



**Antarctic Ice Sounding Experiment using
ESA's P-band Polarimetric Sounder**

Executive Summary

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Sounding the Antarctic ice sheet from space: a feasibility study based on airborne P-band radar data

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ABSTRACT

Space-based radio echo sounding of the continental ice sheets can potentially provide full coverage with uniform sampling and data quality as well as detection of change in environmentally sensitive areas. This paper addresses the feasibility of sounding the Antarctic ice sheets with a space-based P-band radar. The assessment makes use of an electromagnetic model of the ice sheets where most of the model parameters are estimated from data that have been acquired in Antarctica with an airborne P-band ice sounding radar. The performance of a nadir-looking space-based radar, which is similar to the radar of ESA's Biomass mission, is simulated for a set of Antarctic scenarios that are defined based on the statistics of key ice regions. It is found that in about 2/3 of the simulation scenarios clutter and/or thermal noise will obscure the signal from the ice bed.

Index Terms— Radar, ice sheets, Antarctica, sounding, electromagnetic model, P-band, satellite.

1. INTRODUCTION

Since the 1960ies the ice sheets in Greenland and Antarctica have been mapped with airborne ice sounding radars, and radar data acquired from a crisscross of flight tracks are the primary data source for the existing maps of ice thickness and basal topography [1]. Although an extensive data set exists the track spacing is very inhomogeneous, and in some areas the distance to the nearest measurement point exceeds 100 km. A much smaller track spacing (ideally comparable with the ice thickness) is desirable for several applications, including understanding ice sheet dynamics. Since many different radar systems have been used, the existing radar data are also of variable data quality, e.g. in terms of the fidelity of the geolocation and the detection of the ice bed. If feasible, space-based ice sounding could provide a dense and homogeneous sampling with a uniform quality.

Due to the current ITU regulations, the lowest frequency that can be used for space-based Earth Observation is P-band (435 MHz). This is a higher frequency than commonly used for ice sounding, and the properties of the

ice sheets at P-band are not well understood. In order to close this knowledge gap, ESA has funded the development of an airborne P-band ice sounding radar, POLARIS [2], acquisition of P-band data in Antarctica [3], and a study of the feasibility of space-based ice sounding at P-band [4].

The primary aim of the feasibility study described in this paper is to assess whether the base of the ice sheet (i.e. the transition between the ice and the underlying ice bed) can be detected, though other ice sheet parameters are also of interest. In terms of methodology, return waveforms are simulated using an electromagnetic (EM) ice sheet model in combination with a radar system model. First, model parameters are estimated such that the waveforms simulated for key ice types match the corresponding waveforms that have measured with the airborne radar. Subsequently, another set of waveforms are simulated using the system model of a potential space-based radar, and the performance is evaluated by computing the signal-to-clutter ratio (SCR) and the signal-to-noise ratio (SNR) for the basal return.

2. ICE SHEET MODEL

An empirical EM model is used [5]. It is preferred to an analytical model because the EM parameters of the ice surface and base can be estimated directly from the airborne data, without first estimating the ice sheet's surface RMS roughness and correlation length. Such geometric parameters are of glaciological interest, but they are not needed for the feasibility study.

The EM model incorporates the two-way attenuation of the radar signal in the ice sheet, and includes contributions from:

- the air/ice interface
- the ice/bed interface
- the internal layers (isochrones)
- the volume clutter from the firn layer.

The ice sheet model was first developed in support of the design of the POLARIS radar, and subsequently it was upgraded, e.g. to include volume clutter modeling. The model parameters belong to three different categories:

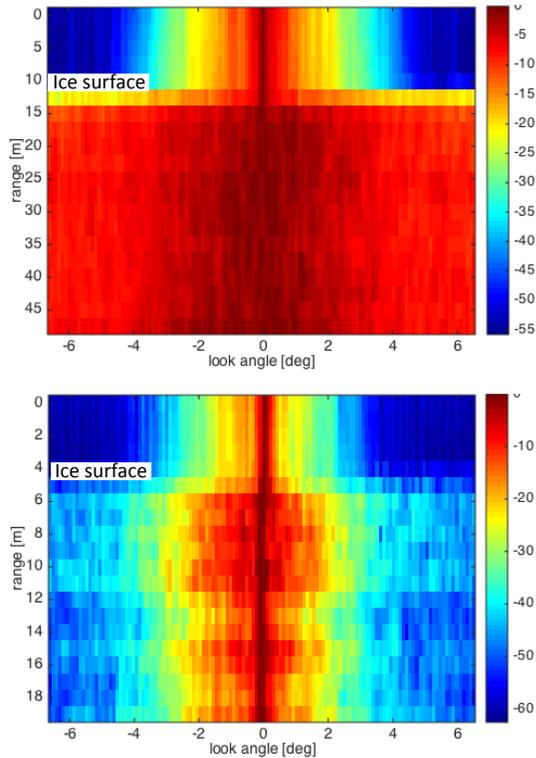


Figure 1 Normalized scattering patterns estimated for the ice shelf (top) and the EPICA ice core drilling site in Dronning Maud Land (bottom). Due to the range sidelobes the surface pattern is also seen above the ice surface.

