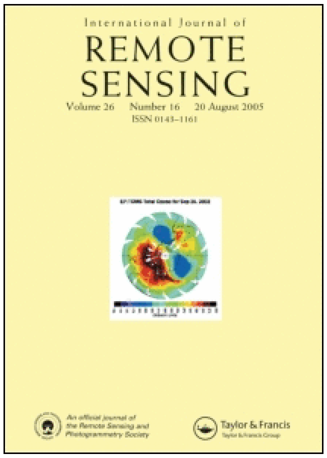

International Journal of Remote Sensing
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713722504

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Online Publication Date: 10 August 2006
To cite this Article: Giles, K. A. and Hvidegaard, S. M. (2006) 'Comparison of space borne radar altimetry and airborne laser altimetry over sea ice in the Fram Strait', International Journal of Remote Sensing, 27:15, 3105 - 3113
To link to this article: DOI: 10.1080/01431160600563273
URL: http://dx.doi.org/10.1080/01431160600563273

International Journal of Remote Sensing
Vol. 27, No. 15, 10 August 2006, 3105–3113

Comparison of space borne radar altimetry and airborne laser altimetry over sea ice in the Fram Strait

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This paper describes the first comparison of satellite radar and airborne laser altimetry over sea ice. In order to investigate the differences between measurements from the two different instruments we explore the statistical properties of the data and determine reasonable scales in space and time at which to examine them. The resulting differences between the data sets show that the laser and the radar are reflecting from different surfaces and that the magnitude of the difference decreases with increasing surface air temperature. This suggests that the penetration depth of the radar signal, into the snow, varies with temperature. The results also show the potential for computing Arctic wide snow depth maps by combining measurements from laser and radar altimeters.

1. Introduction

The majority of general circulation models predict that future warming in the Polar Regions will be greater than for many other regions, and will result in a reduction in the volume of sea ice in the Arctic. Changes to Arctic sea ice affect the climate system by altering the energy fluxes at the Earth's surface. An increase in sea ice cover and/or thickness inhibits the exchange of heat, moisture and momentum between the ocean and the atmosphere. Sea ice also influences the formation of deep water masses (McCarthy *et al.* 2001). Therefore, for future prediction of climate change, it is important that sea ice is well represented within climate models.

Remote sensing techniques are used to monitor sea ice extent, concentration, motion and deformation. However, sea ice thickness is a difficult parameter to measure directly from space as the brine cells in the ice give it a high electrical conductivity so that electromagnetic waves cannot penetrate it.

Common techniques used for the measurement of sea-ice thickness include: Drilling, submarine sonar profiling, moored upward sonars, airborne laser profilometry and electromagnetic induction techniques (Haas *et al.* 1997, Wadhams 2000). Although these techniques provide useful measurements of sea ice thickness, they are often spatially or temporally limited.

Ice monitoring methods using satellite radar altimetry and satellite laser altimetry have the potential to provide extensive spatial and temporal measurements of sea ice thickness. Laxon *et al.* (2003), measure sea ice freeboard from satellite radar

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International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online © 2006 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160600563273

altimetry (ERS1/2), and convert the ice freeboard to thickness by assuming hydrostatic equilibrium. Kwok *et al.* (2004) measure the elevation of the sea ice freeboard plus the snow layer from satellite laser altimetry (ICESat), and use this measurement to estimate sea ice thickness. However, both techniques have uncertainties associated with their estimate of sea ice thickness. Kwok *et al.* (2004) find that unknown snow depth is the largest uncertainty in their ice thickness estimation, and that it could introduce uncertainties of over one metre. Unknown snow loading also introduces an uncertainty in the radar estimates of sea ice thickness, which assume that the radar echo originates from the snow/ice interface. This assumption is based on laboratory measurements by Beaven *et al.* (1995) and Lytle *et al.* (1993) and on large scale comparison with submarine sonar measurements. However there are no direct observations to confirm this assumption (Wingham *et al.* 2001). An additional complication arises as evidence presented in Hallikainen (1992) indicates that even a small (2%) volumetric liquid water content in the snow layer would result in the radar not penetrating to the snow/ice interface. Curry *et al*. (2001) show that snow melt occurs when the surface temperature reaches 0°C and that during the melting period the temperature fluctuates around the melting point. If the radar return does not originate from the snow/ice interface, from within the snow layer, then the ice thickness estimates will be too large. If the radar does penetrate to the snow/ice interface, then combining radar and laser altimetry has the potential to calculate snow depth on a basin wide scale by combining satellite altimetry data from ICESat's laser altimeter and Envisat's radar altimeter. Basin wide snow depth maps would solve an uncertainty associated with the calculation of sea ice thickness from both laser and radar altimetry, as well as providing a valuable data set in its own right.

