Measurement of vertical crustal motion in Europe by VLBI

Station report for Ny-Ålesund

Norwegian Mapping Authority

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Abstract

The Norwegian Mapping Authority (NMA) participates in the project "Measurement of vertical crustal motion in Europe by VLBI" with the space-geodetic observatory at Ny-Ålesund. This observatory is a multi-parameter monitoring site contributing to global geodetic networks. Due to its remote location in the Arctic, the station constitutes a unique cornerstone for these networks. The environmental parameters recorded at the station include sea level, surface deformations and gravity. Meteorological observations including daily radio-sondes are available for the nearby research station of the Alfred-Wegener-Institute.

In the project, NMA contributes to several of the tasks defined in the project workplan. For each task, the status is reported. Up to now, progress has been close to the workplan with some additional contributions reported here.

The comparison of horizontal station velocities to those predicted by the NUVEL-1A model for the Eurasian plate shows a good agreement. Comparison between GPS and VLBI results for station velocities results in significant disagreement for vertical velocities, the reason of which remains to be clarified.

1 Introduction

Within the EU-Project *Measurement of vertical crustal motion in Europe by VLBI*, the Norwegian Mapping Authority participates with the geodetic observatory in Ny-Ålesund. The observatory is a multi-parameter environmental monitoring site located at 78.9 °N and 11.9 °W on the West coast of Spitsbergen, the main island of Svalbard. At this research and monitoring facility, surface displacements of the Earth's crust are monitored with mm precision utilising the most advanced space-geodetic techniques. The geodetic activities at Ny-Ålesund are strongly interwoven with international programs and organisations, which provide the background for monitoring the state of the Earth system and for studies of the system's dynamics and climate. Thus, the Very Long Baseline Interferometry (VLBI) station is contributing to the global VLBI network and all observations are coordinated with international programs such as the one for Continuous Observations of the Rotation of the Earth (CORE). The Global Positioning System (GPS) receivers deliver data to the International GPS Service (IGS), which maintains a network of more than 150 stations globally distributed, though with large spatial gaps in the Arctic. Both networks contribute to the definition and maintenance of the International Terrestrial Reference Frame (ITRF) and the monitoring of the Earth Orientation Parameters (EOP) as available from the International Earth Rotation Service (IERS). The Global Sea Level Observing System (GLOSS) includes the tide gauge operated at Ny-Ålesund. GLOSS strongly recommends the co-location of tide gauges with permanent GPS receivers and gravity measurements, conditions which are both met at the station. The geographical distribution of the sites in all these nets is characterised by a low number of Arctic stations, thus emphasising the importance of Ny-Ålesund for the networks.

According to the workplan of the EU-Project, NMA is supposed to participate in the following tasks within the project:

- The post-processing consisting of the fringe analysis and the geodetic least squares adjustment of baselines, site positions and site velocity vectors.
- Securing the operation of the VLBI facilities for the scheduled Geo-VLBI-experiments including maintenance and test of equipment.
- Survey of antenna stability by local geodetic techniques.
- The processing of GPS data collected at the VLBI sites.

Below, we will report the status concerning each of these tasks. Moreover, at NMA work has been carried out, which is contributing to the following tasks, though NMA according to the workplan originally was not obliged to contribute to these:

- comparison of VLBI and GPS results through data analysis of the continuously operating GPS stations in Europe;
- separation of vertical crustal motions related to different geophysical phenomena;
- connection of tide-gauges, monitoring of sea level changes, subsidence of North Sea lowlands.

For these additional tasks, the status is described below as well. For the last task, it should be mentioned that the connection of tide-gauges and monitoring of sea-level changes is restricted to Svalbard and does not include the North Sea area.

Sections 7 and 8 are slightly more elaborated. In Section 7, the scientific background for determining the vertical crustal motion due to ice-load changes is briefly reviewed, as this defines the requirements for observations. Moreover, the available station velocities are compared to model predictions for tectonic motions. In Section 8, the tide gauge records for Ny-Ålesund and Barentsburg are used to emphasise the value of the geodetically determined vertical crustal motion for the interpretation.

2 Post-processing and Analysis

An initial analysis of the available experiments including Ny-Ålesund was carried out with the OCCAM software by B. R. Pettersen in 1997 in co-operation with O. Titov (see Titov and Pettersen, 1997). Additional processing and determination of co-ordinates for Ny-Ålesund were carried out with OCCAM under an external contract by E. Repstad (see Repstad, 1997). The contract covered the following parts, which were delivered satisfactorily in 1997:

1. Installation of the program OCCAM 3.4 on a PC.

2. Establishment of a database in NGS-format of correlated data for VLBI observations where Ny-Ålesund took part.

3. Diverse calculations with OCCAM 3.4 on the basis of the established database.

4. Presentation of program documentation, user's handbook and results of calculations in a report.

Since autumn 1997, no processing or analysis was done at NMA. Despite considerable efforts, it was not possible to fill a new permanent position dedicated to VLBI analyses. In several rounds attempting to fill the position, no qualified person could be appointed. Currently, another round is in progress and it is hoped to fill the position soon.

Steps have been taken recently to install the CALC/SOLVE software at NMA. If the open position can be filled, then NMA will be able to contribute to the processing and analysis of the VLBI data. In this case, initial focus will be on the European experiments.

As mentioned above, preliminary results of the analysis were described in a paper published in the proceedings of the VLBI workshop held in Hønefoss in 1997 (Titov and Pettersen, 1997). It is interesting to note here that these authors find a discrepancy between the EW-velocity determined from the VLBI observations and the NUVEL1-A prediction. This result is not confirmed by a recent analysis of Ma (1998, personal communication), where a much better agreement between the horizontal components for the VLBI site in Ny-Ålesund and the NUVEL1-A predictions is found. These velocities are also in reasonable agreement with the horizontal velocities determined from the GPS record of the IGS site in Ny-Ålesund . However, the vertical velocities of VLBI and GPS differ significantly from each other (see Section 7 for numbers and a more detailed discussion). In 1999, one focus of the analysis work will be on the reconciliation of these discrepancies between the different analyses as well as the different techniques. Motivated by the significant seasonal signal found particularly in the GPS-heights, emphasis will be on the tropospheric effects on GPS and VLBI co-ordinates.

