both campaigns, and the positions of the well mounted markers were determined with accuracies of a few millimetre by utilising days of GPS data. In addition the 2001 field campaign also included sea-level observations for geoid control.

The GPS data was processed using advanced processing algorithms implemented in the Bernese GPS processing software, along with precise satellite orbit information, earth tide models etc. The positions determined from the two survey campaigns are analysed with the purpose of detecting if any significant relative movements have taken place during the six years, and the vertical movements are compared with a contemporary geodynamic uplift model.

Zusammenfassung: Die Region der Nares Strait zwischen Ellesmere Island und Grönland hat seit vielen Jahren das geologische Interesse auf sich gezogen. Im Detail wird die geologische Entwicklung noch immer diskutiert. Obwohl die Region derzeit seismisch inaktiv ist, lohnt es doch zu prüfen, ob und in welcher Größenordnung die Region von rezenten Bewegungen betroffen ist. Von Interesse sind beide Bewegungskomponenten, die horizontale (so vorhanden) und vor allem die vertikale, da die Region eine größere Hebungs-Anomalie in aktuellen Modellen postglazial-isostatischer Entlastung umfasst. Der Nachweis von geodynamischen Veränderungen ist seit der Entwicklung der GPS-Methoden ein wichtiges Feld für die Geodäsie, die traditionelle geodätische Disziplin, die Größe und Form der Erde beschreibt. Man benutzt Wiederholungsmessungen im Rahmen von hochgenauen geodätischen Netzwerken. Alle durch geodynamische Bewegungen verusachten Änderungen der Referenzpunkte müssen bei der Definition der Netze berücksichtigt werden.

In dieser Arbeit werden zwei geodätische GPS-Kampagnen beschrieben, die in der Region der Nares Strait 1995 und 2001 als Wiederholungsmessungen der klassischen dänisch-kanadischen Triangulation der frühen 70er Jahre durchgeführt wurden. Beide Kampagnen waren „Gelegenheits-Projekte“, die die Logistik eines Gravimetrie-Projekts (1995) und des Forschungseisbrechers „Louis S. St. Laurent“ (2001) nutzten. Etwa zehn geodätische Referenzpunkte wurden in beiden Kampagnen neu bearbeitet. Die Positionen der im Gelände sorgfältig fixierten Messpunkte wurden per GPS mit einer Ge nauigkeit weniger Millimeter bestimmt. Die Kampagne von 2001 umfasste daneben Bestimmungen des Meeresspiegels zur Kontrolle des Geoids. Die GPS Daten wurden mit Hilfe hoch entwickelter Algorithmen der Berner GPS-Software unter Berücksichtigung präziser Satelliten-Bahninformationen, Erdgezeitenmodellen etc. prozessiert. Die auf den beiden Kampagnen gemessenen Positionen wurden analysiert, um wenn möglich deutliche laterale Bewegungen innerhalb dieser letzten sechs Jahre nachzuweisen. Die vertikale Komponente wurde verglichen mit einem modernen geodynamischen Hebungsmodell.

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INTRODUCTION

The Nares Strait separates Ellesmere Island in the Canadian Arctic from Greenland. The exact nature of the plate-tectonics of the region is still being debated. Concerning present-day geodynamic movements, modern geodetic GPS precise positioning techniques have reached an accuracy level down to a few mm so that such methods provide an excellent tool for the investigation of possible present movements of the land, not just in the horizontal coordinates (primarily relating to tectonics) but also in the vertical (related, for instance, to the recent glacial loading history). The use of permanently mounted GPS stations are preferable for investigations of such geodynamical activity. However, permanent GPS stations do require a considerable amount of logistics and infrastructure, and are therefore difficult to establish in remote areas such as the Nares Strait region.

The second best approach is to carry out repeated GPS survey campaigns, where GPS receivers are carefully mounted at benchmarks and left at the sites collecting data for several days. With several days of carrier phase GPS data, and by carefully processing the data relative to the global GPS reference system, coordinates with accuracies at the sub-cm level can be obtained. If the sites are repeatedly visited, the obtainable level of accuracy is sufficient to detect geodynamical activity after a few years. This approach has been followed in the present case of the Nares Strait, where we analyse results of GPS survey campaigns carried out in 1995 and 2001, both as "opportunity missions", with the 1995 campaign measurements being suboptimal, since generally no more than 24 hour GPS observation sessions were possible due to logistic constraints. Seven locations were visited during both campaigns (Fig. 1), and by processing the GPS data from the two campaigns in the exact same way, the two sets of position coordinates can be compared, and the movement of the sites can be determined.

