Terrestrial geodetic measurements in West Greenland for investigating ice mass changes and for establishing ground control for remote sensing

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Abstract - Since 1991, terrestrial geodetic measurements on the Greenland ice sheet are performed in order to determine height change, ice flow velocity and deformation (strain) in a test field around the Swiss-Camp near equilibrium line (1150 m a.s.l.). A new test field (ST2) in lower altitude (1000 m) was established in 2004. The stakes in the test fields are measured by static GPS and topographical survey by kinematic GPS on an area of about 2x2 km^2 each. Digital elevation models are derived in every epoch, so elevation changes and volume changes between different epochs could be calculated.

At the Swiss-Camp the horizontal flow vector between 1991 and 2004 gives a velocity of 0,317 m/d and azimuth of 260,24 gon, so towards Jakobshavn Isbrae. Between 1991 and 2002 the long periodic elevation change is –0,22 m/a, but -0,85 m/a most recently between 2002 – 2004, indicating an acceleration of ice mass decreasing.

All the terrestrial measurements can also be used as control areas for calibration and validation of remote sensing methods, such as ICESat (USA), CryoSat (ESA/Europe) or ERS1/2 (Europe) and some laser altimetry surveys by airplanes (USA, Denmark) . The research areas "Swiss Camp" and "ST2" are small, but elevation, elevation change and flow velocity are precisely determined over many years, and so recommended as control areas.

Keywords: Greenland, elevation change, climate change, terrestrial geodesy, ground control.

1. INTRODUCTION

Geodetic ground measurements had been performed in Greenland especially during the EGIG campaigns (Expédition Glaciologique Internationale au Groenland) in a West-East-profile across Greenland in latitude of about 70°. Major aims were the determination of ice flow vector components (velocity, flow direction) and elevation change of the inland ice. Main campaigns had been performed in 1959, 1968 and 1987-93 (MÖLLER et al. 1996). No results were available near the western ablation area, because repeated measurements at same place were not possible here. Since 1991 the author decided to fill this gap with a test field, located at the SWISS-Camp, managed originally by ETH Zurich/Switzerland, and later by University of Colorado at Boulder/USA (CU).

The geodetic terrestrial measuring technique, in particular if using GPS, offers the advantage that heights and height changes in different years can be determined directly on the ground. Also position and position changes (movement, deformation) of stakes can be precisely determined. Elevation changes are important indicators for climate change. Flow velocity and strain rates are used in ice sheet modelling (Huybrechts et al. 1991, Abe-Ouchi 1993). Another application is validation and calibration of airborne or satellite remote sensing methods.

2. THE GEODETIC MEASURING PROGRAM 1991 – 2004

The test field at Swiss-Camp (ETH/CU-Camp) is situated 80 km East from the West Greenlandic coastal village of Ilulissat, latitude = 69° 34' N, longitude = 49° 20' W , elevation =1150 m a.s.l near the equilibrium line altitude (Reeh 1989).
The test field "Swiss Camp", established in 1991, consists of 4 stakes, forming a triangle with a point in its center. The side length of the network is about 1,5 km. The 3D-positions of the stakes are measured by GPS in relation to a fix point on solid rock at the coast. In order to determine temporal elevation changes of the ice surface, in all subsequent campaigns the previous positions of stakes are reconstructed and actual heights are re-measured. The topography of the whole surface is measured by gridding 200 m and by kinematic GPS profiling. Digital elevation models are derived in every epoch, so elevation changes and volume changes between different epochs can be calculated. The distortion of the network and strain rates are derived from plane coordinates. Campaigns were performed in the years 1991, 94, 95, 96, 99, 2002 and 2004. So it is a long term research project.

In 2004, the research area was extended by a new deformation networks (ST2), situated in lower altitude (1000 m a.s.l) in order to compare elevation change depending on altitude and distance from ice margin. ST2 is located in latitude = 69° 30' 28" N; longitude = 49° 39' 09" W, ellipsoidal height = 1000 m, so 150 m deeper than Swiss-Camp. That location is in the same cross section like the automatic weather stations JAR1-JAR3 and smart stakes SMS1-SMS4 from the GC-Net project (Steffen et al. 2002).

