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ABSTRACT

In this paper the electromagnetic properties of the continental ice sheets are modeled with the aim of assessing the feasibility of space-based radar ice sounding at P-band. The paper focuses on the model itself, as distinct from the estimation of model parameters and the exploitation of the model. The scattering and propagation properties of the ice sheets are characterized using an empirical approach. The model comprises surface scattering from the air/ice interface and the ice/bed interface as well as volume scattering from the firn and the ice. Also specular reflection from the internal layers is modeled. In combination with simple models of the ice sounding radar and the geometry, the electromagnetic model estimates the return waveform and its constituents, such that sensitivity and clutter masking issues can be assessed.

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

1. INTRODUCTION

Space-based radar sounding of the continental ice sheets can potentially offer full coverage, uniform data quality and sampling. Ice sounding radars must operate at low frequencies in order to ensure low attenuation of the signal as it propagates down through the ice and back from the base of the ice sheet. Typical frequencies of airborne radar ice sounders are 60 MHz and 150 MHz. However, the lowest possible frequency for space-based radar ice sounders is 435 MHz. In 2004 the radio regulations of the International Telecommunication Union (ITU) allocated a 6 MHz band at 435 MHz (P-band) enabling space-based Earth observation radar missions at a frequency that might be applicable for ice sounding.

This paper describes a backscattering and propagation model for radar sounding of ice sheets. The model was originally developed in parallel with the design of the Polarimetric Airborne Radar Ice Sounder (POLARIS) [1], but subsequently the model has been upgraded in order to assess the feasibility of space-based radar ice sounding. For that a two-step approach is applied:

(1) Key ice sheet model parameters are estimated from airborne POLARIS data acquired in Antarctica.

(2) The performance of a potential space-based ice sounding radar is estimated based on the ice sheet model, the parameters of the space-based and the data acquisition geometry.

At P-band the attenuation and scattering properties of the ice sheets are not as well known as they are at the lower frequencies commonly used from aircraft, but in 2005 the Technical University of Denmark was commissioned by ESA to development the POLARIS system [1], and encouraging results were obtained with data acquired in Greenland. In February 2011 POLARIS data were acquired in Antarctica as part of the IceGrav campaign [3], the primary objective of which was to measure gravity in Queen Maud Land, but a secondary objective was to acquire P-band sounder data, benefitting from the large coverage offered by the Basler DC3 aircraft used.

2. METHODOLOGY

The backscattering and propagation properties of the ice sheets can either be characterized empirically, or with analytical models like the Kirchhoff Model [4], the Small Perturbation Model [4], and the Picardi model [5]. The analytical approach is preferable if physical parameters like surface roughness and correlation length are of interest, but the analytical approach may be too simplistic for low frequency mapping of complex media like ice sheets. For the purpose in question the empirical approach suffices, i.e. the model parameters are surface and volume backscatter coefficients (including their angular dependency), reflection coefficients (for specular interfaces), and attenuation coefficients (accounting for both absorption and scattering).

The model parameters are estimated by tuning the parameters such that the modeled radar return waveform matches the measured POLARIS waveform. This procedure requires as input (1) the POLARIS system parameters and the data acquisition geometry, (2) scattering patterns estimated directly from the Doppler spectra of the POLARIS data (cf. Figure 1), and (3) ancillary data, i.e. ice sheet parameters from various observational studies. The parameter estimation methodology is presented in [2].
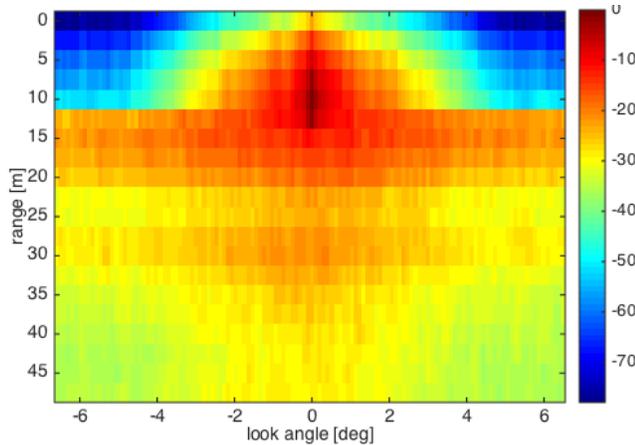
Figure 1 Scattering pattern of an ice shelf surface and the underlying firn layer (color scale in dB). The surface is at a range of 10 m.

3. RETURN WAVEFORM CONTRIBUTIONS

The ice sheet model can be combined with a radar system model in order to generate waveforms representing data that are either unfocused or focused and migration corrected in the along track direction. It is easy to compensate for the along track antenna pattern during focusing, but the resulting waveforms are still impacted by the variation of the scattering pattern within an angular interval defined by the synthetic aperture.