In this paper we present the first comparison of sea ice elevation derived from satellite radar altimetry and airborne laser altimetry. We use elevation measurements from the radar altimeter onboard the European Space Agency's ERS2 satellite and airborne laser data collected by the National Survey and Cadastre, Denmark (KMS) during surveys in April/May 2001 and May 2002. Figure 1 shows the study area and the location of both data sets.

The sampling of each data sets means that it is not possible to do an exact point on point comparison. Therefore we find characteristic spatial and temporal scales within which it is reasonable to assimilate the data sets.

We show that the two independent measurements are comparable and that the laser reflects from a higher surface than the radar, as would be expected. The differences between the two data sets are similar to the expected snow depths off the East coast of Greenland. However, as the temperature increases over the measurement area the difference between the laser and the radar elevations decreases, suggesting that the penetration depth of the radar signal varies with temperature.

2. Data description

Precise satellite radar altimetry measurements of sea ice freeboard and sea surface height (Peacock and Laxon 2004) are obtained by reprocessing of the return echoes (Laxon 1994) and applying corrections to orbits, tides, and atmospheric effects (Cudlip and Milnes 1994). Differentiation between open ocean and sea ice is based on the fact that different shaped echoes are received from each surface. Sea ice

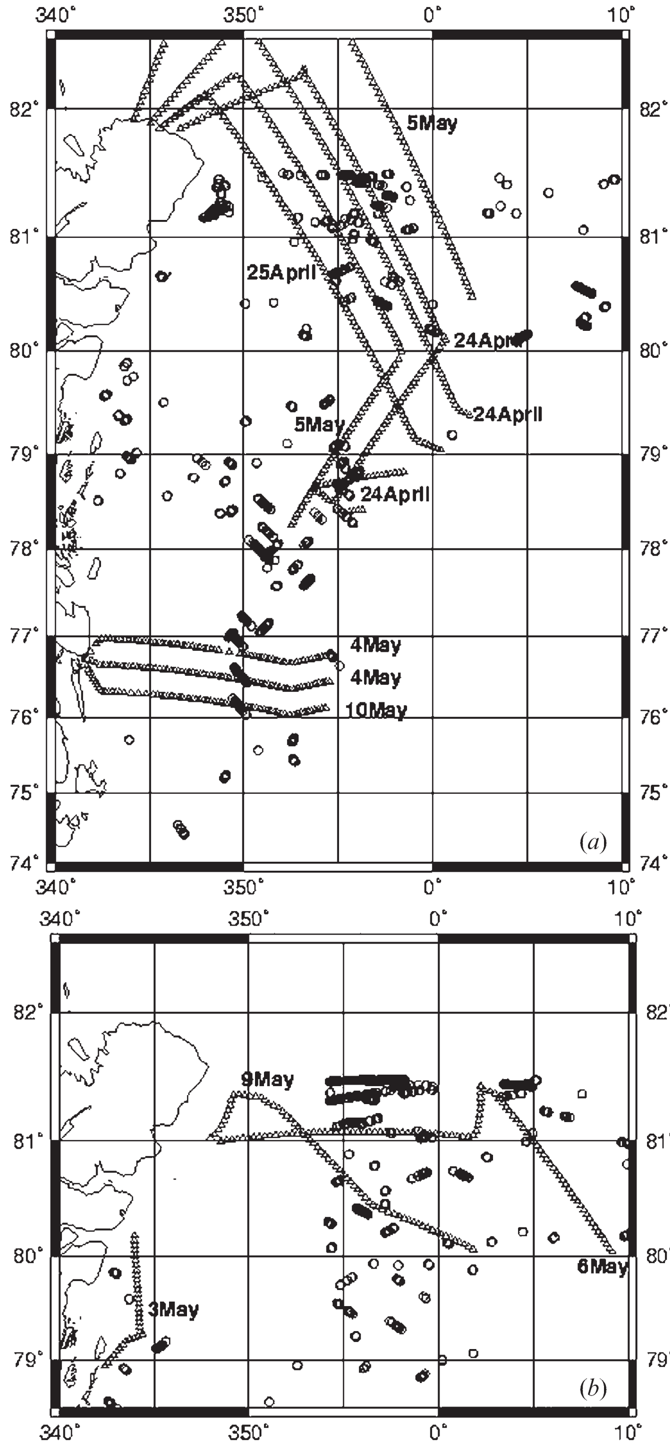

Figure 1. Study area with locations of ERS-2 radar data, (*a*) 19 April 2001–15 May 2001 and (*b*) 28 April 2002–14 May 2002, shown by circles and locations and dates of airborne laser data shown by triangles.

freeboard is calculated by subtracting the sea surface elevation from the ice elevation (Laxon *et al.* 2003). To produce an estimate of sea ice freeboard the entire satellite footprint must be filled with ice. The estimates of sea ice freeboard represent an average value over the 100 km footprint.

An approximate error on the sum of ice freeboard estimates can be calculated from:

$$\sigma_{\Sigma}^{2}=\frac{\sigma_{diff}^{2}}{n}+\sigma_{SLA}^{2} \tag{1}$$