In this paper initially the two survey campaigns are described. This is followed by a brief review of the GPS processing theory, and the processing parameter set-up. The results of the two survey campaigns are compared in order to detect the movements, which have taken place during the six years. The movements are discussed and analysed, and they are compared with the ICE-4G geodynamical model (PELTIER 1996). We

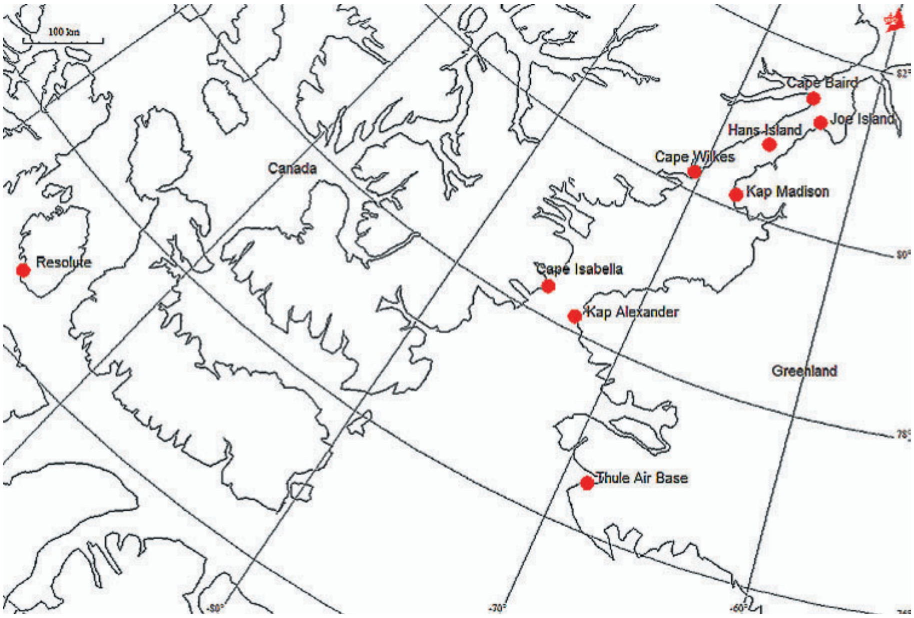

Fig. 1: Stations observed during both the 1995 and the 2001 survey campaigns.

finally also use the results of the combination of GPS and tide gauge data, collected as auxiliary data in 2001, for geoid control.

THE 1995 FIELD ACTIVITY

In 1995 the National Survey and Cadastre of Denmark (KMS) participated in the joint Danish-Canadian "Op Bouguer" project, a joint venture between Mapping and Charting Establishment, (Canadian Defence), Canadian Hydrographic Service, KMS and NIMA. The main purpose of this project was to cover Ellesmere Island and the adjacent parts of Greenland with gravity measurements on a 10-15 km grid, including gravity measurements on the sea-ice of the Nares Strait.

Using the available helicopter logistics, a GPS survey of the older 1970's triangulation points along the Nares Strait was done, mainly in order to establish a "zero epoch" for future geodynamic studies. The survey was done by KMS, in cooperation with the Geodetic Survey Division, Natural Resources of Canada (NRCan), who operated sites at Grise Fjord and Resolute Bay. The field work and the results of the processing are documented in Forsberg et al. (1995). The location of the 19 sites observed with GPS are shown in Figure 2. The permanent GPS station THU1 at Thule Air Base, and station RES1 in Resolute Bay, were operated as reference stations, continuously logging data throughout the field campaign.

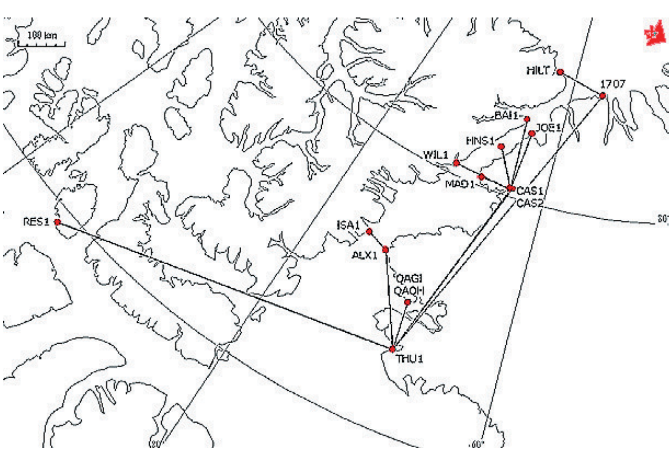

Fig. 2: Network configuration in 1995.

THE 2001 FIELD ACTIVITY

With the Nares Strait GeoCruise 2001, an opportunity arose to revisit the sites observed in 1995, and based on the two different data sets analyse whether any movements (locally or regionally) had taken place over the six years. The Nares Strait GeoCruise was established as a research cruise mainly by initiative of the German Bundesamt für Geowissenschaften und Rohstoffe (BGR), and the Geological Survey of Canada, Bedford Institute of Oceanography. Several other research groups participated in the cruise as well.

A total of 15 sites were visited with GPS during the 2001 GPS campaign, and seven of these sites were identical with sites visited during the 1995 survey. As a part of the 2001 fieldwork, new and more stable station markers were established at the sites in order to improve the accuracy of any future GPS surveys in the area. The new markers are so-called GPS-bolts, drilled and glued into the rock. The GPS antennas can be mounted directed on the bolts, whereby any inaccuracies from the antenna setup are eliminated. Data from short observation time spans (c. 30 minutes) between the old and the new markers were collected to be able to position the two markers relative to each other. The GPS fieldwork of the 2001 survey was carried out as a cooperation between the Geodetic Survey Division of NRCan, Asiaq - Greenland Survey, and KMS. More information on the fieldwork is given by Jensen et al. (2001).

