NERC GEOPHYSICAL EQUIPMENT FACILITY SCIENTIFIC REPORT: LOAN 804

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Calibration and validation of the CryoSat radar altimeter: field studies on the Greenland Ice Cap

Background

The original aim of this proposal followed on from the aims of previous related work (NERC GEF loan 766 Nienow) on the Greenland Ice Sheet to help improve the estimates of elevation change of land-ice and sea-ice as determined from the European Space Agency's CryoSat radar altimeter. In February 2006 the European Space Agency (ESA) confirmed that CryoSat2 would be built to replace the loss of CryoSat following launch failure on 8th October 2005 and so planned ground based calibration activities in spring 2006 continued. One of the goals of the CryoSat mission is to "reduce the uncertainty in the ice sheet contribution to sea level to a magnitude similar to that associated with other sources of sea level rise". The goal is being pursued via repeat measurements of the mass and thickness of ice masses by radar altimetry. A key part of the mission is a field calibration/validation program designed to provide rigorous estimates of the uncertainty of airborne and satellite radar measurements over land and sea ice. This fieldwork program is part-funded through the NERC Consortium bid, "Validation and Provision of CryoSat Measurements of Fluctuations of the Earth's Land and Marine Ice Fluxes" (NER/0/5/2003/00620, P.I. Prof. D. Wingham, co-I's include P. Nienow, D. Mair and E. Morris). Part of the field activity required additional equipment to ensure a successful calibration program. This equipment was provided by NERC GEF in the form of differential GPS equipment that was essential for determining the uncertainty of the radar measurements and thus, the overall accuracy and likely effectiveness of satellite radar altimeter missions.

Original Aims

Two key issues arise when attempting to determine mass balance change from remote sensing platforms. Firstly, satellite radar altimeter (SRA) measurements of ice cap elevation change are dependent on correct identification of snow surfaces, which may be ambiguous owing to strong internal reflections in the near surface snow and firn, known as 'volume backscatter'. Secondly, remote sensing techniques which measure elevation change over large ice masses need to account for temporal and spatial changes in near surface density if they are to be successfully used to estimate ice volume change. The aims of the field program for which the GEF DGPS equipment was required were therefore twofold:

1) To determine the accuracy to which satellite-derived records of the surface elevation of an ice mass represent real surface elevation.
2) To determine the extent to which changes in real surface elevation represent mass change.

The field programme undertaken on Greenland in spring 2006 required the measurement of snowpack properties and precise surface elevation through the percolation zone of the accumulation area of the Greenland Ice Sheet in conjunction with overflights (operated by KMS, Denmark) using an airborne version of the CryoSat radar altimeter (ASIRAS) and a laser altimeter.

Whilst the aim of the CryoSat mission was to record changes in elevation due to the mass balance, this cannot be achieved accurately without knowledge of ice flux divergence at a site. Thus the contribution of ice flow to elevation changes must be measured using *repeat* measurements of large-scale strain grids along transects where ice thickness is known. Initial measurements made during spring and autumn of 2004 had to be repeated to determine the annual flow regime at the study site and confirm evidence for seasonal variability.

Thus to effectively calibrate the ASIRAS radar altimeter required accurate GPS measurements to:

i) Provide ground-based measurements of actual surface elevation;
ii) Assess the contribution of ice flow to elevation changes using repeat measurements of large-scale strain grids along transects where ice thickness is known.

Methodology
Fieldwork was undertaken during a four week period in Spring 2006 between points identified as T01 and T12, and 5 km past T12, along the Expedition Glaciologique au Groenland (EGIG) line. Ground radar measurements were made from T03 and spanned a distance of 106 km with an increase in elevation of over 550 m within the percolation zone of the Greenland Ice Sheet. The impact of physical snow/firn properties on EM-wave characteristics are extremely poorly understood in this complex snow/firn facies. DGPS and ground radar measurements were made in conjunction with ASIRAS airborne radar altimeter over-flights. The radar measurements were made in the Ku band (center frequency around 13 GHz) for relevance to satellite radar altimeters. Accompanying shallow firn cores and snowpits characterized the snow and firn stratigraphy, including density. They enabled a characterization of the effects on radar backscatter from the major spatial and seasonal changes in the snowpack caused by summer melting and refreezing.