where σ_{diff} is the diffuse measurement noise, and is taken to be the standard deviation of freeboard estimates about the mean for a contiguous sequence, σ_{SLA} is error in sea level estimation, and is taken to be the standard deviation of the estimates used to determine the sea surface elevation (above the mean sea surface). We use values estimated from repeat track analysis of 0.14 m for σ_{diff} and 0.022 m for σ_{SLA} (Peacock and Laxon, 1998).

The airborne laser altimetry data was gathered in 2001 and 2002 by KMS, as part of a larger project to measure gravity on the Greenland continental shelf region (Forsberg *et al.* 2002) and as part of a joint gravity and ice mapping survey (Forsberg *et al.* 2003). For both surveys, data were obtained using an Optech near-infrared laser altimeter operating at a wavelength of 904 nm with a 1 m footprint at the operational altitude of 150 to 300 m. Additional data were gathered in 2002 from a scanning laser altimeter, operating at 900 nm. It provided the same measurements as the Optech laser but with greater along track spacing.

The basic measurement principle for the airborne laser altimetry estimate of snow freeboard (the elevation of the sea ice freeboard plus the snow layer) is given by:

$$F=h_{GPS}-H_{laser}-N-\Delta h \tag{2}$$

where F is the snow freeboard height, h_{GPS} the height of the aircraft above the WGS84 reference ellipsoid determined by GPS, H_{laser} the laser range corrected for roll and pitch from the internal navigation system, and N the geoid height. N is taken from a model derived from airborne gravity measurements from previous airborne KMS surveys. Δh describes the deviation of the sea surface from the geoid caused by errors in the geoid model and changes in the sea-surface topography due to tides and permanent sea-surface topography. Also included in Δh are errors from possible laser offsets and misalignments and GPS errors. All components of Δh have long-wavelengths compared to the sampling frequency and Δh is generally less than 1 m. Δh is estimated and eliminated by the filtering described below.

The exact location of the sea surface, i.e. the size of Δh, is found by fitting a second order polynomial to the minimum values of the data output from (2). This approach assumes that minimum values in the data correspond to leads or thin, newly refrozen areas. The filter is designed to remove errors of wavelengths longer than about 10 km. By subtracting the polynomial from F, the final freeboard heights are found. More details of the processing of the airborne laser data can be found in Hvidegaard and Forsberg (2002).