3 Participation in experiments and maintenance of the VLBI antenna

In Table 1 all experiments for the period Oct. 96 to Dec. 98 are compiled. The table demonstrates that Ny-Ålesund managed to participate in all but one of the scheduled experiments.

At Ny-Ålesund VLBI is operated by the observatory staff of currently one station manger and two engineers. The VLBI activities are dominated by taking part in international VLBI-experiments (VLBI Europe, pre-CORE, NEOS, and VLBA) as well as the testing of equipment and the maintenance of the station. For example, in 1997, 41 experiments with a total of 35 observing days were successfully carried out, while six of the scheduled days were lost due to overhaul of the receiver, broken capstan motor and problems resulting from an upgrade of the tape station. In 1998, the level of activity increased slightly compared to 1997.

To maintain the ever improving technical level required for international co-operation and participation in future experiments, several major actions have been necessary, namely (1) to change the dewar and carry out an overhaul of the receiver (March 1997), (2) to change the Field System computer and upgrade it from FS 8 to FS 9.3.16 (July 1997), (3) to upgrade the tape station and MARK III to MARK IV with thin tape (September 1997), (4) to mount an extra timer for TAC - Formatter measurement during experiments (October 1997), and (5) to carry out a thorough maintenance of the Maser (March 1997).

The remote location of the observatory requires special

Table 1: Participation of Ny-Ålesund in the EUROP experiments.

Year	Exper.	Date	Comment
1996	Europ5	3 Nov.	Small problems with two video converters within the first hour
	Europ6	5 Dec.	Field system computer stopped once. No other specific problems
1997	Europ1		participation of NMA not scheduled
	Europ2	17 Mar.	Not participated due to repair of receiver
	Europ3	16 Jun.	
	Europ4	25 Aug.	
	Europ5	30 Oct.	
	Europ6	8 Dec.	
1998	Europ41	02.02.	
	Europ42	20.04.	
	Europ43	22.06.	
	Europ44	17.06.	
	Europ45	20.10.	loss of one pointing due software failure in field system (on-off procedure)
	Europ46	14.12.	a few problems due to short power dip; high SEFD values for S-band

considerations concerning possible break-downs, thus, for example, a spare FS computer was acquired for the site. Yielding to the climate conditions, heating cables were isolated and mounted on the gearboxes to the antenna. Moreover, the antenna was painted in 1997 in order to reducing effects due to solar warming and thus to increase the over-all receiving characteristics.

Considerable activity has focused on determining the stability of the observatory with respect to the surrounding area and to control the stability of the antenna. The status of this work is reported in Section 4.

Other activities at the observatory relevant to the EU Project include the connection of the tide gauge to the observatory, the observation of Earth tides (relative gravity), absolute gravity measurements and the operation of the IGS receivers.

At the IGS site, the old monument was sitting in permafrost and some instabilities were suspected. Therefore, a new monument firmly attached to the bedrock was constructed (in June 1997), and an additional GPS receiver was installed at the new location. IGS requests to operate the two receivers in parallel for a total period of one years. Today, the two receivers continue to observe in parallel. Both receivers provide high-quality data. Analysis results show a clear seasonal signal in the height component, which is most likely due to tropospheric effects.

Relative gravity is continuously monitored at a location in the vicinity of the observatory and the analysis of the time series indicates high-quality results.

Absolute gravity measurements were carried out (by BKG, Germany) at the observatory in early July 1998 on a solid monument attached to the bedrock. Since the small laboratory planned to be built above the monument could not be finished in time, a temporary cabin was erected to shelter the instrument. A preliminary analysis of the observations shows an extremely low noise level at the site. It is now planned to finish the laboratory in 1999 and to install (in international co-operation) a superconducting gravimeter at this monument.

The tie between the near-by tide gauge and the geodetic observatory has been re-measured. The measurements indicated that there is no significant movement of the tide gauge with respect to the land.

4 Surveying the antenna

The local control network in Ny-Ålesund consists of 8 reinforced concrete pillars with Wild brass screws for horizontal reference and a brass levelling bolt for vertical reference (Grimstveit and Rekkedal, 1998). The pillars are drilled into bedrock and they are insulated and protected against sunlight. Moreover, the ground around the pillars is insulated to avoid melting during summer. Additionally, brass bolts have been located in the fundaments of the different antennas. While most of the local control network was established in the period 1991 to 1995, the bolts in the fundament of the VLBI antenna were attached in 1998.

Major campaigns were carried out in 1992 (levelling), 1995 (directions and zenith angles), 1997 (levelling, some directions and zenith angles). The main goals of the measurements were to check the axes of the VLBI antenna and to tie the different techniques together. However, the severe weather conditions did not allow to fix the orientation of the VLBI with the available instruments. Therefore, the antenna could not be tied to the other techniques, and changes in the position of the VLBI antenna could not be determined.

In 1999, a new attempt to measure the antenna will be made based on more advanced instruments allowing a much faster measuring. Moreover, the bolts in the fundament of the antenna have been measured in 1998 and will be re-measured in 1999.

The analyses of geodetic measurements of the local control network around the VLBI antenna and the GPS sites indicate some deformations in the control network, which may be due to movements of the pillars in the permafrost.

To assess the regional stability, a regional control network has been established in July 1998 around Ny-Ålesund with eight new geodetic markers drilled into what was considered to be stable bedrock. The network has an extension of about 50 km in east-west and 30 km in north-south direction and crosses several major geological faults. Apparently, these faults are not active today. In a first-epoch campaign carried out in September 1998, seven of these points could be measured simultaneously with GPS for five full days. In addition, simultaneous GPS measurements were carried out on a mountain close to the observatory (Zeppelinfjellet), and these observations are currently being used together with the data from the regional network for tropospheric and ionospheric studies.