Locations of the GPS sites that were visited during the 2001 survey campaign, and the network used for the GPS data processing are shown in Figure 3. The GPS stations THU2 at Thule Air Base, RES0 in Resolute, GRIS in Grise Fiord and EURK in Eureka were operated as reference stations collecting GPS data continuously during the cruise. The permanent station in Thule is an IGS station operated by KMS, and the

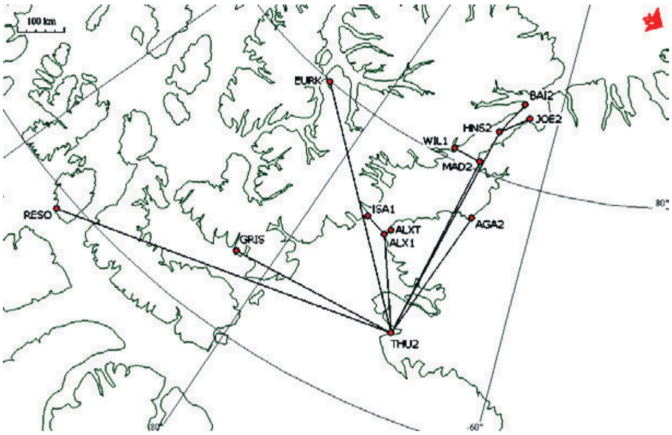

Fig. 3: Network configuration in 2001.

permanent stations in Eureka and Resolute are operated by NRCan. The stations in Thule and Resolute are new installations, and thus not the same as the ones used for the 1995 survey. The station in Grise Fjord was a temporary set-up for the duration of the 2001 cruise.

GPS DATA PROCESSING THEORY

Before the processing procedure and parameters used for the present GPS data processing are described, a brief summary of the GPS carrier phase based positioning theory is given below.

When using GPS for high accuracy differential positioning, at least two GPS receivers must be used. One receiver is located at a reference point with known coordinates and the other receiver (the rover) is located at a point with unknown coordinates. The position of the rover is then determined based on the vector between the two stations, or in other words relative to the reference station.

To obtain the high position accuracy both code and phase observations collected by the two receivers are used. The GPS positioning process is based on the phase observation equation as described, for example, in Kleusberg & Teunissen (1996). With observations from two receivers and two satellites at the same epoch in time, the observation equation can be generated for each receiver-satellite combination, and the equations can be twice differenced (double differenced). The result is the double differenced phase observation given in Equation (1):

$$\Delta\nabla\Phi = \Delta\nabla\varrho + \Delta\nabla d_{\varrho} - \Delta\nabla d_{ion} + \Delta\nabla d_{trop} + \lambda\Delta\nabla N + \Delta\nabla\varepsilon$$

Where $\Delta\nabla$ is the double difference operator, ϱ is the geometric distance between receiver and satellite, d_{ϱ} is the error in the satellite position, d_{ion} is the ionospheric delay, d_{trop} is the tropospheric delay, λ is the wave length, N is the ambiguity - the initial number of full carrier phase cycles, and ε is the noise term including mainly multipath and receiver noise, but also any un-modelled errors. All elements are given in range units.

The double differenced ambiguity, $\Delta\nabla N$, is by nature an integer number and to obtain position accuracies of a few cm or mm the correct integer number for the double difference ambiguity must be determined. This is not a trivial task, but several ambiguity resolution techniques do exist, see for instance Han & Rizos (1997) for a review of some techniques.

The sizes of d_{ϱ}, d_{ion}, and d_{trop} (the spatially correlated errors) are reduced when performing double differencing, and for vectors shorter than approximately 20 km these errors are generally negligible after double differencing.

For longer vectors the spatially correlated errors do not cancel out, and may therefore be treated as part of the positioning process. For post processed positioning the error in satellite position can be mitigated by using precise post processed satellite orbit information for instance from the IGS (Neilan et al. 1997).

The ionosphere is dispersive for radio waves, so the ionospheric effect is different for the two GPS frequencies referred to as L1 and L2. When working with dual frequency receivers which is normally the case for high accuracy positioning, the ionospheric error can therefore be mitigated by using the so-called ionosphere free linear combinations of the L1 and L2 observations (Seeber 1993). Hereby the first order ionospheric effects are removed from the positioning process. Higher order effects of the ionosphere will still be present, but for vectors of 50-100 km their influence is relatively small. For longer vectors, the higher order effects should, however, be considered (Brunner & Gu 1991). The ionospheric activity is correlated with the solar activity and thus also with the geomagnetic activity. It is therefore possible to use indices for solar and geomagnetic activity as indicators for the amount of ionospheric activity, and this has also been done in the present case, as described in the following sections of the paper.