The contributors to the return waveform are the ice surface, the ice bed, internal layers (isochrones) and diffuse scatterers in the firn and in the ice. Figure 2 shows the geometry in the cross track plane. The pulse-limited foot-print on the ice surface is an annular ring in the unfocused case and two small rectangles (to the right and to the left of the nadir point) in the focused case.

Internal layers contribute a signal with a very narrow scattering pattern (reflection only in the direction perpendicular to the surface), whereas diffuse scatterers result in a volume contribution with a wider scattering pattern (volume clutter). When using airborne data to assess the feasibility of space-based ice sounding it is important to discriminate between a near-nadir contribution and a surface (or near-surface) contribution with the same equivalent depth, i.e. the same two-way time delay. Surface clutter (or near-surface volume clutter) at a given incidence angle coincide with a much deeper nadir signal in the satellite case than in the aircraft case, and since the depth signal of interest is much more attenuated, it is likely to be masked by the clutter.

A narrow scattering pattern in combination with a small attenuation coefficient implies that most of the volume clutter is coming from near nadir, and it could actually be modelled like the contribution from the internal layers
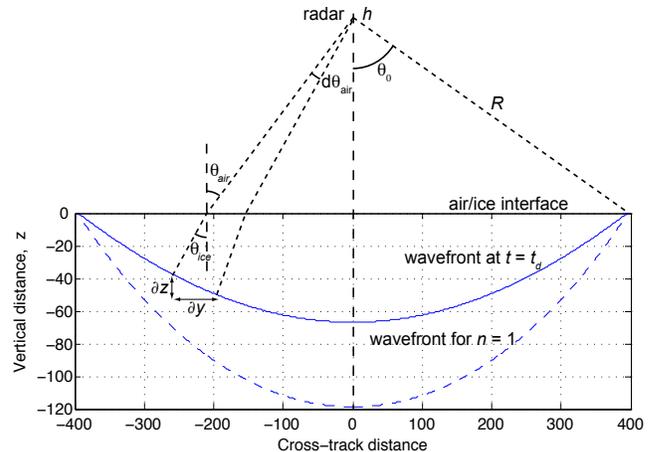

Figure 2 Ice sounding geometry. The dashed line illustrates the circular wavefront that would result if the ice had a refractive index of $n = 1$.

(except for the different geometric spread). On the other hand, a wide scattering pattern implies significant volume clutter from the off-nadir, near-surface part of the slant range cell illustrated with the solid blue line in Figure 2.

3.1. Surface contribution

The surface clutter contribution is computed from the radar equation and the radar cross section, which in turn is the product of the surface backscattering coefficient σ^0_{surf} and the area of the resolution cell A_{surf} (annular ring or two rectangles for unfocused an focused data, respectively)

$$\sigma = \sigma^0_{surf}(\theta) A_{surf}(\theta) \tag{1}$$

Once $\sigma^0_{surf}(\theta)$ is estimated from the airborne ice sounder data, σ can be computed for the satellite case using the system parameters of the space-based radar.

3.1. Bed contribution

Likewise, the bed signal is computed from the radar equation and the effective radar cross-section, which in turn depends on the two-way transmission coefficient at the air/ice interface and the attenuation that results from the two-way propagation through the ice. The model supports a depth-dependent attenuation. The refraction at the air/ice interface has a focusing effect, which is taken into account by including a refraction gain [6].

3.1. Volume clutter contribution

The volume clutter of a resolution cell in focused data is computed by integrating the power along the solid blue line in Figure 2.

$$P_V \approx \frac{\lambda^2 G_g P_t}{(4\pi)^3 R^4 L_{tx}} \int_{\theta_{air}=-\theta_0}^{\theta_0} G(\theta_{air})^2 \sigma_{eff}^0(z,\theta_{ice}) \, dV \qquad (2)$$

The parameters are:

λ wavelength
G_g refractive gain
P_t transmit power
R range (electrical distance)
L_{tx} system loss
G antenna gain
θ_{air} cross track angle in air
θ_{ice} cross track angle in ice
θ_0 clutter angle = incidence angle at surface
z equivalent depth (nadir depth corresponding to a given time delay)

The effective backscatter coefficient is:

$$\sigma_{eff}^0(z,\theta) = G_g(\theta)\left(1 - R_{01}^2(\theta_0)\right)^2 E(z,\theta) \sigma_{vol}^0(z,\theta) \qquad (3)$$

It incorporates:

- the refraction gain G_g
- the two-way transmission coefficient of the air-ice interface $\left(1 - R_{01}^2(\theta_0)\right)^2$
- the attenuation (or extinction) caused by two-way propagation through the ice $E(z,\theta)$
- the backscattering coefficient (radar cross section per unit volume) $\sigma_{vol}^0(z,\theta)$.