It is planned to re-measure the control network in August/September 1999 with GPS. This campaign will not only include all regional but also all local points.

The large east-west extension of the control network, which is almost perpendicular to the ice sheet east of Ny-Ålesund may allow to use the observations to determine the surface deformations due to changes in the ice load. The application of the GPS and VLBI measurements for this task is part of a co-operation with GFZ Potsdam (Germany).

5 Processing the GPS data

The processing of the data from the continuously recording GPS (CGPS) sites operated by NMA is carried out routinely. Using the precise point-positioning technique (Zumberge *et al.*, 1997), daily co-ordinates are estimated for all CGPS sites as soon as the precise orbits and clocks become available from IGS/JPL. For most of the sites, data have been processed in this way since January 1997.

For Ny-Ålesund , this routine analysis includes the observations of two GPS receivers. One of them delivers data to IGS since 1991. This long record has been analysed by M. Heflin (JPL), and the resulting time series is used below for comparision with the VLBI series.

6 Comparison of VLBI and GPS data

In Figures 1 - 2, we compare the time series of GPS and VLBI for the three components. The VLBI series were produced in a global analysis (Ma, personal communication) of all available data up to the beginning of 1998. The GPS series was taken from Heflin (1998) in Mai 1998. In the two horizontal components, the linear trends for VLBI and GPS are in good agreement with each other. This is also demonstrated by the numbers given in Table 2A for these two analyses. This agreement lead to correlation coefficients of the order of 0.8. However, if the linear trends are removed from the two time series, then there is virtually no correlation between the VLBI and GPS co-ordinate variations. Partly, this may be due to differences in the analyses and the models used to account for atmospheric effects. But it may also indicate that at time scale of days, the two techniques may by affected by noise sources in a different way. For geophysical applications such as studies of atmospheric loading, it is crucial to understand the reason for the un-correlated variations in the co-ordinates as determined by VLBI and GPS.

In the height component, apparently significant discrepancies are found in Ny-Ålesund (see also Table 2). It is important to mention that the time series given by Heflin (1998) are continuously up-dated and the velocities given may change with time. Thus, in May 1998, the vertical rate for Ny-Ålesund was as large as 5.54 mm/yr while in February 1999 it has decreased to 4.20 mm/yr. The uncertainties estimated for the global analysis are formal errors which are rather optimistic. Thus, a large part of the discrepancy may still be due to underestimated uncertainties. Moreover, the VLBI time series at Ny-Ålesund is still short (in the Ma analysis, slightly more than three years were used) and the trend is likely to change with increasing length.

A similar comparison of the two analyses for Wettzell and Onsala (Table 2B and 2C, respectively) results in an agreement in horizontal velocities on the 1-2 mm/yr level, while in Wettzell disagreement in height is at the same level as in Ny-Ålesund , i.e. at 3 mm/yr.

Comparing the results of Titov and Pettersen (1997), which are based on the EUROPE experiments, only, to the global analysis, good agreement is found in the north-south rate while the east-west rate resulting from the Europe analysis is too small by a factor of two. Titov and Pettersen (1997) consider the geometry of the network as a possible explanation for this result.

In height, no significant difference is found between the two analyses. However, analyses of the VLBI data carried out in other studies result in vertical rates differing significantly from those of Ma (1998). For example, Tomasi and Rioja (1998) report a vertical rate of 6.4 ± 1.0 mm/yr for Ny-Ålesund . However, their value is associated with an unrealistic result for the horizontal motion.

Comparing NMA's results of the analysis of the Ny-Ålesund GPS data to those provide by Heflin (1998) results in correlation coefficients of the order of 0.7 to 0.8 for the residual time series (i.e. when linear trends are removed). This indicates that small differences in the analysis strategies and models used have a large effect on the day-to-day variations. Again, for geophysical applications, these differences need to be understood in detail.

The comparison of different techniques and analyses so far started, emphasises the need for further studies. At the moment, it is not possible to resolve the discrepancies between the different VLBI analyses as well as