The tropospheric delay is caused by refraction of the satellite signal as it is transmitted through the lowest parts of the Earth atmosphere. The refraction, and thereby the signal delay, is a function of the meteorological conditions along the signal path, and for positioning purposes the majority of the effect is handled by global tropospheric delay models. For high accuracy positioning the residual effect after both modelling and double differencing can be estimated through the positioning process. This tropospheric effect is considerably smaller than the ionospheric effect and for differential GPS positioning carried out in dry cold conditions, the residual tropospheric effects are normally not causing any problems in the positioning process.

The effect of the remaining error sources i.e. receiver noise and multipath is small because of the high quality equipment used, and because the GPS-sites are all located in environments with little multipath.

GPS PROCESSING CHARACTERISTICS

In 1995 GPS data were collected from 27 May to 19 June. At the time of observation the solar activity cycle was close to a minimum, and the days were all characterized by a low to moderate ionospheric activity, which is not expected to cause any disturbance in the positioning process. In 1995 the observation time spans for the stations of interest were 24 to 36 hours for each station except for the station on Hans Island, which was only observed for 45 minutes.

In 2001 GPS data were available from 28 July to 24 August. This fieldwork took place at the peak of the current solar activity cycle, but fortunately during a time period with low to moderate ionospheric activity. The observation time spans in 2001 were between one and a half and three and a half days for each station.

The 1995 data were initially processed right after completion of the survey campaign, but in order to have as similar conditions as possible for the coordinate comparison, the data were reprocessed along with the 2001 data set. Both processing runs were carried out using the same processing parameters, and also, in order to have as similar conditions as possible, the differential GPS networks to be processed were designed to be as identical as possible (see Figs. 2, 3).

The IGS stations at Thule Air Base have been used as the central reference stations, and have thus been constrained at their given coordinates. For the 1995 data, station THU1 was used, and the nearby and newer station THU2 was used for the 2001 data.

For differential GPS positioning a higher accuracy is obtained by using long observation time spans and short inter station vectors. In our case the distances from some of the stations in the Nares Strait region to Thule Air Base are long, so in order to obtain the best accuracy possible, the stations with the longer observation time spans were used for processing of the long vectors. Vectors with short observation time spans could then in most cases be tied to stations located closer than the stations at Thule Air Base. Hereby shorter GPS vectors, and thereby a better position accuracy, is obtained.

For the data processing precise satellite positions, the final precise post-processed orbits from the IGS, were used in order to minimise the influence of errors in the satellite positions. The data were processed with a 15° elevation mask in order to eliminate the noisy data received at the lowest elevation angles. The tropospheric error was mitigated using the Saastamoinen global tropospheric delay model (Saastamoinen 1973), and an ionosphere free linear combination of the observations from the L1 and L2 frequencies was used to mitigate the ionospheric effect.

The data were processed using the Bernese Software version 4.2 (Beutler et al. 2000). The processing software is considered to be one of the best and most advanced processing softwares, and the only known differential residual factors that are not handled by the software, and could have an influence on the positions, are ocean and atmospheric loading effects. Both are, however, expected to be negligible in the present case.

The GPS data processing is carried out in several steps; first preliminary station coordinates are determined, then the ambiguities are resolved, and more precise station coordinates are determined. For these initial processing steps it is important to avoid geometrical misalignments in the processing, and the coordinates used for the reference station must therefore be given in the exact same reference frame as the satellite positions. The initial data processing is therefore carried out using the ITRF93 reference frame for the 1995 data, and ITRF97 for the 2001 data (Boucher & Altamimi 1996). When the ambiguities are resolved and the vector components are determined, the final coordinates in the reference frame wanted for the results can be then determined. More information on the GPS data processing is given by Weber (2003).

PRELIMINARY RESULTS OF THE PROCESSING

In Figure 4 the RMS of repeatability is given for some of the stations. RMS values are only determined for stations with more than one observation session, i.e. stations observed for more than 24 hours.

The RMS values give an indication of the stability of the solution. Generally the 2001 data set is better than the 1995 data. There are many small gaps in the data from 1995, probably caused by the older generation of equipment used, but also the observation time intervals were shorter in 1995, and in some cases really too short considering the length of the vectors. Stations with only a few observation sessions are generally more sensitive to noisy data, so both the shorter observation time spans and the increased amount of noise in the 1995 data translate into worse position accuracies and thereby the poorer repeatabilities shown in Figure 4.

Generally the repeatability is about 1 cm in the horizontal, and 1.2 cm in the vertical for the 1995 data, and 3 mm in the horizontal, and 6 mm in the vertical for the 2001 data. In order to estimate the level of position accuracy, external error sources, mainly centring of the GPS antennae, should also be considered. In this case, special small tripods were used, and great care was taken in centring and in measurement of antenna height, and the contribution of antenna centring to the error budget is estimated to be 1-2 mm, at the most.

FINAL GPS RESULTS

For the final processing step both THU1 and THU2 were constrained to coordinates given in the ITRF97 epoch 15 August 2001. When constraining the two Thule stations to coordinates given at the same epoch in time any movement that might have taken place in the Thule area within the six years is neglected, and Thule is thereby assumed to be a stable. This is of course not the case in reality, but the assumption makes it possible to analyse whether the entire Nares Strait region is moving in the same way.