The error on an individual ice freeboard measurement is 13 cm. This error reduces to 5 cm when averaged as described below, since measurement noise is negligible.

3. Data reduction

Spatial scales for the comparison were chosen based on the spatial autocorrelation estimated from the laser data. The distance to the first zero crossing ranged between 50 km and 100 km.

Due to the low spatial density of the radar data we chose to compare data within 100 km of each laser point. To estimate the temporal correlation of the data sets we examined the ice drift velocities from drifting buoys from the International Arctic Buoy Program (Rigor 2002). Typical velocities of 10–15 cm/s occur in the northern part of our study area in spring. 15 cm/sec corresponds to about 65 km in 5 days. To avoid over sampling, and to keep in mind the rapidly changing distribution of sea ice in the Fram Strait, we chose a temporal search radius of 4 days.

A 100 km moving average was computed over the laser data in an along track direction. The average elevation was computed at each datum point by taking the average of the elevations $\pm$ 50 km from the datum point (approximately 14000 points in each average). To reduce data volume, 0.1% of the averages were kept, providing an elevation estimate every 6.5 km. For each estimate of snow freeboard from the laser data, the average radar derived ice freeboard was computed from all points falling within 100 km and 4 days of the laser point. All freeboard values below 0.05 m were excluded from both data sets to ensure that no open water values were included in the calculation. The difference between the two data sets (laser minus radar) was then computed for all averages that included at least 30 radar points. Taking an estimate of 0.05 m for the error on the laser data and using (1) to calculate the error on the radar data, assuming that the two data sets are independent and errors are added quadratically, the maximum error on the difference between the laser and the radar data is 0.06 m. To investigate whether changes in the difference between the laser and radar elevations corresponded to temperature change, the daily maximum 2 m temperatures from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational data (http://badc.nerc.ac.uk/data/ecmwf-op/) were averaged over the periods of the investigation and used to create a temperature contour map of the region.

The differences in freeboards from the 2001 and 2002 flights, along with the temperature contours, are presented in figure 2(*a*) and 2(*b*).

4. Results

Figure 2(*a*) shows the difference between the snow freeboard derived from the laser data and the freeboard derived from the radar data in 2001. The differences range between −0.10 and 0.35 m. The highest values are found close to the east coast of Greenland. For a comparison, the sea ice thickness ranges from about 1.5 m to 4 m in the study area as estimated from our data sets.

Area I generally has the largest difference towards the northwest and differences decrease towards the southeast. In area II we see an agreement in the differences at the crossovers that are within 1 day of each other, (for dates of the tracks see figure 1). Area III shows decreasing differences with distance as we move away from the Greenland coast. Here we see differences slightly below zero. They are caused by a combination of the measurement error and a result of sampling differences.

Figure 2(*b*) shows the difference between the snow freeboard derived from the laser data and the freeboard derived from the radar data in 2002. We find