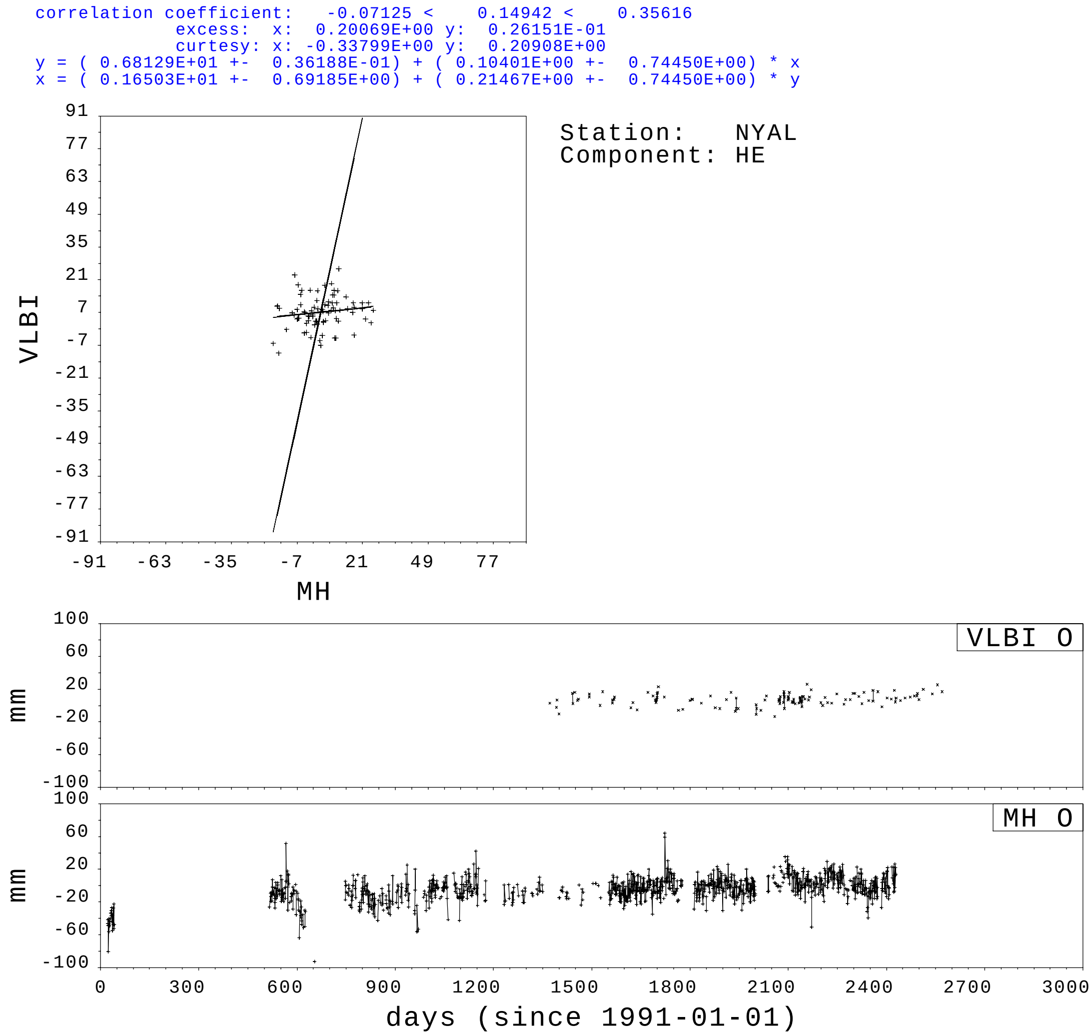

Figure 1: Variations of VLBI and GPS heights at Ny-Ålesund

Lower diagram: GPS taken from Heflin (1998); middle: VLBI taken from Ma (1998, private communication); upper: regression of GPS and VLBI.

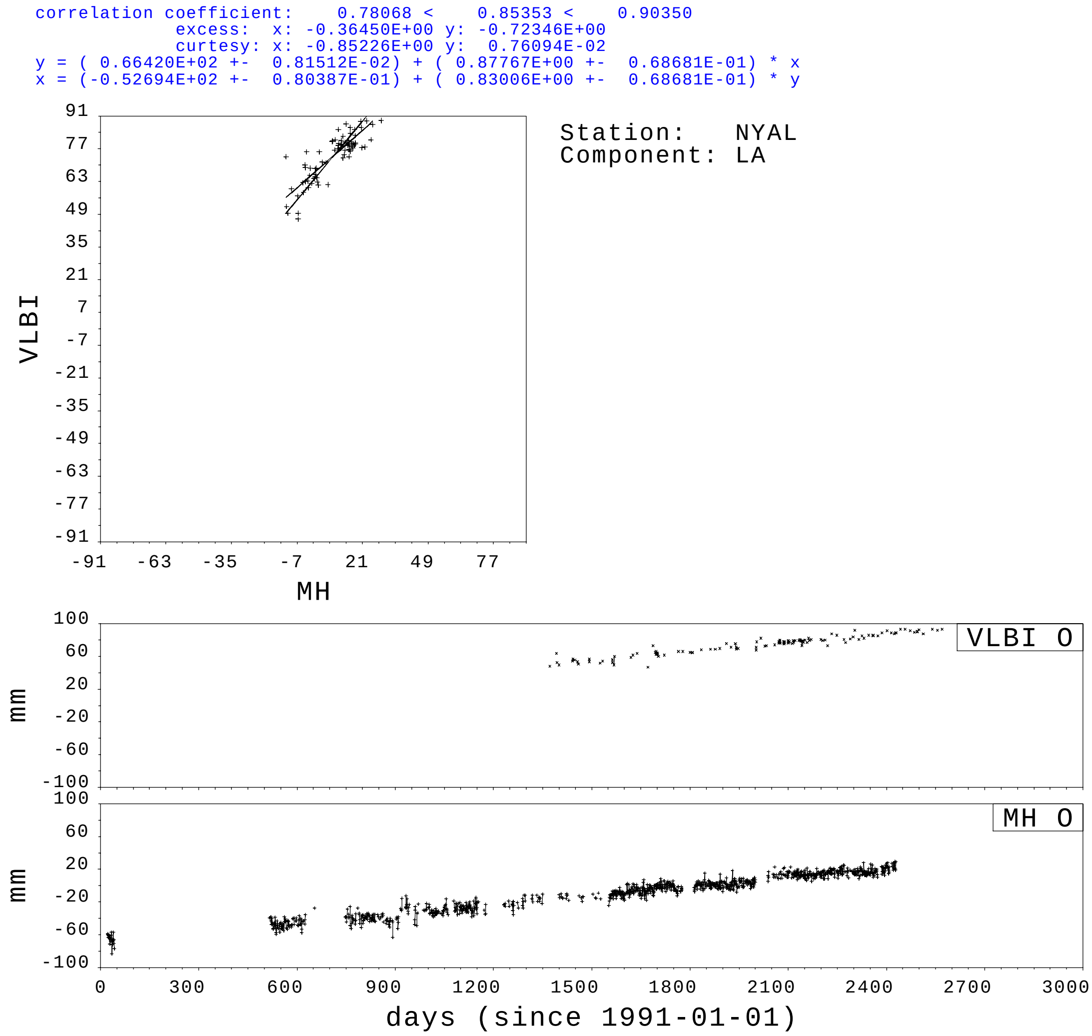

Figure 2: Variations of VLBI and GPS latitudes at Ny-Ålesund
Lower diagram: GPS taken from Heflin (1998); middle: VLBI taken from Ma (1998, private communication); upper: regression of GPS and VLBI.