The general movements in the Thule area can be determined from the ITRF97 global GPS velocity solution, where Thule has moved –10 cm in the North direction, 10 cm in the East direction and –2 cm in the Up direction over the six years.

For any future observation campaigns the new station markers (postfix 2 in the station name) will be used since they are more stable than the old markers (postfix 1 in station name). The new markers will thus be used for analysing the movements in the area and it is therefore necessary to generate 1995-coordinates for these markers that were established in 2001. For this purpose the vector components obtained between the old and the new markers from the processing of the 2001 data, are used to generate 1995 coordinates for the new markers. The distances between the old and the new markers are between 15 and 40 metres, and it is assumed that no local movements have

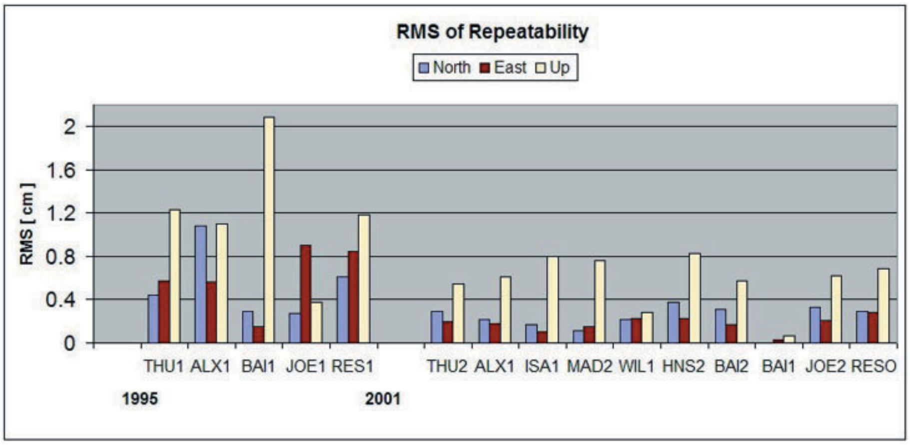

Fig. 4: RMS of repeatability for the coordinates from 1995 and 2001.

taken place between the location of old and the new markers at the various sites during the six years.

Final coordinates for 1995 and 2001, expressed as Northing, Easting and height above the reference ellipsoid, for all the stations used for the geodynamic analysis are shown in Table 1.

COMPARISON OF 1995 AND 2001 CAMPAIGNS

Coordinate differences between the two sets of coordinates (Tab. 1) can now be determined. The coordinate differences, and thereby an indication of the movements that have taken place at the locations between May/June 1995 and August 2001, are shown in Table 2. These coordinate shift values should be seen in relation to the accuracy estimates (Fig. 4). Generally the coordinate shifts in the horizontal are larger than the RMS of the coordinate values, indicating that the movements are significant. For the height the results are generally more noisy. This is further discussed below.

The large differences for station HNS2 are caused by problems with resolution of the ambiguities in processing of the 1995 data. The observation time span in 1995 was only 45 minutes, and this is not sufficient for a vector of about 90 km. The 1995 results for this station are therefore considered unreliable, and the station is not used for any further analysis in this paper.

For station WIL1 the differences are also large, about 7-9 cm for each coordinate component. The RMS values (Fig. 4) are only a few mm for the 2001 data, and the explanation for the large differences might thus be found in the first data set. In 1995 the observation time span was 24 hours for the 130 km vector, and the observations were collected on June 3. When analysing the Northern Polar Cap Geomagnetic index a slightly increased geomagnetic activity during the morning hours of the current day is found and this might have affected the GPS signal propagation and thereby also have decreased the positioning performance. The results for station WIL1 are therefore also considered inaccurate, and will not be analysed any further.

The apparent movements in the horizontal for the remaining stations are plotted in Figure 5, where the size and direction of the 6-year coordinate shifts are indicated by the length and direction of the black vectors in the plot. There seems to be a correspondence between the size and direction of the movements of stations ISA1, ALX1 and MAD2. However, station JOE2 and BAI1 move in other directions, and the magnitude