As an example, the measuring program 2004 is demonstrated here:

Swiss-Camp (August 2004) :

- GPS reference point EUREF 0112 in Ilulissat on solid rock,
- Temporal ice GPS reference at Swiss-Camp,
- Static GPS baseline 80 km, measured for 6 hours,
- Re-measurement of the actual positions of all four stakes of the deformation network by real-time GPS,
- Reconstruction and staking out of old positions from 1991, 94, 95, 96, 99 and 2002,
- Measuring actual heights at all these old positions,
- Measuring of snow depth in order to reduce heights to ice surface,
- Topographical survey of snow surface around Swiss-Camp by grid points every 200 meters and kinematic GPS profiling,

ST-2 (11.08.2004 – 17.08.2004)

- Establishing of a new deformation network, consisting of 4 stakes (triangle with central point), side lengths 600 – 1100 m.
- Stakes constructed by 3 aluminium elements at 2 meters each, diameter 32 mm, implanted in ice at depth 4,0-4,5 m, with black flag on top.
- Static GPS measurement in the same method like Swiss-Camp,
- Topographical survey: Gridding 200 m and kinematic GPS profiling,
- Re-measurement of stakes after 6 days on August 17th.

3. RESULTS

3.1 Area „Swiss-Camp“

Elevation changes can be derived from concrete previous point positions and from the ice surface topography as well. The digital elevation model at Swiss-Camp (figure 1) displays a rather smooth and uniform slope (about 1-2%) with little undulations.

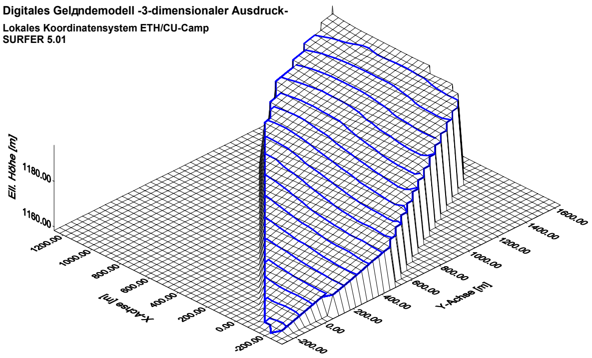

Figure 1: Digital elevation model Swiss-Camp 2002

All heights and positions are absolute values in WGS84 due to attachment to the reference point EUREF 0112 in Ilulissat on solid rock. From concrete points, we obtain the elevation change by averaging all points and positions, respectively (figure 2). The adjusted straight line over the whole period 1991-2004 represents an elevation decrease of –0,285 m/a. Without the last campaign we should obtain only –0,22 m/a, agreeing with results from airborne laser altimetry for the period 1993-1999 (Krabill et al. 2000). Obviously, the extraordinary warm summers 2003 and 2004 had effected an extremely big elevation decrease of –1,7 m, or –0,85 m/a. In previous campaigns, only in 1995-1996 we found similar big values of –0,74 m/a.

According to calculations of Reeh 1989, the Swiss-Camp formerly had been situated at the equilibrium line, but now it seems to belong to the ablation area. The equilibrium line now obviously was shifted to higher regions. The resulting growing of the ablation area with high melting rates at the ice margin are also stated at several other research areas, especially in South Greenland, reported for example by Taurisano & Boeggild 2004 or Krabill et al. 2004.

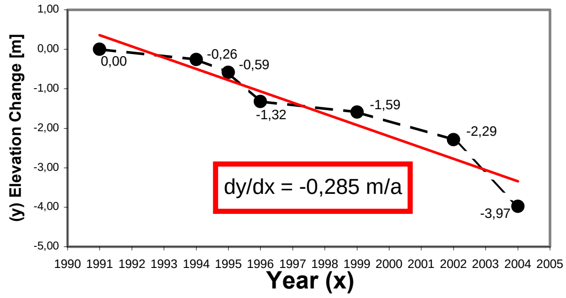

Figure 2: Swiss-Camp, elevation change of ice horizon for all 4 stakes.

The same elevation change, for example between 2002 and 2004, can be derived from topographical surveys and digital elevation models as result from grid measurements and kinematic GPS profiling (figure 3). Only in the North-East of the test field we find more irregular values, which are caused by lack of some measurements 2004 in this corner.