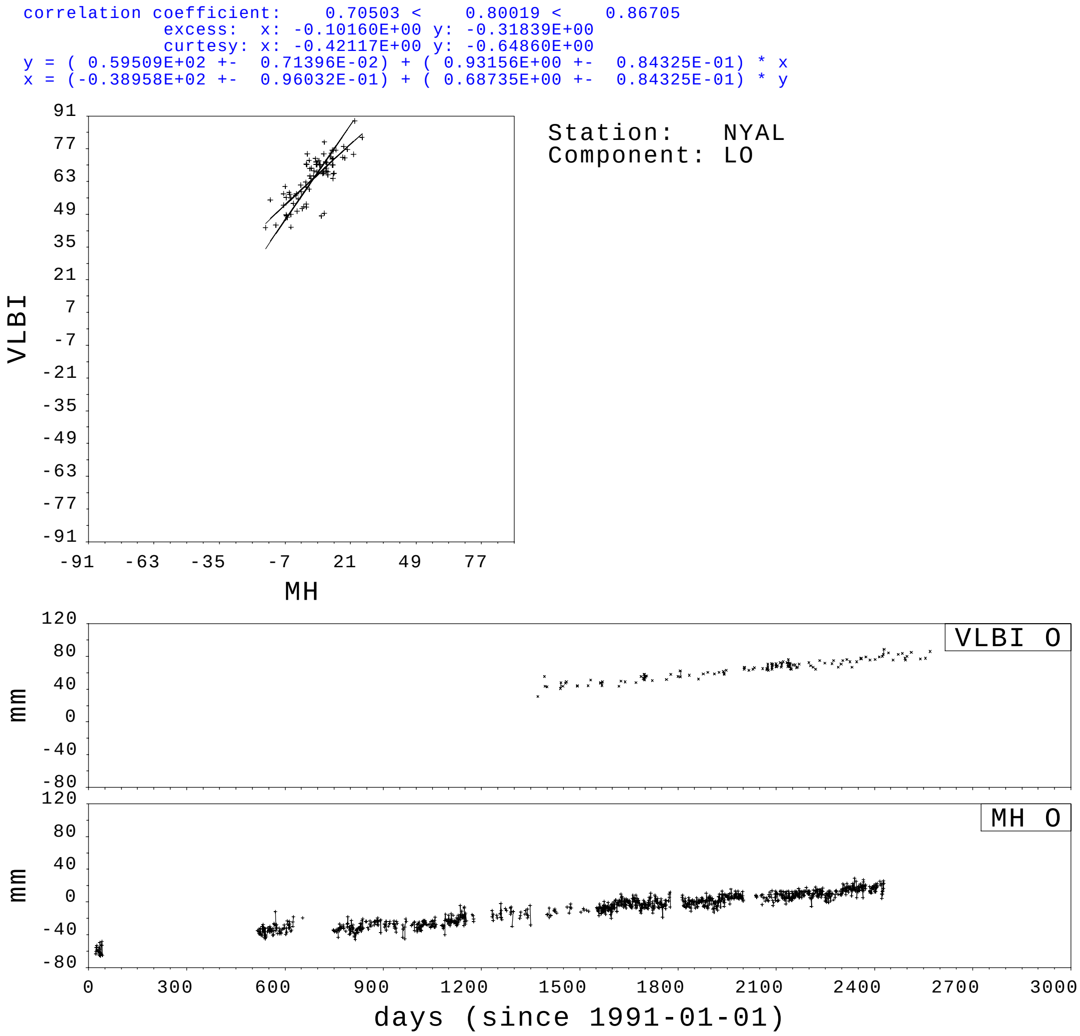

Figure 3: Variations of VLBI and GPS longitudes at Ny-Ålesund

Lower diagram: GPS taken from Heflin (1998); middle: VLBI taken from Ma (1998, private communication); upper: regression of GPS and VLBI.

Table 2: Crustal motion at Ny-Ålesund.

Velocities are in mm/yr. NUVEL1-A (NUV.) are from Ma (1998, personal communication). VLBI rates are from Titov and Pettersen (1997) (VLBI T&P) and Ma (1998, personal communication; VLBI MA). GPS results are from Heflin (1998) in the version of 8 February 1999.

A) At Ny-Ålesund

Component	NUV.	VLBI T&P	VLBI MA	GPS
Radial	0.00	0.4 ± 3.6	$1.16 \pm .54$	4.20 ± 0.28
Latitude	13.60	13.9 ± 1.3	$13.50 \pm .17$	14.63 ± 0.07
Longitude	12.95	6.0 ± 2.4	$11.75 \pm .17$	10.64 ± 0.08

B) Wettzell

Component	NUV.	VLBI MA	GPS
Radial	0.00	$-0.82 \pm .16$	-3.75 ± 0.33
Latitude	13.46	$13.58 \pm .12$	14.48 ± 0.09
Longitude	20.34	$20.35 \pm .02$	21.14 ± 0.13

C) Onsala

Component	NUV.	VLBI MA	GPS
Radial	0.00	$3.40 \pm .20$	1.53 ± 0.16
Latitude	13.61	$12.84 \pm .05$	13.74 ± 0.05
Longitude	18.65	$17.63 \pm .06$	16.61 ± 0.07

between GPS and VLBI. The discrepancy between the global VLBI results and the GPS results in Ny-Ålesund may be due to a problem of the reference frame and the realisation of the no-net-rotation and no-net-translation criteria in the VLBI analysis. If we assume, for a moment, that the global VLBI analysis and the GPS result provide correct vertical rates for Ny-Ålesund in nearly the same reference frame, then the differential motion between GPS and VLBI antenna could be due to a sinking of the VLBI antenna or a slow uplift of the GPS monument in the permafrost. These possibilities and the wide range of vertical rates obtained emphasises the need for a control of the local ties between the various techniques with a high temporal resolution.