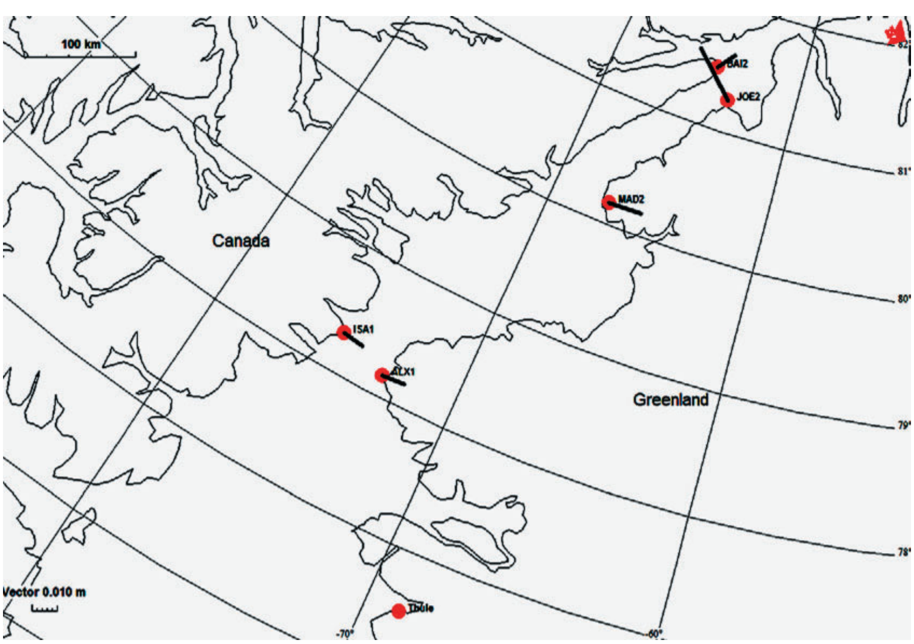

Fig. 5: Horizontal movements 1995 to 2001, relative to Thule.

Station	Northing (m)	Easting (m)	Height (m)
		1995	
THU1	8564551.348	44337.085	54.992
ALX1	8770583.822	8258.430	422.415
ISA1	8804883.408	-29250.315	250.113
MAD1	8943470.978	192674.577	126.948
MAD2	8943507.131	192689.427	124.602
WIL1	8966157.950	137999.005	1061.537
HNS1	9009926.421	228186.439	177.827
HNS2	9009937.292	228157.919	177.210
BAI1	9073062.004	276886.610	867.637
BAI2	9073091.914	276896.144	866.791
JOE1	9044261.113	289016.321	210.479
JOE2	9044270.689	289026.686	210.390
		2001	
THU2	8564808.017	43406.657	36.065
ALX1	8770583.818	8258.439	422.445
ISA1	8804883.403	-29250.308	250.112
MAD1	8943470.974	192674.590	126.956
MAD2	8943507.127	192689.439	124.610
WIL1	8966157.880	137999.081	1061.626
HNS1	9009926.450	228186.482	177.551
HNS2	9009937.321	228157.962	176.935
BAI1	9073062.008	276886.617	867.642
BAI2	9073091.919	276896.151	866.796
JOE1	9044261.133	289016.310	210.517
JOE2	9044270.709	289026.675	210.428

Tab. 1: Final GPS coordinates, UTM zone 22 and ellipsoidal heights, ITRF97

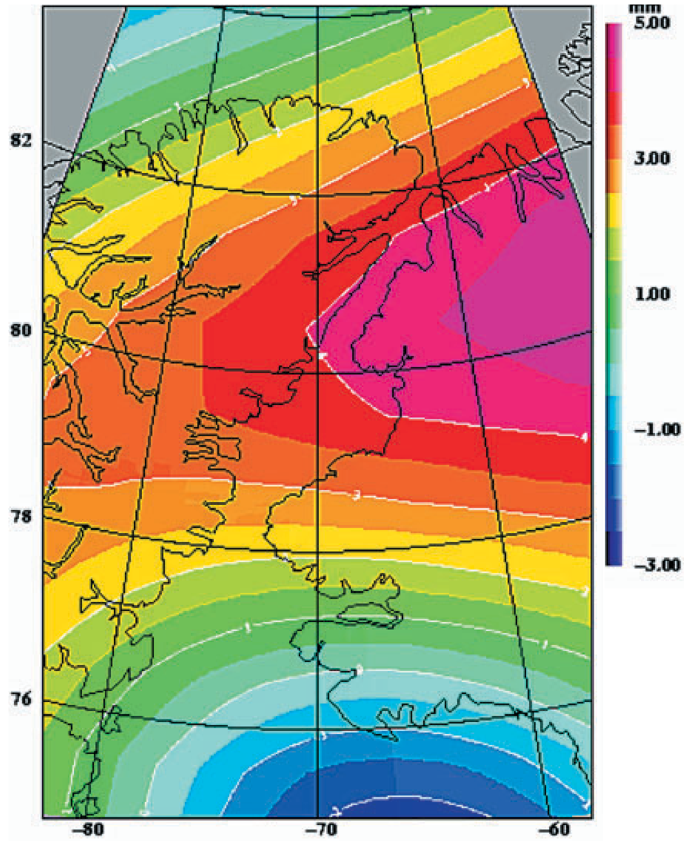

Fig. 6: Uplift (mm/yr) from the ICE-4G glacio-isostatic model.