At T05 (~ 1940m elevation at 69º 51’N, 47º 15’W), a nested stake array at intervals of 1m, 10m, 100m and 1km was established along 2 perpendicular transects (Fig. 2). At each stake, physical properties of the snowpack were derived at high resolution (< 5cm scale) using snowpits, shallow (<3.0m) firn cores and a neutron-probe density profiler (Morris and Cooper, 2003). VHB radar profiles were retrieved along 1km transects from T05 to T05E4 and T05-S4 (Fig. 2).

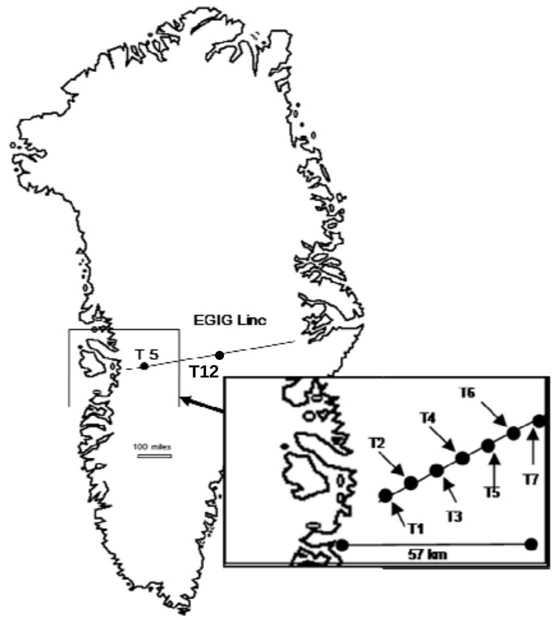

Figure 1: Location of T01 to T12 along EGIG line, Greenland Ice Sheet.

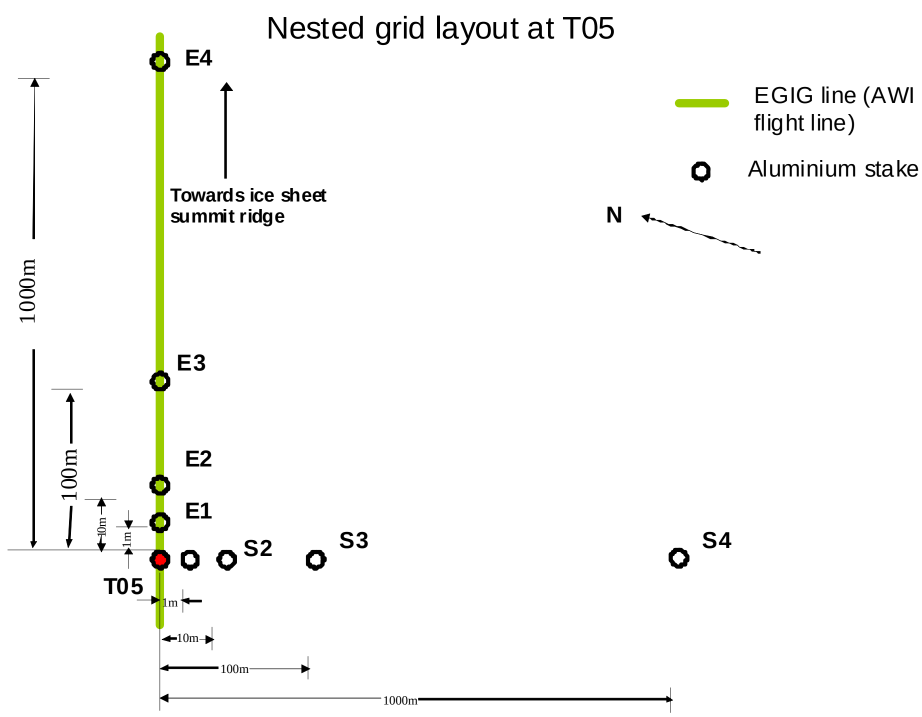

Figure 2. Nested grid layout at T05

GPS measurements were used to constrain the height of the ice sheet surface at each stake. Additional stake positions were obtained at T05N and T05W which were required to determine the contribution of ice flow to surface elevation change at T05 through variations in longitudinal and vertical strain. A base station, mounted on the NERC-GEF tripod, was established at T05 and was occupied for between 4 and 14 hours on four occasions during the field campaign (25th and 26th April during the ASIRAS overflights and 10th and 11th May for ice dynamic repeat survey of all stakes). The GPS rover was used to simultaneously log each stake location for ~ 5-10 minutes to determine the stake positions relative to the base station to an accuracy of +/- 0.01m. The GPS data was processed in the field to ensure that the sampling times were adequate to obtain the requisite accuracy.