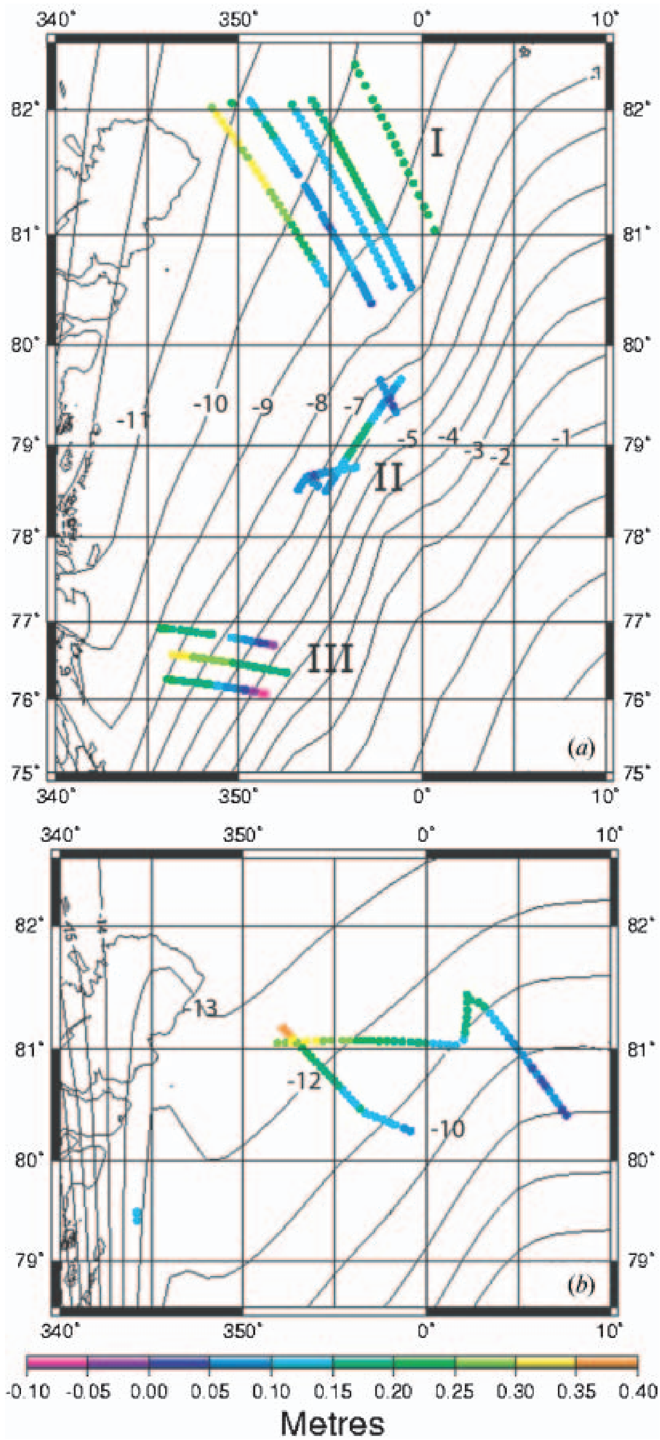

Figure 2. Snow freeboard minus ice freeboard differences for 2001 are shown in (*a*) and for 2002 in (*b*), along with contours showing the average maximum daily 2 m temperature from ECMWF.

differences between 0.05 and 0.40 m and again we see the highest values towards the west.

Comparison of the difference estimates with the temperature contours shows that as the air temperature increases, the difference between the two data sets decreases.

5. Discussion

Figure 3 shows the snow depths predicted by Warren et al. (1999), we have annotated the diagram to show the location of the top of the experiment area. The highest differences between the laser derived snow freeboard and the radar derived freeboard (0.3–0.4 m) correspond well to the snow depths at the top of the Fram Strait, in figure 3.

Comparing data from 2001 and 2002, we see similar differences in area I (where we have data for both years), and in both years we see the differences decrease as the temperature increases and as we move from west to east. The values of the temperature contour lines in figure 2(*b*) are lower than those in the same location in 2(a). However, this is not unexpected since we are looking at data from two different years, and comparisons of the ECMWF reanalysis data with observational data (Hagemann and Dümenil Gates 2001) show differences between 1 and 5 degrees along the East Greenland coast and we expect similar differences in the operational data. However we do expect the pattern of the temperature gradient to be correct.

The decrease in the difference between the laser and the radar elevations as we move from west to east has two possible causes. The first is that the depth of the snow cover decreases from west to east and the second is that partially melted snow, resulting from the increase in temperature, causes the reflecting surface of the radar to change. We do not have coincident data on snow depth in this region. However, we do not expect that the snow depth will be equal to zero over 100 km averages. Gow and Tucker (1987), estimate the average snow depth on multi-year ice floes to be 0.29 m between 78°20′N to 80°42′N latitude and 7°16′E to 7°10′W longitude during June and July 1984, and state that multi-year ice fraction is greater than 75%

