Satellite data synergies for monitoring Arctic ice masses

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Abstract

Mass balance is a key parameter for assessing the health of a glacier or ice cap. By routinely locating the position of the snow line, and hence equilibrium line, at the end of the ablation season it is possible to monitor changes in mass balance. Currently this is not possible using single satellite data sources, but we demonstrate that by combining different satellite data sets it is possible to generate a DEM and locate the position of the snow line.

Keywords: glaciers, ice caps, Landsat, radar altimeter, SAR

Introduction

The mass balance of a glacier or ice cap at any time is defined as the sum of the ablation and accumulation. Measured at the end of the ablation season, it is a key parameter for monitoring the health of a glacier and hence possible changes in the climate. Due to the inaccessability of the polar regions, satellite remote sensing provides an ideal tool for monitoring these changes. In this paper we explore possible synergies between ERS-1 radar altimetric (RA), synthetic aperature radar (SAR) and Landsat visible data, and how these might be used to monitor changes in mass balance. To date, our work has been focused on the smaller terrestrial ice masses of the High Arctic and here we present data from Austfonna and Finsterwalderbreen, a glacier and ice cap on Svalbard (9-27 E, 77-81 N).

Monitoring mass balance from space

There are three possible approaches to measuring mass balance from space: direct measurement of the accumulation and ablation terms, direct monitoring of the glacier volume or monitoring the equilibrium line that separates the ablation zone from the accumulation zone. Direct measurement of the accumulation and ablation terms has proven difficult. Zwally, 1977 and Rotman *et. al.*, 1982 have shown that it is possible to determine the accumulation rate from passive microwave observations, but only to an accuracy of 20 %. In any case, the spatial resolution available from spaceborne passive microwave radiometry is extremely coarse and is therefore only of use for monitoring the ice sheets of Greenland and Antarctica. Similarly, the only ablation term that may be measured from space is calving volumes estimated from iceberg areas. Direct measuremnt of surface melting and run-off is currently not possible.

In order to measure changes in the glacier volume it is necessary to make observations of the surface topography with a repeatable accuracy of better than 0.1 m (Rees and Squire, 1989). Possible techniques for achieving this include the use of RA data, shape-from-shading algorithms applied to visible/near infrared imagery and interferometric SAR (InSAR). However, these methods have all proven problematic and are not currently capable of reaching the required accuracy. The RA is a low data-rate sensor with poor spatial resolution. Uncertainties in the penetration depth can introduce errors of the order of 8 m (Ridley and Partington, 1988) and slope-induced errors of the order of 50 m for slopes of 0.01 radians are possible. Over steep slopes the onboard tracker can lose lock which consequent loss of data. Over dry snow areas a shape-from-shading algorithm can generate slope information from visible imagery. However, it is both necessary to calibrate the slope map and define a constant of integration to produce a topographic map. Both of these require some form of ground control data which is generally not available. InSAR techniques have potential but they are difficult to process. The technique requires at least two successive images that are highly correlated. This can be problematic because weathering and other environmental effects, such as glacier movements, can act to cause temporal decorrelation between the imagery. Furthermore ground control points are required for phase unwrapping otherwise the resulting DEM 'floats' in a similar way to the shape-from-shading algorithm.

The final method for measuring mass balance involves monitoring the position of the equilibrium line. At the end of the ablation season the position of the equilibrium line is close to the snow line (Paterson, 1994). If the snow line can be routinely detected and superimposed on a sufficiently accurate digital elevation model (DEM), changes in the equilibrium line altitude (ELA), and hence mass balance can be monitored. It is well established that the snow line can be identified in visible imagery (Williams *et. al.*, 1991), but these data can not be routinely used in the High Arctic because of severe cloud problems. Marshall *et. al.*, 1994 have shown that the likelihood of acquiring cloud free visible imagery of Svalbard at the end of the ablation season is less than six percent. However, this problem of timing can be circumvented by the use of SAR data that are potentially available in all weather conditions and at any time of year. Interpretation of SAR imagery is notoriously difficult because variations in the backscatter are caused by changes in the surface dielectric properties, roughness and topography. Despite this Jezek *et. al.*, 1993 and Marshall, 1995 have used *in situ* data to demonstrate that it is possible to delineate the snow line in SAR imagery acquired at the end of the ablation season. Without the benefit of *in situ* data we explore the possiblity of using data synergies to monitor the snow line.

Synergistic approach

Data synergy involves the combination of independent datasets to extract new or to obtain more accurate information about a parameter being measured. Here we aim to demonstrate the power of this approach to *(a)* develop a DEM by using RA data to calibrate a shape-from-shading algorithm applied to visible imagery, and *(b)* to combine visible and SAR data to locate the position of the snow line, and consequently the equilibrium line at the end of the ablation season .