Data Quality

Table 1 demonstrates the quality of the stake positions *relative* to the base station derived from Leica Geo-Office software and clarifies that accuracies achieved were all under +/- 0.01m. It also reveals that the absolute accuracy of the base station was +/- 0.017m after 8 hr continuous sampling.

Point ID	Epoch	Lat	Long	Elev	Pos Q	Ht Q	Pos H Q
ref (s3)	04/26/2006 17:12:46	69° 50' 59.51062" N	47° 15' 24.02683" W	1940.635	0.0071	0.0148	0.0165
s2	04/26/2006 18:32:51	69° 51' 01.82562" N	47° 15' 29.18121" W	1939.742	0.0005	0.0008	0.0010
cref	04/26/2006 18:40:54	69° 51' 01.82552" N	47° 15' 30.93468" W	1939.472	0.0004	0.0007	0.0008
t5	04/26/2006 18:47:01	69° 51' 02.07288" N	47° 15' 29.71544" W	1939.822	0.0005	0.0009	0.0010
e3	04/26/2006 18:54:51	69° 51' 03.61509" N	47° 15' 21.38560" W	1940.655	0.0004	0.0006	0.0007
e2	04/26/2006 19:31:40	69° 51' 02.22795" N	47° 15' 28.90451" W	1939.826	0.0005	0.0009	0.0010
s4	04/26/2006 20:09:11	69° 50' 33.92400" N	47° 14' 43.19316" W	1937.901	0.0005	0.0012	0.0013
n	04/26/2006 20:47:41	69° 51' 30.64406" N	47° 16' 13.13277" W	1936.835	0.0004	0.0006	0.0007
s1	04/26/2006 21:20:40	69° 51' 02.05307" N	47° 15' 29.66095" W	1940.119	0.0005	0.0007	0.0009
e1	04/26/2006 21:26:31	69° 51' 02.08177" N	47° 15' 29.63210" W	1939.996	0.0003	0.0005	0.0005

Table 1. Sample of UTM coordinates and position quality for the base station and measured rover points within the nested grid at T05 obtained on 26 April 2006.

Results

DGPS results

The data from the GPS surveys provide effective estimates of ice sheet elevation across the nested grid (Table 1). The spring 2006 survey also enabled estimates of ice dynamics and local strain rates during the period since the 2004 surveys. Flow velocity at T05 between 7 May 2004 and 26 April 2006 was 98.43 m yr +/- 0.03m and demonstrated, using the ‘strain-diamond’, that T05 is in a zone of longitudinal extension (0.004 yr^{-1}). These results are very similar to the velocity and strain rates observed between 22 April and 18 Sept 2004 of 97.33 m yr +/- 0.05m and 0.003 yr^{-1} respectively.

Comparison with radar “surface”

Winter snow accumulation on top of the end of summer surface creates a double ground radar power return with the actual surface providing a lower power return than the buried end of summer surface (Figure 3). The double return is further complicated by strong returns from icy windcrusts within the snowpack. The lower resolution of the airborne ASIRAS radar means that the surface return is combined with these layers making the tracked surface lower than the actual surface. This was certainly true of Spring 2004 data which showed that the ASIRAS surface was consistently 13 cm *lower* than the actual surface measured on the ground using DGPS [Helm et al., 2007].

Moving up the percolation zone from higher to lower melt regions, there is a point where summer densification features from several years become resolvable (Figure 3). The resolution of such annual layers is dependent on the strength of individual melt years and the subsequent depth of percolation prior to refreezing.