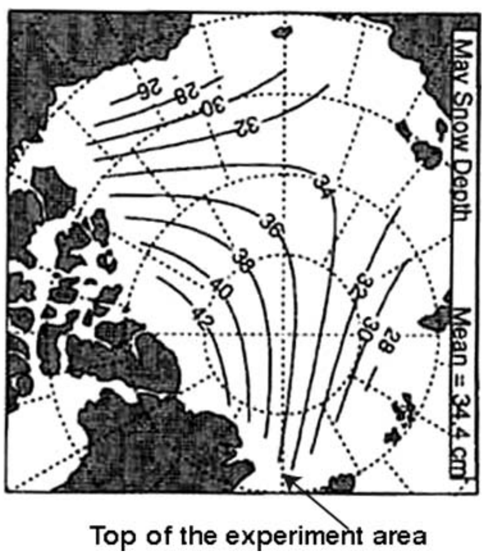

Figure 3. Mean snow depth for 1954–91 for May from Warren *et al.* (1999).

in that area. Warren et al. (1999) also state that the average snow depth on multi-year ice reaches a maximum in May. Therefore the correlation between the increase in temperature and the decrease in the difference between the laser and the radar elevations suggests that the radar signal may not penetrate to the snow/ice interface as the surface temperature increases.

6. Conclusions

For the first time we have compared measurements from airborne laser and satellite radar altimeters over snow covered sea ice. We have analysed the spatial and temporal properties of snow freeboards and found scales within which it is reasonable to compare the two types of measurement. We find that the two independent measurements show comparable results with differences in areas close to the coast of Greenland similar to expected snow depths. We see that at most points the laser estimates are higher than the radar as would be expected. The results show a correlation between negative gradients in the differences and positive gradients in the 2 m air temperature, which suggests that the reflecting surface of the radar varies with temperature. Unfortunately, as we do not have in-situ data we cannot confirm these results. Further investigations are needed to clarify these results.

Our results have implications for future planning of field campaigns to assess the accuracy of satellite estimates of sea ice freeboard from both radar and laser altimeters, such as those onboard CryoSat and ICESat. Sampling difficulties in our study could be resolved by designing aircraft flight lines to be coincident in space and time with satellite ground tracks and data should be collected pre-melt.

Our study indicates the potential for estimating Arctic wide sea ice snow depth and an ice thickness data set using coincident laser and radar altimetry during winter periods. However, in-situ snow depth measurements are required to assess whether this technique can provide accurate snow depth estimates.

Acknowledgement

Funding for the KMS airborne gravity and laser surveys was partly provided by the US National Imagery and Mapping Agency (2001) and by European Space Agency (2002). The airborne campaign was planned and executed and the data processed by R. Forsberg, K. Keller, A. Olesen and N. Dalaa, from KMS, in addition to S. Hvidegaard.

ERS2 data was provided by the European Space Agency. The authors are grateful to S. Laxon for advice during both the analysis and writing. K. Giles is funded by the UK National Environmental Research Council.

References

Beaven, S.G., Lockhart, G.L., Gogineni, S.P., Hosseinmostafa, A.R., Jezek, K., Gow, A.J., Perovich, D.K., Fung, A.K. and Tjuatja, S., 1995, Laboratory measurements of radar backscatter from bare and snow-covered saline ice sheets. *International Journal of Remote Sensing*, **16**, pp. 851–867.

Culdip, W. and Milnes, M., 1994, Overview of altimeter data processing at the UK Earth Observation Data Centre. *International Journal of Remote Sensing*, **15**, pp. 871–887.

Curry, J.A., Schramm, J.L., Perovich, D.K. and Pinto, J.O., 2001, Applications of SHEBA/FIRE data to evaluation of snow/ice albedo parameterizations. *Journal of Geophysical Research*, **106**, pp. 15345–15355.

FORSBERG, R., OLESEN, A., KELLER, K. and MØLLER, M., 2002, Airborne Gravity Survey of Sea Areas around Greenland and Svalbard 1999–2001. *KMS Technical Report*, 18.