In this work we recognise that the absolute accuracy of the DEM will not be accurate enough for monitoring temporal changes in mass balance. Nevertheless, we suggest that the DEM will be sufficiently accurate to monitor relative changes in the ELA, which may be deduced from visible and SAR imagery.

Digital elevation model

To date, airborne radio echo sounding surveys have been used to map selected ice-covered areas of the world, but these surveys are one-off and expensive. More recently Seasat, Geosat and ERS-1 RA data have been used to map the ice sheets of Greenland and Antarctica (Zwally, *et. al.*, 1983; Rapley, *et. al.*, 1993), demonstrating the role of satellite remote sensing for mapping the polar regions. However, satellite altimetric data have not been used to map smaller ice caps because of limitations in available data. Figure 1 shows the available data on Austfonna after averaging three cycles of ERS-1 35-day repeat data. Only summer data were used in order to reduce penetration effects. The resulting DEM (Figure 2) contains predominately low spatial frequencies and is consequently of little value. In order to improve the spatial frequency we have applied a shape-from-shading algorithm (Rees and Dowdeswell, 1988) using a Landsat MSS image to model the topography of the ice cap and the ERS-1 RA data to constrain the model. In order to acheive this, profiles of Landsat MSS band 6 brightness values were generated from transects running parallel to the solar azimuth and separated by one pixel in the east--west direction. Whenever a transect crossed an ERS-1 RA data track the surface height measured by the RA and position along the transect were recorded and used to constrain the modelled DEM. At least three tie-points are required to calculate the coefficients necessary to invert the algorithm. When this was not possible, coefficients from the nearest available constrained transect were used.

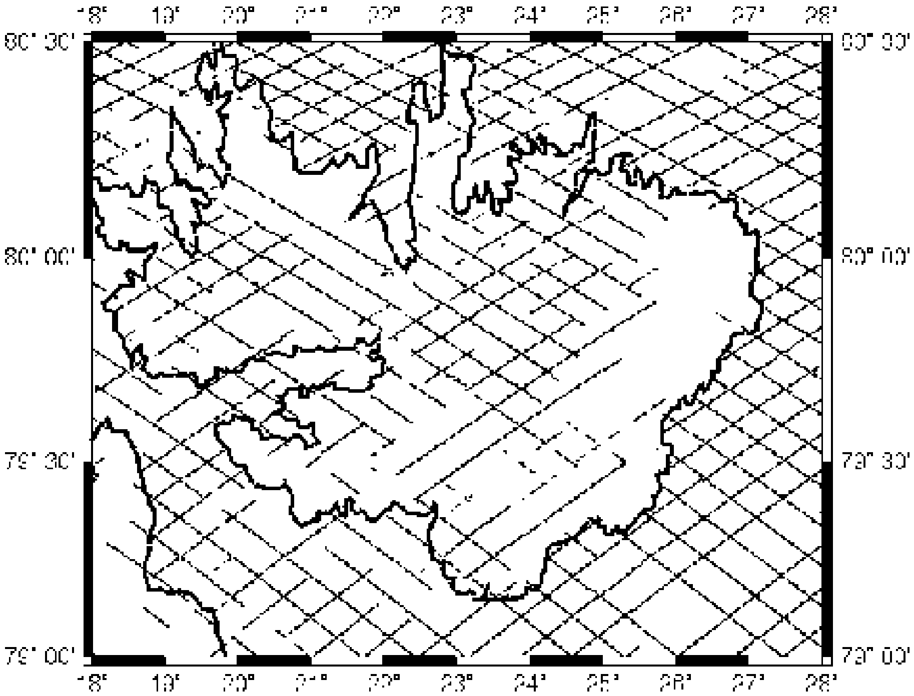

Figure 1: Available ERS-1 altimetric data over Austfonna, for 3 cycles worth of 35-day repeat data acquired in the summer of 1992.