2001-1995				
ALX1	2025:	ΔN	=	-0.004 m
		ΔE	=	0.009 m
		ΔH	=	0.030 m
ISA1	2026:	ΔN	=	-0.005 m
		ΔE	=	0.007 m
		ΔH	=	0.000 m
MAD2	2293:	ΔN	=-	-0.004 m
		ΔE	=	0.013 m
		ΔH	=	0.008 m
WIL1	2071:	ΔN	=	-0.071 m
		ΔE	=	0.076 m
		ΔH	=	0.090 m
HNS2	2294:	ΔN	=	0.029 m
		ΔE	=	0.044 m
		ΔH	=	-0.276 m
JOE2	1070:	ΔN	=	0.021 m
		ΔE	=	-0.011 m
		ΔH	=	0.038 m
BAI2	1071:	ΔN	=	0.005 m
		ΔE	=	0.007 m
		ΔH	=	0.006 m

Tab. 2: Differences between station coordinates in 1995 and 2001.

of JOE2 is much larger than the other stations, and could be affected by local effects. The overall pattern of the horizontal movements show that no major strike-slip movement exist along the Nares Strait, but otherwise results are consistent with a residual plate tectonic rotation relative to Thule.

For the five "good" stations (Tab. 2) the movements in the vertical direction are about 1-4 cm over the six years. These numbers can be compared to contemporary glacial-isostatic uplift models, expressing the modelled land uplift due to historical changes in ice load coupled with a rheological earth model. Figure 6 shows the uplift from the ICE-4G model (Peltier 1996). It is seen that relative to Thule the central Nares Strait region is a region of high uplift, up to 5 mm per year, thus given a 3 cm effect over 6 years which – barely – should be detectable.

Figure 7 shows the GPS-observed relative height change over the 6-year period. The data are seen to be quite noisy, but at least the sign and order of magnitude of the movements are consistent with ICE-4G. It is therefore clear that on longer time spans (say, 10 year+), monitoring of uplift in this region by campaign-style GPS should have a lot of potential, especially considering the improved mounting and superior GPS observation quality of the 2001 campaign.

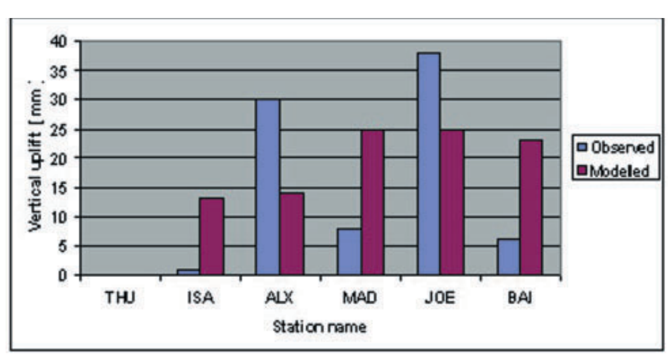

Fig. 7: Observed and modelled land uplift for 1995-2001 for the roughly South to North transect of "good" GPS stations along the Nares Strait, relative to Thule.

GPS AND SEA-LEVEL GEOID COMPARISON

The Nares Strait GeoCruise provided an opportunity to additionally collect GPS positions linked to mean sea-level. These data are useful for evaluating the geoid models of the region for major systematic errors. The basic equation for the geoid height, N, derived from GPS and tide-gauge observations is

$$N^{GPS} = h^{GPS} - H^{sea\text{-}level} - \zeta \qquad (2)$$

where h is the GPS ellipsoidal height, H the height above mean sea-level of a local tide gauge benchmark, and ζ the mean sea-surface topography. The latter is a small number (sub-m) and likely rather constant in a small sea area like the Nares Strait, and it is neglected in the sequel, together with the differences in the permanent tidal effects (GPS and geoid is referred to a tide-free system, whereas the mean sea level is by definition in the mean tidal system; this might yield an insignificant error at the cm-level, much smaller than geoid errors).

The contours of the geoid of the Nares Strait region are shown in Figure 8. This geoid model is derived from a mix of satellite data, gravity data, and terrain models, as part of an Arctic-wide gravity field compilation, the "Arctic Gravity Project" (Kenyon & Forsberg 2001). The model should be reasonably good in the Nares Strait region, partly because of the 1995 gravity project. The features on the geoid are essentially corresponding to low-pass filtered gravity free-air anomalies, with the major low in Kane Basin due to a deep regional mass deficit.