FORSBERG, R., KELLER, K., HVIDEGAARD, S.M. and OLESEN, A., 2003, ESAG-2002, European airborne gravity and lidar survey in the Arctic Ocean, *KMS Technical Report*, 21.

GOW, A.J. and TUCKER III, W.B., 1987, Physical Properties of Sea Ice Discharged from the Fram Strait. *Science*, **236**, pp. 436–439.

HAAS, C., GERLAND, S., EICKEN, H. and MILLER, H., 1997, Comparison of sea-ice thickness measurements under summer and winter conditions in the Arctic using a small electromagnetic induction device. *Geophysics*, **62**, pp. 749–757.

HAGEMANN, S. and DÜMENIL GATES, L., 2001, Validation of the hydrological cycle of ECMWF and NCEP reanalysis using the MPI hydrological discharge model. *Journal of Geophysical Research*, **106**, pp. 1503–1510.

HALLIKAINEN, M., 1992, Review of the Microwave Dielectric and Extinction Properties of Sea Ice and Snow. *Geoscience and Remote Sensing Symposium, IGARSS '92, International*, **2**, pp. 961–965.

HVIDEGAARD, S.M. and FORSBERG, R., 2002, Sea-Ice Thickness from Airborne Laser Altimetry over the Arctic Ocean North of Greenland. *Geophysical Research Letters*, **29**, pp. 1952.

KWOK, R., ZWALLY, H.J. and YI, D., 2004, ICESat observations of Arctic sea ice: A first look. *GRL*, **31**, L16401, DOI: 10.1029/2004GL020309.

LAXON, S.W., 1994, Sea ice altimeter processing scheme at the EODC. *International Journal of Remote Sensing*, **15**, pp. 915–924.

LAXON, S.W., PEACOCK, N. and SMITH, D., 2003, High Inter-Annual Variability of Sea Ice Thickness in the Arctic Region. *Nature*, **425**, pp. 947–950.

LYTLE, V.I., JEZEK, K.C., HOSSEINMOSTAFA, A.R. and GOGINENI, S.P., 1993, Laboratory backscatter measurements over urea ice with a snow cover at Ku band. *IEEE Transactions on Geoscience and Remote Sensing*, **31**, pp. 1009–1016.

MCCARTHY, J.J., CANZIANI, O.F., LEARY, N.A. and WHITE, K.S., (Eds.), 2001, Climate Change 2001: Impacts, Adaptation & Vulnerability. Contribution of Working Group II to the *Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* (Cambridge: Cambridge University Press), chapter 16.

PEACOCK, N.R., 1998, Artic sea ice and ocean topography from satellite altimetry. Pho thesis, University of London.

PEACOCK, N.R. and LAXON, S.W., 2004, Sea Surface Height Determination in the Arctic Ocean. *Journal of Geophysical Research*, **109**, C07001, DOI: 10.1029/2001JC001026.

RIGOR, I., 2002, *IABP Drifting Buoy, Pressure, Temperature, Position, and Interpolated Ice Velocity*, Compiled by the Polar Science Centre, Applied Physics Laboratory, University of Washington, Seattle, in association with NSIDC. Boulder, CO: National Snow and Ice Data Centre. Digital media.

WADHAMS, P., 2000, Ice in the Ocean. (Amsterdam, The Netherlands: Gordon and Breach Science Publishers).

WARREN, S.G., RIGOR, I.G., UNTERSTEINER, N., RADIONOV, V.F., BRYAZGIN, N.N., ALEKSANDROV, Y.I. and COLONY, R., 1999, Snow Depth on Arctic Sea Ice. *Journal of Climate*, **12**, pp. 1814–1829.

WINGHAM, D.J., FORSBERG, R., LAXON, S., LEMKE, P., MILLER, H., RANEY, K., SANDVEN, S., SCHARROO, R., VINCENT, P. and REBHAN, H., 2001, CryoSat: Calibration & Validation Concept, Centre for Polar Observation & Modelling, University College London, Doc. CS-PL-UCL-SY_004, 14 November.