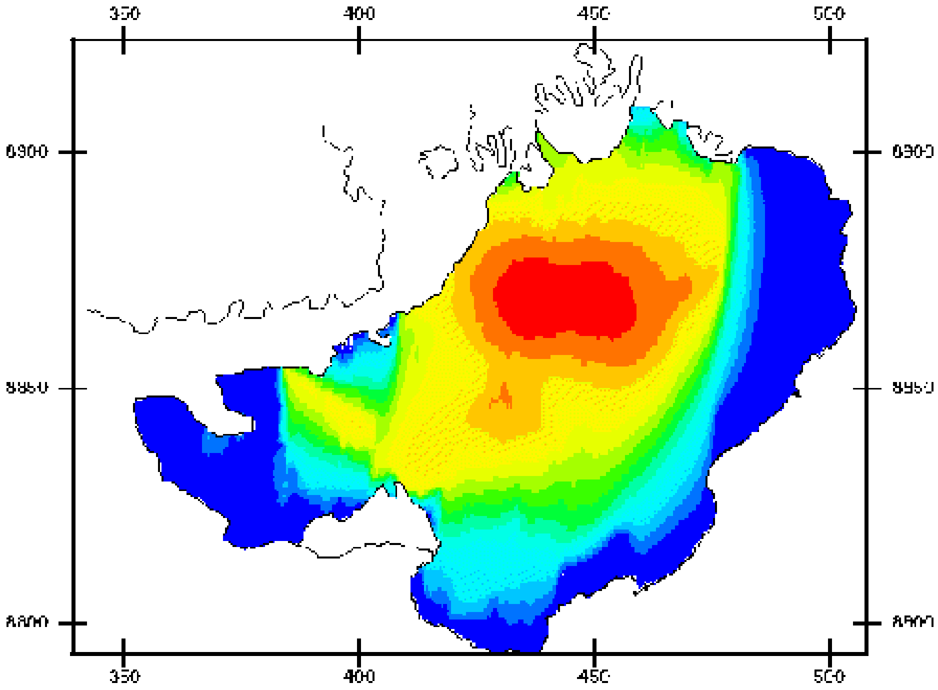

Figure 2: DEM of Austfonna produced entirely from ERS-1 radar altimetric data.

The new DEM (Figure 3) combines the high spatial frequency information contained in the MSS imagery with the low spatial frequency altimetric data. The result is a DEM that is a significant improvement on the DEM derived from altimetric data alone. The absolute accuracy of the DEM is still poor due to contamination by slope-induced errors, although in principle these my be removed when appropriate techniques are available. Moreover, with the development of the EOS GLAS many of these problems will be eliminated. Comapared with radio echo sounding data, the new DEM, even using slope-uncorrected RA data, has an RMS error of less than 30 m.

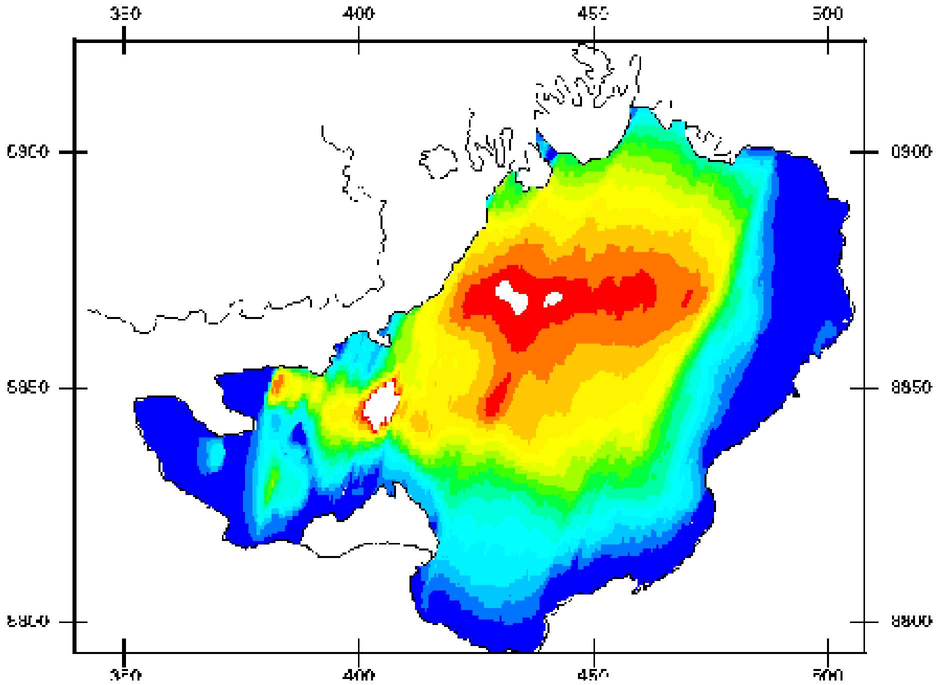

Figure 3: DEM of Austfonna produced from a shape-from-shading algorithm applied to a Landsat/MSS image and constrained with ERS-1 altimetric data.