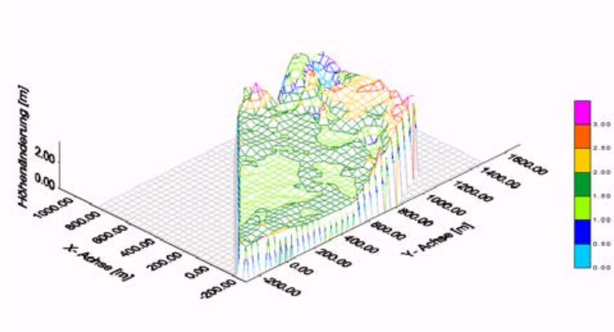

Figure 3: Swiss Camp, volume decrease from digital elevation models, difference 2004 minus 2002 (X-Axis = NORTH, Y-Axis = EAST)

period	flow velocity [m/d]	flow direction [gon]
1991-1994	0.313	259.60
1994-1995	0.319	260.17
1995-1996	0.313	260.00
1996-1999	0.320	260.46
1999-2002	0.318	260.98
2002-2004	0,319	261,29
average	**0.317**	**260,42**

Tabel A: Ice flow vector Swiss Camp 1991 – 2004

The ice flow vector was determined by comparison of stake positions in different years. The resulting ice flow velocity in average is 0,318 m/d, with slightly (but not significantly) increasing values over the years (table A).

We expect little growing ice mass outflow. As we always measure in summer time, we only can derive average velocities in years, seasonal variations are not detectable. Also the flow direction (azimuth) did not much change in time. In average the azimuth is 260,24 gon, with little significant turn to North-West, which may be caused by bedrock topography. The azimuth indicates the draining ice masses towards the "North glacier" nearby the Jakobshavn glacier.

Deformation and strain: From the distortion of the stake network between two campaigns principal axis of strain and strain rates can be derived. The method was explained in Stober 2003. Applied to all epochs 1994-1995, 1995-1996, 1996-1999, 1999-2002 and 2002-2004 we obtain the following results (table B):

Date		Strain rates [ppm/a]		Azimuth e1 [gon]
Epoche 0	Epoche 1	e1	e2	
19.6.94	15.6.95	917	-912	29,1
15.6.95	15.6.96	926	-848	25,0
15.6.96	30.7.99	1267	-927	20,7
30.7.99	30.7.02	1223	-905	13,5
30.7.02	14.8.04	413	-1751	-3,0

Table B: Swiss-Camp, strain rates and azimuth of principal strain, 1994 - 2004

From 1994 until 2002, the strain rates and azimuth of principal strain are changed slowly but systematically, with almost linear trend. Such a trend could be expected, because the stake network is moving 115 meters in a year, so the deformation between two epochs is referred to an average position, which is varies every year, and therefore refers to areas in lower altitudes. Now, in 2004, we suddenly find completely different strain values, probably due to loss of 2 stakes, melted out in 2004. The calculated strain values 2002-2004 therefore might be from less quality and doubtful. But also the 2 remaining stakes are indicate a significant change in strain rates.

Summarizing it is shown that elevation change and melting since 1991 are continuously increasing with even extremely high rates in last years. This corresponds to global warming with particularly high temperature increasing in the northern polar regions (even more than world wide average!), figure 4, Köberle/Lemke 2004.

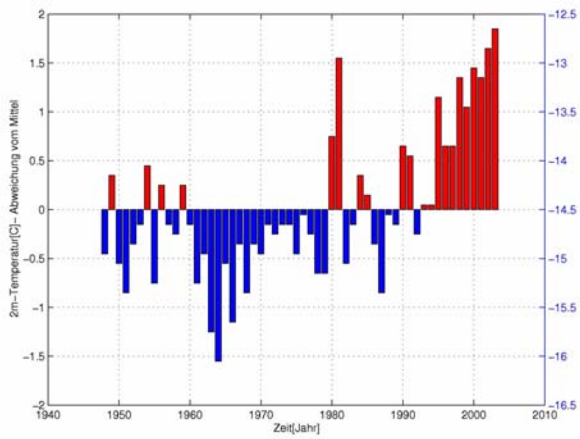

Figure 4: Air temperature 1948 – 2003 in North polar region, deviation from average, (Köberle/Lemke 2004).

3.2 Area „ ST2"

As mentioned above, a new deformation network was established in 2004. Design and measuring methods are the same as at "Swiss Camp". The stakes and the topography were measured by static and real-time kinematic GPS (figure 5).
Compared to Swiss-Camp, the digital elevation model at ST2 demonstrates more topographical structures (figure 6). The re-measurement of ST2 is planned for 2005 or latest 2006.