1. Parameters estimated directly from the POLARIS data: Backscattering coefficients and scattering patterns of the surface, the firn, and the base.
2. Parameters estimated by matching the modeled waveforms to the measured POLARIS waveforms: Ice and firn thickness. Internal layer reflectivity.
3. Parameters obtained from other data sets: Attenuation coefficient.

The internal layers are considered specular reflectors characterized by a reflection coefficient normalized by the vertical resolution. Consequently the specular version of the radar equation is used.

The air/ice and ice/bed interfaces are considered surface scatterers characterized by a scattering pattern, which can be estimated by applying a Doppler analysis to the POLARIS data [5]. Using level-1 processed data, the effect of range migration and non-linear flight tracks can be neglected. The backscattering coefficients are obtained by normalizing the measured radar cross section by the area of the footprint, which is pulse-limited in the across-track direction and defined by the aperture synthesis in the along track direction.

The depth-averaged attenuation coefficient is obtained from an independent data set [6]. If the attenuation and the basal backscattering coefficient were both estimated from

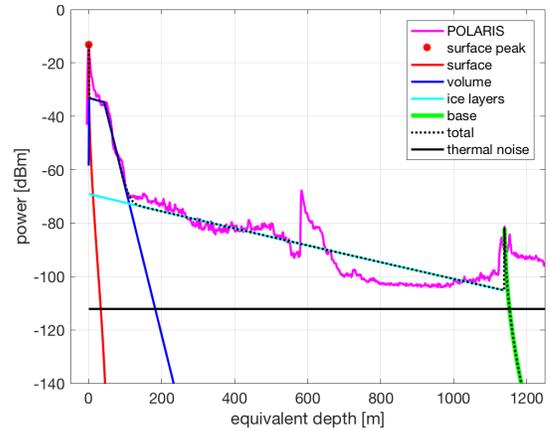


Figure 2 Comparison of two return waveforms generated with the scattering model and measured with the POLARIS radar, respectively. The contributions to the modeled waveform are shown separately. The peak at an equivalent depth of 600 m is a double bounce signal (between the ice sheet surface and the aircraft), which is not modeled.

the POLARIS data, the result would be ambiguous, because the estimation is subject to a single constraint in that the product of the two parameters is fixed in the radar equation, i.e. if one is estimated too high (or too low), so is the other.

Figure 1 shows the result of a range-Doppler analysis of POLARIS data from two different sites. The Doppler frequency has been converted into an along track look angle, and a normalization has been applied such that the maximum is unity at all ranges. The scattering pattern of the surface is narrow at both sites, whereas that of the firn is much wider at the ice shelf (probably due to ice inclusions in the firn). However, even the narrow scattering patterns are significantly wider than the pattern of a calm ocean surface. This suggests that the upper and lower interfaces of the ice are not specular reflectors at P-band, or at least that they have a significant scattering component. The width of the scattering pattern is crucial for the SCR, because the altitude of a space-based radar is too high for the antenna beam to suppress off-nadir clutter from the across track direction. (The aperture synthesis suppresses the clutter from the along track direction.)

Figure 2 shows an example of a waveform from the dry zone of Antarctica. The POLARIS waveforms typically have a “shoulder” next to the surface peak like in the figure, and Lewis et al. [7] have presented evidence of a relationship between the shoulder and the density gradient within the firn layer.