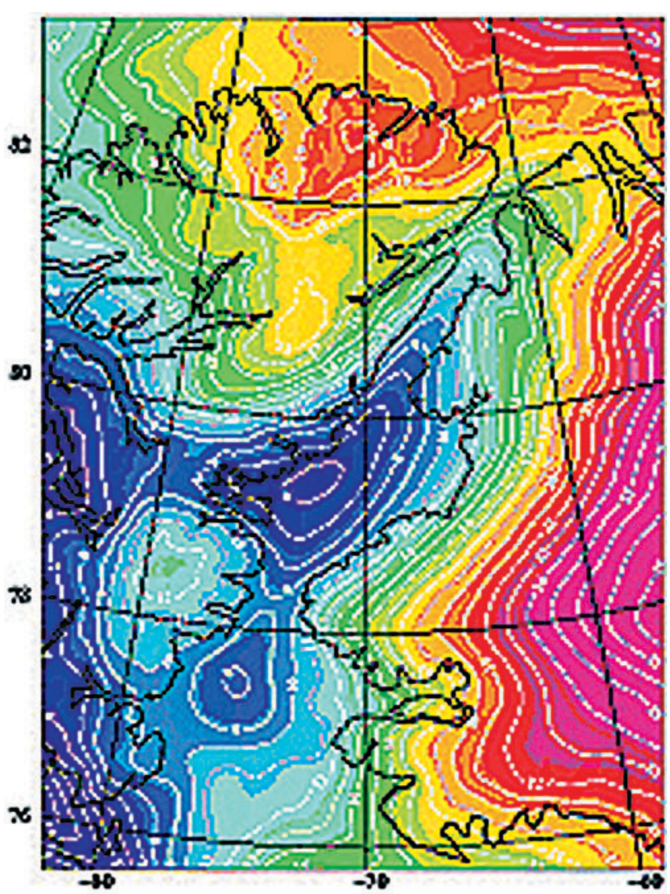

Fig. 8: Geoid heights (meter) in the Nares Strait region from the ArcGP geoid model. Crosses show location of GPS sea-level points.

At two locations in Inglefield Land (Cape Alexander and Cape Agassiz) temporary tide gauges were placed for a few days as part of the 2001 survey, and the tide gauge reference points were tied to GPS bolts onshore. Both a conventional portable tide gauge and a low-cost unit were tested. Figure 9 shows an example of the sea-level record at Cap Agassiz of the low-cost unit. With the relatively short duration of the sea-level observations (2-3 days) only a rough mean sea-level can be estimated, since long-period tides will produce aliasing. However, for geoid control, accuracies of a few dm are sufficient to control possible long-wavelength geoid errors.

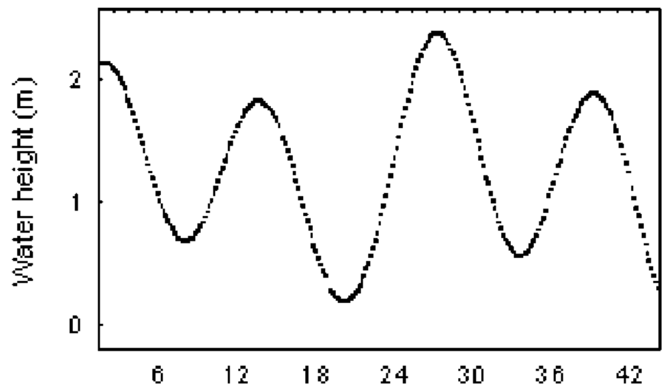

Fig. 9: Tide-gauge observation at Cape Agassiz, as a function of relative time (hours).

Table 3 shows the elevation above sea-level results of the new tide gauge observations (denoted new) and older local mean sea-level observations, both given for nearby GPS points, locations of which are shown with crosses in Figure 8. Also in Table 3 geoid heights derived from GPS and sea-level observations, using Equation (2), are shown for the same points. Because the older points are tied in with triangulations up to some 10-20 km extent, the older values of sea-level height can be quite uncertain, which is indicated in the last column in Table 3 where the differences between the observed geoid

GPS point	Elevation above sea-level (m)	Geoid height from GPS and tide obs. (m)	ArcGP difference (m)
Alert (68B25)	79.52	19.63	0.55
Joe Island (1007)	199.93	10.46	(-1.14)
Cape Madison (2055)	118.77	8.07	-0.35
Cass Fjord (2094)	59.29	12.71	-0.09
Cape Agassiz (2292 *new*)	7.27	13.67	-0.02
Cape Alexander (2290 *new*)	11.68	10.60	-0.18
Qaanaaq (3407)	3.70	14.60	-0.25
Thule astro (3130)	8.25	15.55	-0.45

Tab. 3: Elevation above sea-level, derived geoid heights at the GPS points, and difference to ArcGP geoid model, derived from both new and older sea-level observations.

heights and the geoid heights from ArcGP are given.

It is seen that Joe Island does not fit well, and indicates a gross error in the old triangulation (the 1976 sea-level observation was on the mainland of Greenland and not on Joe Island itself). Also, at Alert the elevations seem not consistent, and the accuracy of connection from the benchmark 68B25 to sea-level is unknown. For the other points the consistency of the data seems reasonably accurate, with the 20 cm RMS variability being within the range of errors as possible in the ArcGP geoid, and also in the variability domain of the sea-surface topography. The new points observed in 2001 fit well with the other points, and have complemented the older data with new, more reliable, points and observations.

CONCLUSIONS

Due to the opportunity of the 2001 Nares Strait GeoCruise seven GPS sites first observed in 1995 were revisited. The two GPS data sets from the stations have been processed and analyzed in order investigate the geodynamical activity that has taken place in the area within the six years. Reliable results were obtained for five of the stations, and all five stations seem to be rotating relative to Thule. Vertical movements of the stations are roughly coincident with contemporary glacial-isostatic rebound models, but for more reliable estimates future campaigns should be carried out, utilising the new improved benchmarks put in place 2001.

With the additional observation of sea-level GPS heights, new reliable "GPS-levelling" data were added to the Greenland set of such data, allowing the calibration of geoid ties to mean-sea level, in principle defining the vertical datum surface. The data along with older data indicate that the recent ArcGP geoid model seems quite accurate.

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