When modelling the radar altimeter return from the percolation zone of an ice sheet it is important to be aware of the significant spatial, seasonal and interannual variations that can occur. If a greater proportion of the return signal was to originate at or near the surface it could be retracked as a false elevation increase. Strong reflecting layers nearer to the surface may appear in the satellite data as an elevation increase. This may even account for some of the calculated increase in ice thickness observed at high elevations [Johannessen et al. 2004; Zwally et al. 2005]. If the percolation zone continues to move up the ice sheet [Steffen et al. 2004; Ngheim et al., 2005] it could affect the elevation changes being measured by satellite altimeters, by placing strong reflecting ice layers near to the surface. This effect could cause an overestimation in surface elevation increase and must be modelled to improve the confidence in current mass balance estimates.

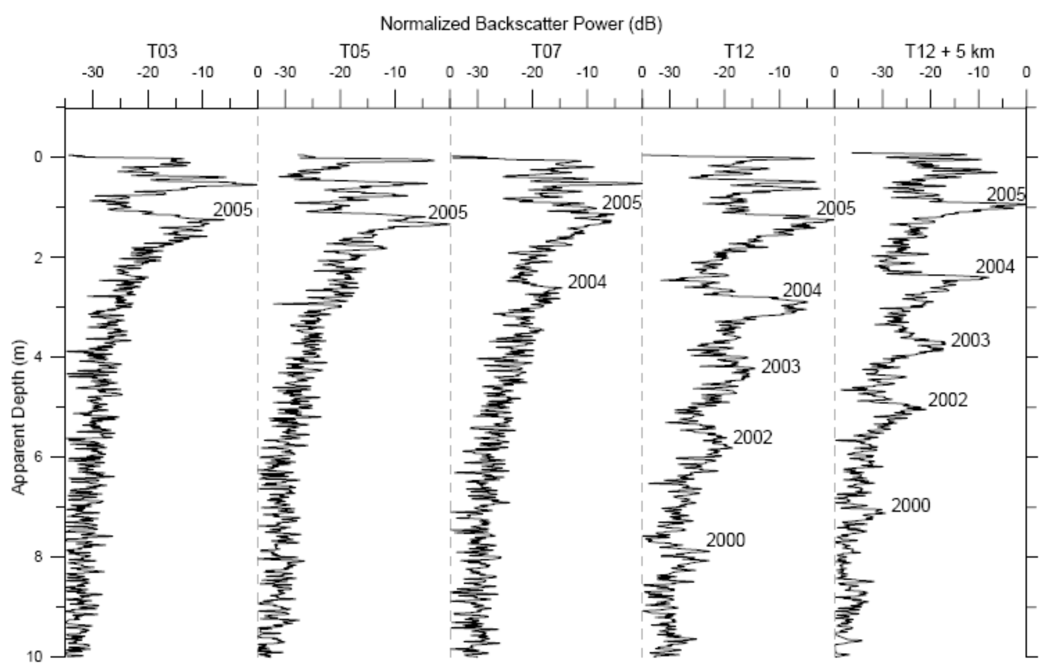

Figure 3: Normalized radar backscatter power return with depth across the percolation zone from T03 to T12, from measurements in April and May 2006. Centre frequency 13 GHz, bandwidth 8 GHz. Interpreted positions of summer melt surfaces are marked with dates. These surfaces correlate well with the surfaces tracked along EGIG from a borehole near summit using neutron probe density profiles.

Conclusions

The accurate calibration of airborne and satellite radar altimeters is essential if estimates of ice-sheet elevation change are to be effectively derived from such platforms. Experiments on the EGIG line of the Greenland Ice Sheet reveal clear variations in the near surface density of the surface snow/firn pack which significantly impact on elevation estimates derived from radar altimetry. The use of the NERC-GEF Leica GPS system enabled accurate estimation of ice sheet elevation (+/- 0.02m) and reveal the degree to which actual elevations (as measured on the ground) compare with estimates derived from an airborne radar altimeter (ASIRAS) with the same centre frequency and range as the forthcoming CryoSat2 altimeter. Two important effects have been identified from these measurements which may compromise the accuracy of existing radar power surface retracking algorithmns. Firstly, multiple power returns from near surface ice layers within the snowpack are sometimes indistinguishable from the surface return at the low vertical resolution of the airborne ASIRAS and CryoSat2 radar meaning that the tracked surface is lower than the actual surface. Secondly, a temporal change in the depth from which the greater proportion of the return signal originates could be retracked as false surface elevation change.