Figure 5: Tracks of kinematic GPS Measurements at ST2.

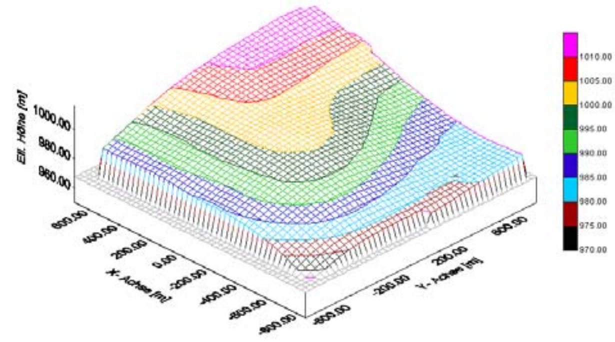

Figure 6: 3D-Digital elevation model at ST2.

4. ACCURACY OF GEODETIC POSITIONING

The accuracy of geodetically determined points, surface elevations and temporal elevation changes is influenced by several error sources:

- measuring accuracy of GPS,
- reconstruction of old point location,
- reduction from snow surface to ice.

GPS measurements in Greenland differ from middle Europe as follows:

- worse satellite geometry (GDOP, VDOP) because of high latitude, especially concerning the vertical component,
- big signal disturbances by ionosphere,

We can assess the accuracy of the 80km-baseline (measuring time several hours) and local differential GPS around the test fields (distance 2 km) with a standard deviation

horizontal component s_P = 0,02 m,
vertical component s_V = 0,03 m.

The old stake location can be easily reconstructed within 1 m. The height will be influenced depending on the local slope (1-3%), so the elevation may be diluted by about 0,01 – 0,03 m.

The most critical error may exist in the height reduction from snow to ice horizon. We dig snow pits, but the ice horizon sometimes is not easy to detect. Local surface sastrugies and refrozen ice layers (superimposed ice) could affect the heights sometimes up to 0,1 – 0,2 m.

Summarizing we can assess the height accuracy from GPS measurement within s_H = 0,03 m , additional reduction errors can increase the standard deviation (only for comparison between repeated ice measurements) by 0,1 – 0,2 m.

5. CALIBRATION AND VALIDATION FOR REMOTE SENSING

Two research satellites with remote sensing techniques, especially created for research of the cryosphere, are already working or are expected to work in near future : ICESat (USA) and CryoSat (ESA/Europe). Also other satellites, like ERS1/2 and airborne Laser tracking systems, for example the American P-3 ATM (Airborne Topographic Mapper), are in use. In principal there are two systems: microwave RADAR and Laser altimetry. Both measuring techniques are influenced by typical systematic errors, partly resulting from the distance measuring device and partly from position or attitude errors of the tracking vehicle. ICESat uses a 1064 nm laser with footprint diameter of about 70 m and footprint separation of about 170 m.
CryoSat will be equipped with radar interferometry (13,8 GHz) with along-track footprint diameter 250 m and lateral resolution 125 m. Level-2-data can be used for validation. Especially microwave measurements are also influenced by unknown signal penetration in the snow/ice surface, this error can be determined by using the level-1-data of CryoSat.

For calibration and validation for all theses remote sensing systems, control areas with precisely measured surfaces are necessary (ground control areas). Information about surface slope and surface undulations from terrestrial ground control are available by our long-term measured areas at Swiss-Camp and recently at ST2, as well. Although both areas are small (about 2x2 km^2) they can be used as ground control with different elevation, slope and surface undulation, not large enough for calibration, but useful for validation.

6. SUMMARY

Between 2002 and 2004, at Swiss-Camp we find accelerated melting rates and differing strain rates, compared to the long-term trend. The results confirm experiences from other parts in Greenland with increased thinning in the ablation areas near the ice margin. The equilibrium line originally was situated in altitude of Swiss-Camp, but now is shifted to higher areas, caused by climate change, especially in North polar regions.

The two test areas "Swiss-Camp" and "ST2" are precisely measured networks with well known topography and digital elevation models. Although principally intended for investigation of elevation change and ice flow parameters, they can be recommended for validation of remote sensing methods, such as laser altimetry or microwave RADAR techniques (ICESat, CryoSat etc.).

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