3. SIMULATION SCENARIOS

Once the EM parameters have been estimated at a given site the performance of a space-based radar at the same site can easily be assessed by changing the parameters of the radar model, i.e. by replacing airborne sensor parameters to those of a space-based sensor. However it is desirable to extend

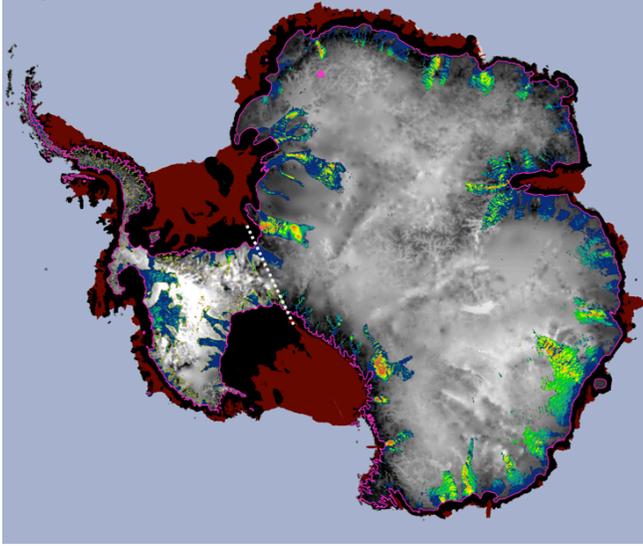


Figure 3 The principal regions of the Antarctic.

the assessment to the entire Antarctic continent. One way of doing this is to estimate the statistics of the EM parameters for a number of sites that are considered representative for key ice regions encapsulating the majority of the continent. Each region differs from the others in terms of the statistics of its EM model parameters and its geometry, e.g. ice thickness.

The principal regions of the Antarctic are shown in Figure 3. The pink polygon is the 1,000 m surface height contour, which encloses the dry zone, separating it from the wet zone, which occupies the exterior regions of the continent. Within the wet zone there are two sub-regions: the ice shelves (red), and the grounded ice (black) whose surface height is below the 1000 m contour. Within the dry zone two sub-regions are delineated by the 20 m/yr surface velocity contour. Ice velocities above the threshold are shown in a color representation. The white dotted line is the boundary between the East Antarctic Ice Sheet (EAIS) and the West Antarctic Ice Sheet (WAIS). Whilst the EAIS sits on an elevated craton the WAIS occupies a deep rift forming a marine based ice sheet, and the different regimes provide differing ice thickness and absorption distributions. For simplicity the relatively small region above 1000 m of the Antarctic Peninsula is included within the WAIS dry zone.

For each region a number of simulation scenarios are defined, based on the parameter statistics. A Monte Carlo simulation of the entire parameter space would be quite comprehensive, so in order to reduce the number of simulations, the scenarios are defined by the mean value for most parameters and the mean value \pm the standard deviation for parameters with particularly large variation.

Table 1 presents the statistics of the ice sheet parameters that are obtained from independent datasets [1], [6], [8]. The firn depth is defined as the depth at which a density of 830 kg m^{-3} is reached. Generally this depth matches quite

Table 1 Ice sheet parameters from independent datasets.

Region	Thickness [1]	Firn depth [8]	Attenuation [6]
Ice shelves	467 m ± 266 m	55 m	32.4 dB/km ± 11 dB/km
Grounded ice, $h < 1$ km	920 m ± 508 m	35 m	34.4 dB/km ± 12 dB/km
WAIS $h > 1$ km $v > 20$ m/yr	2032 m ± 795 m	58 m ± 14 m	36.8 dB/km ± 10 dB/km
EAIS $h > 1$ km, $v > 20$ m/yr	2057 m ± 708 m	57 m ± 11 m	24.8 dB/km ± 11 dB/km
WAIS, $h > 1$ km, $v < 20$ m/yr	1775 m ± 807 m	58 m ± 12 m	33.8 dB/km ± 7.6 dB/km
EAIS $h > 1$ km $v < 20$ m/yr	2499 m ± 802 m	73 m ± 16 m	23.8 dB/km ± 5.4 dB/km

Table 2 Selected ice sheet parameters from radar data.

Region	Surface σ^0	Basal σ^0	Layer refl. coeff.
Ice shelves	2.3 dB ± 0.9 dB	-1.4 dB ± 3.2 dB	-75 dB/m
Grounded ice $h < 1$ km	-2.5 dB ± 4.9 dB	-30.0 dB ± 3.9 dB	-104 dB/m
WAIS $h > 1$ km $v > 20$ m/yr	6.3 dB ± 1.0 dB	4.8 dB ± 5.3 dB	-61 dB/m
EAIS $h > 1$ km $v > 20$ m/yr	6.3 dB ± 1.0 dB	4.8 dB ± 5.3 dB	-61 dB/m
WAIS, $h > 1$ km, $v < 20$ m/yr	3.8 dB ± 3.5 dB	-21.7 dB ± 9.4 dB	-86 dB/m
EAIS $h > 1$ km $v < 20$ m/yr	3.8 dB ± 3.5 dB	-21.7 dB ± 9.4 dB	-86 dB/m

well the width of the POLARIS waveform shoulder. The attenuation is a two-way absorption coefficient accounting only for the ice conductivity [6], which is almost frequency independent across the HF and VHF bands. The attenuation caused by scattering is not accounted for, and this contribution is expected to (1) depend on the inhomogeneity of the firn/ice and (2) be higher at P-band than at the lower frequencies normally used for ice sounding.