References

Morris, E. M. and Cooper, J.D. 2003. *J. Glac.* **49**(167), 599-604.
Johannessen et al. 2005. *Science* **310**, 1013
Zwally et al. 2005. *Journal of Glaciology*, **51**(175), 509-527.
Steffen et al. 2004. *Geophysical Research Letters*, **31**, L20402.
Ngheim et al., 2005. *Journal Of Geophysical Research*, **110**, F02017, Doi:10.1029/2004jf000234
Helm et al., 2007. *Geophysical Research Letters,* **34** (6), L06501, doi:10.1029/2006GL029185

Publications

de la Peña, S, Nienow, P, Shepherd, A, Mair, D, Cullen, R, and Wingham, D. In prep. “Analysis of altimeter radar waveforms recorded over the Greenland Ice Sheet and the impact on elevation change estimates”, *Geophysical Research Letters.*

Parry, V., Nienow, P., Mair, D. and Scott, J. 2008 “Greenland: Bringing together remote sensing and fieldwork” , *Scottish Geographical Journal*, **124:2**, 211 - 217: DOI: 10.1080/14702540802411840

Parry, V., Nienow, P., Mair, D**.**, Scott, J., Hubbard, B., Steffen, K. and Wingham, D. 2007. “Investigations of meltwater refreezing and density variations in the snowpack and firn within the percolation zone of the Greenland Ice Sheet.”, *Annals of Glaciology*, **46**, 61-68.

Helm, V., Rack, W., Cullen, R., Nienow, P., Mair, D., Parry, V. and Wingham, D. 2007. “Winter accumulation in the percolation zone of Greenland measured by airborne radar altimeter”, *Geophysical Research Letters,* **34** (6), L06501, doi:10.1029/2006GL029185

Scott, J.B.T., Nienow, P.W., Mair, D.W.F., Parry, V., Morris, E.M., and Wingham, D.J. 2006. “The importance of seasonal and annual layers in controlling backscatter to radar altimeters across the percolation zone of an ice sheet”, *Geophysical Research Letters*, **33**, L24502, doi: 10.1029/2006GL027974.

Scott, J.B.T., Mair, D.W.F., Nienow, P.W., Parry V.L. and Morris. E.M. 2006. “High frequency ground based radar measurements in the percolation zone of the Greenland Ice Sheet”. *Remote Sensing of Environment.* **104**, 361-373.

Conference presentations

de La Peña, S., Nienow, P., Mair, D., Scott, J., Parry, V., Giannopoulos, A., Shepherd, A., Cullen, R. and Wingham, D. 2008. “A Study of Airborne Radar Altimetry Waveforms and Ku Band Ground Penetrating Radar Measurements From the Percolation Zone of the Greenland Ice Sheet”, American Geophysical Union, Fall Meeting December 2008.

Parry, V., Nienow, P., Mair, D. and Scott, J., 2007. “Variations in mass balance and density of the snowpack and firn in Greenland`s percolation zone”, Workshop on the dynamics of and mass budget of glaciers (GLACIODYN(IPY)), Pontresina, Switzerland, January 2007

The committee made the following comments ..

Data quality: the standard errors in Table 1 are formal errors from LGO and not to be believed under any circumstances! (they do indicate successful processing though). The figure for "absolute accuracy" of the base station is also unclear - does this refer to (i) a stand-alone pseudorange position computed by LGO, or (ii) a baseline carrier phase solution relative to some permanent base station (e.g. on the coast), or (iii) a precise point position computed by something like Auto-GIPSY? If (i), then the error is very optimistic; if (ii), then the tropospheric modelling/estimation strategy in LGO is critical and what was done needs to be stated; if (iii), then GPS antenna phase centre corrections are critical and again confirmation is needed that these were made. Either way, there could be a bias in all ensuing quantities.

Surface elevation bias: is the reported 13 cm bias before or after applying the multi-return correction described in Helm et al? Can the PI be sure that other sources of bias have been eliminated as described above, and also bias in the aircraft positioning (which is presumably reliant on a long-baseline kinematic GPS solution to some base station on the coast; again, tropo modelling/estimation is critical).