Unfortunately, the available classical techniques for obtaining these ties require considerable human resources (see also Section 4). Based on these techniques, a high temporal resolution will be difficult if not impossible to achieve. The development for techniques that would allow a more or less continuous tie between different antennas would be most welcome.

7 Identifying the cause of crustal motion

7.1 Surface-load induced deformations

Climatologically, Svalbard is located within the northernmost part of the area with strong seasonal changes in sea-ice (see, e.g., Barry, 1989). This area is likely to be affected by climate change at an early state. The main ice drift in the Arctic Ocean is characterised by the Transpolar Drift, which carries ice from the Beaufort Sea and the eastern Arctic Ocean westward towards the Fram Strait west of Svalbard, through which most of the ice exits into the North Atlantic (see Gordienko and Laktionov, 1969). Moreover, the main current due to the Arctic Ocean Interbasin exchange passes along the Fram Strait, too (see, e.g., Fig.1-1 in Schmitz, 1996).

A large part of Svalbard is covered by ice and it can be expected that the ice mass responses sensitively to changes in the climate around Svalbard. In fact, changes in the ice mass on Spitsbergen can already be deduced from observations (see, e.g. Amelien *et al.*, 1998). However, our current knowledge of changes in the cryosphere is uncertain in several aspects. Consequently, recent estimates of the contribution of glaciers and ice sheets to sea level changes vary by a factor >2 (see Warrick *et al.*, 1996, for a recent summary). Geodetic measurements of changes in the ice surface are either sparse (levelling) or still controversial (satellite altimetry). Mass balance models based on observations are hampered by large uncertainties in the contributing factors and often poorly constrained by observations (Warrick *et al.*, 1996). Therefore, additional constraints are most helpful in understanding the response of ice sheets and glaciers to climate variability and, eventually, climate change.

Changing ice loads induce significant visco-elastic deformations of the Earth's crust and mantle as is documented by a wealth of observations related to the post-glacial rebound induced by the last ice age. The present-day deformations are the results of a convolution of the Green's function (i.e., the impuls response of the Earth to surface loading) with the complete time history of the combined ice and water load. Therefore, these deformations are also affected by recent changes in both the present-day ice sheets and the ocean waters. The effect of the present-day forcing potentially is large enough to use the induced deformations to constrain, for example, concurrent changes in the volume of the Antarctic and Green-

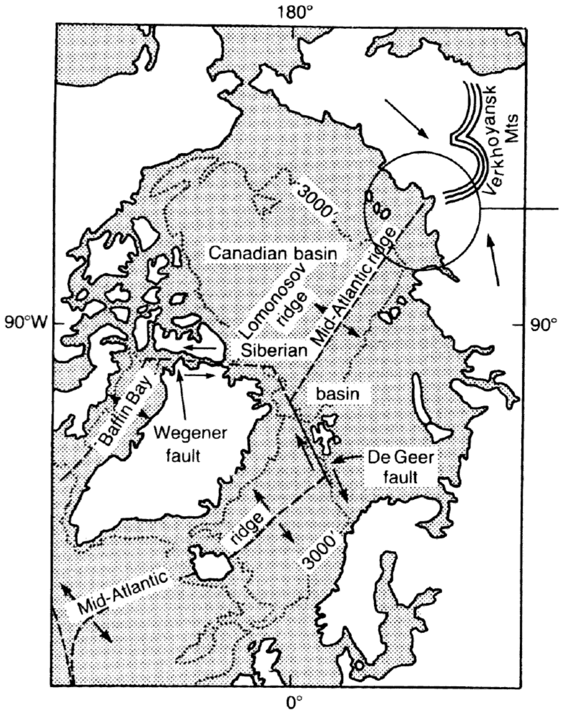

Figure 4: Tectonics of the Arctic Ocean. From (Kearey and Vine, 1990).

land ice sheets (e.g. Conrad and Hager, 1995; James and Ivins, 1995; Wahr and Han, 1997). However, the post-glacial signal in these deformations is of the same order as the deformations induced by present-day ice changes. Any interpretation therefore requires the separation of the two effects. According to the results of extensive numerical experiments carried out by Wahr *et al.* (1995), the ratio between gravity and height changes $\dot{g}/\dot{u}$ associated with purely viscous deformations due to past mass movements (i.e. ice and water load) is approximately equal to -0.15 μgal/mm. This constant ratio provides the basis for the required separation. Presently, the only observations to test this empirical relation are found in Scandinavia. A comparison of observed gravity and height changes in the land-uplift area in Scandinavia indicates a ratio of $\dot{g}/\dot{u} = -0.24$ μgal/mm (Ekman and Mäkinen, 1990). However, the ≈ -0.09 μgal/mm in excess of the theoretically expected value may represent the elastic response to present-day mass changes, which partly are to be explained by the deloading of the Baltic Sea as a consequence of the land uplift. In summary, we can expect that high-precision space-geodetic observations of present-day deformations in the vicinity of ice sheets together with gravity measurements, in principle, provide valuable constraints on changes in the ice cover. However, the combination of vertical rates with gravity changes is mandatory for a meaningful interpretation.

7.2 Tectonic movements

Tectonically, Svalbard is located on the north-eastern side of a long north-northwest striking transform fault (the De Geer fault, Fig. 4), which connects two parts of the mid-Atlantic ridge, namely the north-east striking ridge segment in the Norwegian Sea (north of Iceland) to the more north-northeast striking segment in the Siberian basin (Kearey and Vine, 1990). The active mid-Atlantic ridge passing through Iceland terminates SW of Svalbard at the De Geer Fault. This dextral ridge-ridge transform connects to the northernmost part of the mid-Atlantic ridge, which in turn transforms into the Verkhoyansk Mountains of Siberia by means of rotation about a fulcrum in the Siberian Islands. However, there are rather large uncertainties in the actual structure of the ridge segment south-west of Svalbard. For example, in Johnson *et al.* (1979), the large DeGeer transform fault is replaced by a north striking spreading centre. Again another sketch can be found, for example, in Birkenmajer (1981). Nevertheless, the distance of the ridge-related tectonically active region to Svalbard is small (of the order of 100 km) and the activity might well have some regional to local effects at the Kings Bay and Ny Ålesund. At large scales, the motion across the ridge segment in the Siberian basin and particularly its change along the ridge leads to a rotation in the Arctic affecting the position of Svalbard in a global reference frame.