Table 2 presents the statistics of the ice sheet parameters that are obtained from the POLARIS data. The standard deviation of the backscattering coefficients is estimated by analyzing large segments of radar data. The backscattering coefficients and reflection coefficients listed for the WAIS are the same as for the EAIS because no POLARIS data are available from West Antarctica. The basal σ^0 has a large region-to-region variation, and part of this variation could be due to attenuation estimates that are not valid at P-band.

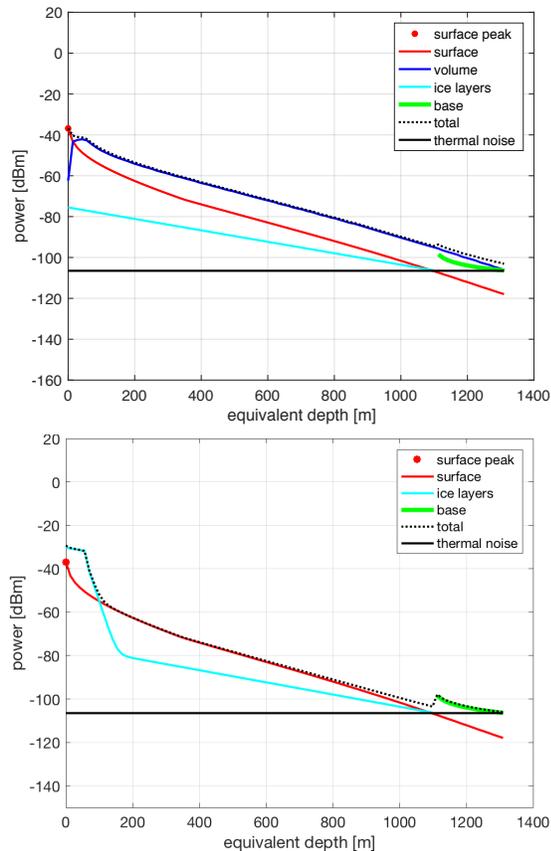


Figure 4 Return waveforms for a space-based ice sounding radar. In the top plot the ice sheet parameters are the same as in Figure 2, whereas the firm contribution is attributed to specular reflectors in the bottom plot.

4. RESULTS

Figure 4 shows return waveforms simulated for a P-band, space-based radar, which is similar to ESA’s Biomass mission radar in nadir viewing geometry. The ice sheet parameters in the top plot are those estimated from the measured waveform in Figure 2. In this example, the volume clutter prevents detection of the base, as its power level exceeds that of the basal return (and the surface clutter). In the bottom plot the firm is modeled as layers of specular reflectors, i.e. no firm contribution is received from off-nadir directions. The two sets of ice sheet parameters are estimated such that the same total waveform results for the airborne radar, but for the space-based radar there is a critical difference. The example shows the importance of modeling the wave interaction mechanisms correctly.

The satellite scenarios have been simulated with surface and firm contributions modeled in accordance with the scattering patterns estimated from the POLARIS data. For simplicity, the base is deemed detectable if the SNR and the SCR both exceed 0 dB.

5. CONCLUSIONS

This study has demonstrated that at P-band – in addition to surface clutter – within-ice volume clutter has a large potential to obscure the basal return. Volume scattering is most significant in the firm layer, the upper tens of meters of the ice sheet, where ice is not fully compacted.

Another important finding is that the upper and lower interfaces of the ice cannot be considered specular reflectors at P-band. A non-specular base has a stronger dependency on range, which adversely impacts the retrieval of the bed position and characteristics using the ESA Biomass radar configured for space-based ice sounding.

Almost 60 scenarios, which are believed to be representative for the entire Antarctic continent, have been defined and simulated. Clutter and/or thermal noise obscure the base in 2/3 of these scenarios. Additional studies are required to extrapolate and interpret these results in a continental context. Nevertheless, the Biomass mission is an excellent opportunity to be the world’s first in demonstrating feasibility of Antarctic ice sounding from space.

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