Reply to comments from GEFSC

Data quality:

The committee is correct to point out that the data shown in Table 1 are the formal errors from the Leica Geo Office processing software and that even the relative positioning errors with respect to the base station are clearly optimistic. The committee rightly sought clarification of the quoted "absolute accuracy" of the base station. This is based on post processing using the GIPSY-OASIS II software package (Webb and Zumberge, 1995), which includes models and estimation algorithmns, developed by NASA's Jet Propulsion Laboratory (JPL), that account for orbit, Earth orientation, clock biases and a range of other geodetic and astronomic parameters. The 1σ uncertainty in *horizontal* positioning was <0.02m (pers comm., J.F. Zumberge). The vertical position accuracy is likely to be considerable poorer than this. A better estimate of the vertical accuracy would require additional expert post-processing (see below). Ultimately the committee's concern that the quoted value for the over-all position accuracy is optimistic is justified.

The post-processing of GPS data has been carried out successfully (as recognized by the committee) following training provided by GEF instructors and to a level that is likely to be common to most awardees of GEF DGPS equipment. The committee's question as to what GPS antenna phase centre corrections were made and what effect this would have on biases in all outputs falls beyond our expertise. Clearly, for some applications a considerably higher degree of accuracy is critical and would require further discussions with a DGPS processing expert before publication. The cm scale accuracy of horizontal measurements quoted is sufficient for long term surface velocity and strain measurements reported here. The committee are concerned that unaccounted for biases may have implications for the discrepancies between ground and airborne measurements reported by Helm et al (2007) but the absolute vertical accuracy of the DGPS data is not relevant to this problem as we now discuss.

Surface elevation bias:

The Report on Loan 804 was possibly misleading by saying that "the ASIRAS surface was consistently 13 cm lower than the actual surface measured on the ground using DGPS". The bias that Helm et al (2007) report is between the airborne radar (ASIRAS) elevation and the airborne laser scanner (ALS) elevation which remains after the application of the multi-return correction. It is not meaningful to directly compare the elevation measured at a single point on the ground using DGPS with either ASIRAS or ALS derived elevations since these are both determined from spatially averaged data. However, there was good agreement in the *elevation difference* between the corner reflector tip and the ice sheet elevation for both ground measurements and ALS measurements. Thus the statement in the report is still valid but we know this based on the relative position of the corner reflector tip with respect to the snow surfaces rather than on their absolute positions.

The calibration of the ASIRAS and ALS altimeters over the runway at Kangerlussuaq was successful (Helm et al, 2007 report an error of ± 2 cm) and so the cause of the bias reported over the ice sheet is almost certainly due to the difficulty that any re-tracking algorithm has in distinguishing the surface backscatter from the volume backscatter. The explanation we propose in the Report on Loan 804, that multiple reflections from near surface ice layers can cause the ASIRAS surface return to be "dragged down", is more fully explained by Scott et al (2006) based on earlier work carried out at our field site in autumn 2004. There may also be complications caused by the use of an average density when calculating the velocity for radar wave travel time through the snowpack when in reality the snowpack displays considerable heterogeneity in its density stratigraphy, both vertically and horizontally. These issues and others represent a major challenge for satellite radar altimetry and is the focus of ongoing calibration and validation work in advance of the launch of CryoSat2 scheduled for December 2009.

References

Helm, V., Rack, W., Cullen, R., Nienow, P., Mair, D., Parry, V. and Wingham, D. 2007. "Winter accumulation in the percolation zone of Greenland measured by airborne radar altimeter", *Geophysical Research Letters,* **34** (6), L06501, doi:10.1029/2006GL029185

Scott, J.B.T., Mair, D.W.F., Nienow, P.W., Parry V.L. and Morris. E.M. 2006. "High frequency ground based radar measurements in the percolation zone of the Greenland Ice Sheet". *Remote Sensing of Environment.* **104**, 361-373.

Webb, F.H. and Zumbrge, J.F.. 1995. "*An introduction to GIPSY/OASIS-II*". Pasadena, CA, California Institute of Technology. US National Aeronautics and Space Administration. Jet Propulsion Laboratory.