Detailed knowledge of the present-day motion of the tectonic plates is fundamental for the validation of geophysical and geological models related to plate tectonics. The plate motion also constitutes a crucial contribution to the motion of any point on the Earth's surface. As the plate move, any fixed co-ordinates for observing sites become inconsistent. Relative motion between observing sites in the global geodetic networks are of the order of 5 cm/yr or larger. Therefore, accounting properly for the motion is a principle task in the definition and realisation of any terrestrial reference frame. The 1996 IERS conventions (McCarthy, 1996) recommend that the NNR-NUVEL1A model (DeMets *et al.*, 1994) is used to represent the velocities due to plate motion. The residual velocity vectors at all geodetic sites can then be used to validate and/or improve this model.

In Table 2, we compare the horizontal and vertical motion determined in different VLBI and GPS analyses. It should be mentioned that the uncertainties given for the global VLBI analysis are too optimistic (Ma, 1998, personal communication). Taking into account this comment, then the horizontal velocities determined in the global VLBI analysis and for the long GPS time series agree well with each other and with the model predictions.

In summary, the results indicate that this part of Svalbard, despite its nearness to the Mid-Atlantic ridge, is already on the stable part of the European plate. This is further supported by the small base line changes between Ny-Ålesund and Wettzell (see, e.g. Tomasi and Rioja, 1998).

8 Monitoring sea-level changes

Sea level changes due to mass exchange betwee cryosphere and ocean are not globally uniform (Farre and Clark, 1976). Due to the combined effect of th visco-elastic response of the Earth to ice deloading an ocean loading and the change in the gravitational poter tial, relative sea level will fall close to a melting ice shee while at intermediate distances there will be nearly n changes. A rise in sea level will only be observed in th far-field. Thus, melting/accreting Antarctic ice will hav a sea-level signature distinctively different from mel ing/accreting Greenland ice. Tide gauges should record the "footprint" in relative sea level due to present-day changes in the large ice sheets. Tide gauges in the near-field are particularly important for this detection. Therefore, the tide gauge data observed at Ny-Ålesund combined with space-geodetically observed crustal motion at the location is an important contribution to the monitoring of the current pattern in relative sea level changes particularly in the Arctic ocean.

In Figure 5 the monthly mean values for the tide gauge records at Ny-Ålesund and Barentsburg are shown. The data are taken from the global database of the *Permanent Service for Mean Sea Level* (PSMSL), which contains more than 1700 quality-controlled records (Spencer and Woodworth, 1993). At both locations, the monthly means are dominated by a seasonal signal with an amplitude of ≈150 mm and a maximum sea level in November. Non-seasonal variations are generally of the order of ±150 mm with a few exceptional sea levels exceeding ± 200 mm. Also shown is the monthly difference between the two time series. The distance between Ny-Ålesund and Barentsburg is roughly 100 km and long-period sea level changes should be rather similar at both sites. In fact, for most of the months the difference is of the order of ±50 mm, while only a few months show differences of more than ±200 mm. Particularly for 1980, large differences occure indicating data errors in one of the two records. After 1993, the differences contain a strong linear trend, which is due to an apparent decrease of the relative sea level at Barentsburg. This may be related to an poor maintenance of the local tide gauge benchmark or a problem with the tide gauge itself. However, the overall trend in Barentsburg is not significantly affected by this possibly erroneous part of the record.

To determine the trend in RSL, a model consisting of a seasonal cycle and a linear trend is fitted to the two time series in a least squares fit. The seasonal cycle is represented by an annual and a semi-annual harmonic constituent. The trends resulting from the fits are compiled in Table 3 together with other relevant parameters of the two time series.

A change in sea level measured relative to a benchmark on land is the difference between geocentric sea surface changes and geocentric vertical motion of the tide gauge benchmark (ideally this is identical to the vertical motion

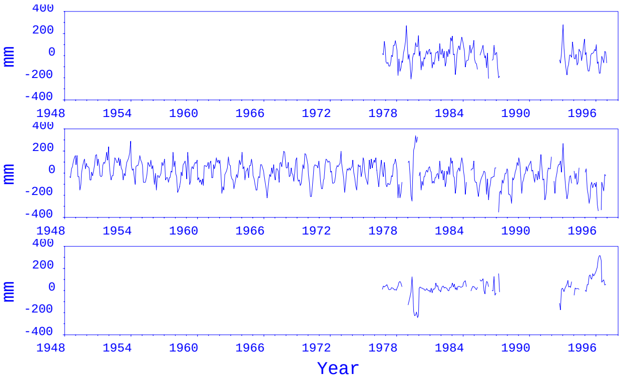

Figure 5: Tide gauge records at Ny-Ålesund and Barentsburg.
Upper diagram: Ny-Ålesund; middle: Barentsburg; lower: Ny-Ålesund - Barentsburg. The time series are monthly mean sea levels in mm.

of the crust). For linear trends, we therefore can write

$$r = t + v \qquad (1)$$

where r is the geocentric sea level trend (positive for rise), t the RSL trend (positive for rise), and v the geocentric vertical crustal motion (positive for uplift). The determination of the geocentric sea-level changes thus requires knowledge of the vertical crustal motion v. At Ny-Ålesund, the tide gauge is regularly connected to the space-geodetic benchmarks by precise levelling. As reported in Section 4, the measurements so far do not indicate a relative movement of the tide gauge with respect to land. VLBI and GPS provide information on the three-dimensional movement of the crust. Unfortunately, the results from the two main techniques monitoring crustal movements in Ny-Ålesund do not agree for the height component (see Table 2 and Section 7). Possible explanations for the discrepancies may be in problems of connecting VLBI and GPS in a unique way to the solid Earth or local effects at the VLBI and/or GPS antenna in Ny-Ålesund. A more detailed investigation is required before reliable estimates of v can be deduced. Nevertheless, after eliminating known contributions by using available models we can extract useful information from the RSL trends.