Snow line estimation

Having demonstrated the possibility of generating an accurate DEM by combing ERS-1 RA and visible wavelength data, we now consider the possibility of defining the position of the snow line at the end of the ablation season, and hence the equilibrium line, on a routine basis. Figure 4 shows a SAR image of Finsterwalderbreen acquired at the end of the 1995 ablation season. On the basis of tonal variations, the glacier can be readily divided into a number of altitudinal zones with well defined boundaries. These boundaries (SL1, SL2 and SL3 in Figure 4) are possible locations for the snow line. However, without other information it is impossible to confirm which of these, if any, is the real snow line. Figure 5 shows a Landsat/TM image of the same area acquired during the middle of the 1993 ablation season. Although this image was obtained in a different year and at a different time in the ablation season, there are clear spatial similarities with Figure 4. This permits an unambiguous attribution of the 'potential' snow lines, SL! and SL2, to morphological features and the real snow line as SL2. Verification of this has further been obtained from aerial photography coincident with the SAR image.

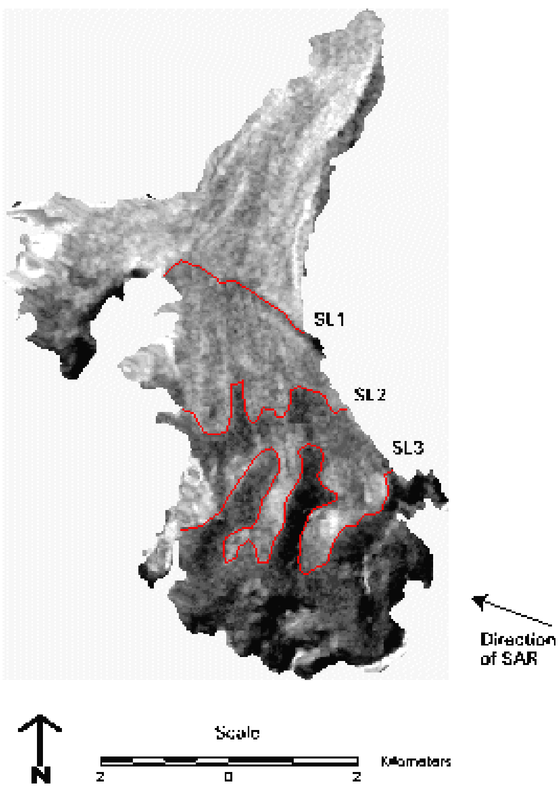

Figure 4: SAR image of Finsterwalderbreen acquired at the end of the 1995 ablation season.

SL1, SL2 and SL3 are possible locations of the snow line.

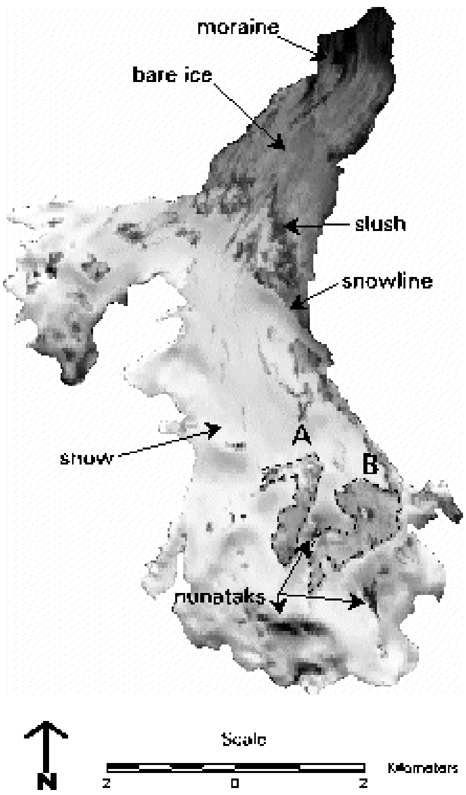

Figure 5: Landsat/TM image of Finsterwalderbreen acquired during the mid 1993 ablation of the ablation season.

Conclusions

No single satellite remote sensing technique can currently give mass balance measurements with sufficient accuracy. However, the work presented here suggests that there is scope for combining RA, visible and SAR imagery to *(a)* generate a DEM and *(b)* combine the end of ablation season snow line on with the DEM in order to infer changes in the ELA and consequently changes in the mass balance with sufficient accuracyn any case, the spatial resolution available from spaceborne passive microwave radiometry is extremely coarse and is therefore only of use for monitoring the ice sheets of Greenland and Antarctica. Similarly, the only ablation term that may be measured from space is calving volumes estimated from iceberg areas. Direct measuremnt of surface melting and run-off is currently not possible.

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