Currently, a major contribution to RSL changes is coming from the on-going post-glacial rebound induced by the disintegration of the large ice sheets at the end of the last ice age. To decontaminate RSL trends from the post-glacial signal (pgs), Peltier and Tushingham (1989) used a geophysical model to compute the pgs in RSL, p, and computed a decontaminated geocentric sea level

$$\hat{r} = t - p. \qquad (2)$$

In another approach, Zerbini *et al.* (1996) used

$$v_o = -(t - p - r'); \qquad (3)$$

assuming $r' = 1.8$ mm/yr to determine crustal vertical motion in the Mediterranean and found small (of the order of ±1 mm/yr) and spatially consistent values for the

Table 3: Trends in sea level at Ny-Ålesund and Barentsburg.

N is the number of monthly values in the record. t is the linear term and δt the standard error resulting from the fit of a trend plus annual and semi-annual constituent to the time series. $\hat{r}$ is computed from eq. 2, while v_o results from eq. 3 assuming $r = 1.8$ mm/yr. The indices 1 and 2 refer to the two models for the pgs (see text). All rates in mm/yr.

Station	Long.	Lat.	Begin	End	N	t	δt	p_1	p_2	$\hat{r}_1$	$\hat{r}_2$	v_{o1}	v_{o2}
Ny-Ålesund	11°56'E	78°56'N	1976	1996	175	-1.373	0.8	-0.9	-1.3	-0.5	-0.1	2.3	1.9
Barentsburg	14°15'E	78°04'N	1948	1996	560	-2.253	0.3	-2.0	-2.6	-0.3	0.3	2.1	1.5

crustal motion. In Table 3, $\hat{r}$ and v_o are given for the two stations using two different post-glacial rebound models provided by Mitrovica (1996, personal communication). Model 1 has an elastic lithosphere of 120 km, and upper and lower mantle viscosities of 1×10^{21} Pas and 2×10^{21} Pas, respectively. Model 2 is identical to Model 1 except for a lower mantle viscosity of 4.75×10^{21} Pas. The ice model used is ICE-3G (Tushingham and Peltier, 1991).

For both post-glacial rebound models, the values for $\hat{r}$ are close to zero indicating that any vertical crustal motion others than post-glacial rebound is nearly compensating any geocentric sea level change. Assuming tentatively a geocentric sea level rise of 1.8 mm/yr (Douglas, 1997), non-post-glacial vertical crustal uplift rates of the order of 2 mm/yr can be deduced. However, since both steric and non-steric sea-level changes are likely to display a large spatial variability, this assumption is not very helpful.

The determination of vertical crustal motion with an accuracy of better than 1 mm/yr would allow to separate the crustal motion and geocentric sea-level changes. Using, for example, the GPS-determined rate of $v = 4.20$ mm/yr, we get a geocentric sea-level rate r of $+2.93$ mm/yr at Ny-Ålesund . It would be interesting to compare this trend to sea-level rates determined from satellite altimetry.

For further interpretation, it will be helpful to separate the pgs in RSL according to $p = p_s - p_v$ with p_s the geocentric pgs in sea level and p_v the geocentric pgs in vertical crustal motion. Thus we get

$$r' = t - (p_s - p_v) + v_o \qquad (4)$$

with $v = v_o + p_v$ and v_o the vertical crustal motion others than the pgs. The uncertainty of the pgs predicted by geophysical models is for the Svalbard area at least of the order of 1 mm/yr. Nevertheless, using model predictions of the pgs would help to explain a part of the 3 mm/yr geocentric sea-level rate quoted above.

9 Additional comments

The Earth tide observations have resulted in a long and high-quality time series, which has been used to determine preliminary Earth tide parameters for Ny-Ålesund . Particularly in the semi-diurnal band, a large ocean loading signal is found. Preliminary computations of ocean loading carried out by Scherneck (1998, personal communication) and Baker (1998, personal communication) reveal considerable discrepancies between the observations and the model predictions as well as between different ocean tidal models. Using the observed parameters in the processing of the absolute gravity measurements, small residual tidal signals were left in the absolute measurements indicating that the tidal parameters were not adequate. The distance between the Earth tide observatory and the absolute point is about 1.8 km. Due to the large ocean loading signal and the short distance to the coast, a large spatial gradient in the Earth tide parameters can be expected. Moreover, significant temporal variations have been detected in the Earth tide parameters, and these may be due to seasonal changes in the semi-diurnal ocean tides or to unaccounted variations in the calibration factor of the gravimeter.

To get precise Earth tide parameters for the geodetic observatory to be used in the VLBI analysis, it will be important to carry out tidal measurements at the observatory with a superconducting gravimeter.

10 Conclusions

The VLBI station at the geodetic observatory of NMA in Ny-Ålesund has participated in the European VLBI experiments nearly as scheduled. A proper maintenance of the antenna and the equipment has been provided. Due to a lack of human resources, analysis work has been delayed. However, it is expected that new analysis work can be started in 1999. The discrepancies between GPS and VLBI determined vertical rates will be one of the problems to focus on. In this context, the contribution of unmodelled tropospheric effects to station co-ordinates will be investigated.

Summarising the results of the interpretations reported above, we can state that the geodetic multi-parameter observations collected at Ny-Ålesund are of high potential value for global change studies and the value of the data set is expected to increase greatly as the observation period is extended into the future. Nevertheless, results relevant to the EU project can be expected from a continuation of the exploitation of the available data. In particular, more advanced analyses of the space-geodetic observations will allow to reduce the uncertainty of the geocentric vertical crustal motion and thus provide a better estimate of the geocentric sea-level trend.

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