Eq. 3 is an approximation neglecting the along track variation of the backscatter coefficient within the synthetic aperture.

Figure 3 shows an example where the volume backscattering coefficient is depth independent and has a cosine dependency on the incidence angle. The nulls of the antenna pattern show up in blue. The contribution of the volume clutter to the return waveform is computed by integration over all look angles at each equivalent depth, i.e. by row-wise integration in Figure 3.

3.1. Internal layer contribution

The internal ice layers are considered specular reflectors. The specular version of the radar equation is

$$P_L \approx \frac{\lambda^2 G_g G(0)^2 \Gamma(z) E(z,0) P_t}{(4\pi)^2 (2R)^2 L_{tx}} \qquad (4)$$

Here $\Gamma(z)$ is the subsurface Fresnel reflectivity at depth z, i.e. the reflection coefficient of the interface between two internal layers with refractive indices n_1 and n_2
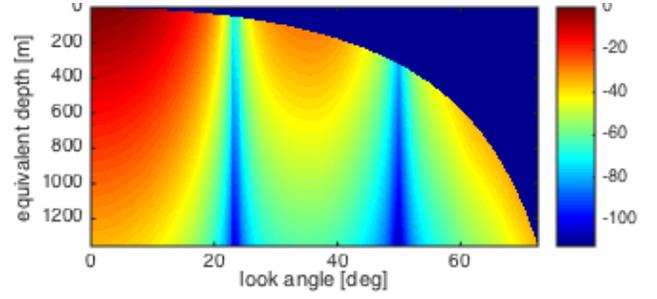

Figure 3 Volume clutter example (color scale in dB). The blue area in the upper right corner represents the air, and the remainder of the plot represents the ice (the equivalent depth of the surface increases with increasing look angle).

$$\Gamma(z) = R_{12}^2 = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2 \qquad (5)$$

Mirroring the radar in the reflecting surface, Eq. 4 can be interpreted as the result of a one-way propagation geometry with twice the range and a transmission coefficient given by the Fresnel reflection coefficient of the internal ice layer. The specular version of the radar equation does not involve any integration, as the reflection is effectively confined to the first Fresnel zone, which is so small that the antenna gain can be considered constant.

The estimation of $\Gamma(z)$ and $E(z,0)$ from the return waveforms of an airborne ice sounder is ambiguous, as only the product of the two parameters is observed. The same applies to the product of the basal backscatter coefficient and the two-way attenuation. The ambiguity is not a problem when assessing the performance of another (space-based) radar at the location, where the ice sheet parameters were estimated, as the ambiguous parameters also appear as a product in the radar equation for that radar. The ambiguity is more problematic when assessing the performance at another location, and consequently various observational studies are used for regularization [2] by providing estimates of dielectric absorption [xx], firn depth [yy] etc.

3. RESULTS

The model has been implemented in Matlab. The runtime depends on the ice thickness and the number of range cells, but it is typically a few seconds, and it is dominated by the volume clutter computation, due to the integration over the extent of each range cell.

Figure 4 shows an example where a measured and a modeled return waveform are compared. The peak at 1130 m is the basal return. The peak at 600 m is irrelevant, as it is an artifact caused by double bounce reflection (ice – aircraft – ice). The "shoulder" next to the surface peak is due to the firn, which typically has a high intensity. In this
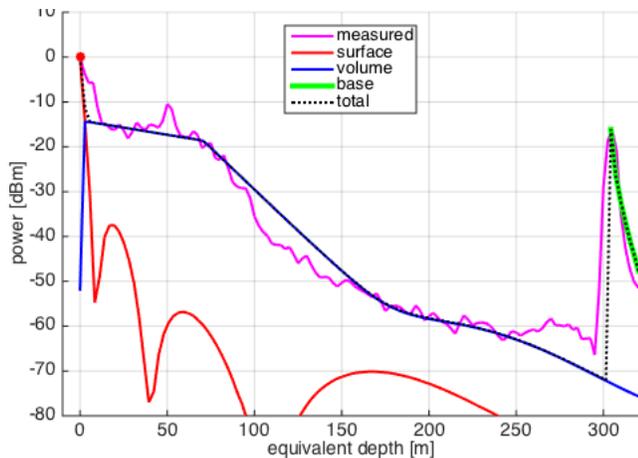
Figure 4 Return waveform measured with POLARIS over the ice shelf, Queen Maud Land, Antarctica. The modeled return waveform (black dotted) is the sum of the contributions from the surface, the volume clutter, and the bed. The measured and the modeled waveforms are both normalized to a maximum of 0 dB.

case the firn contribution is modeled as specular reflection from internal layers, because such layers are visible in the radargramme, and the scattering pattern of the firn is narrow. This is seen when comparing Figure 1 and Figure 5.

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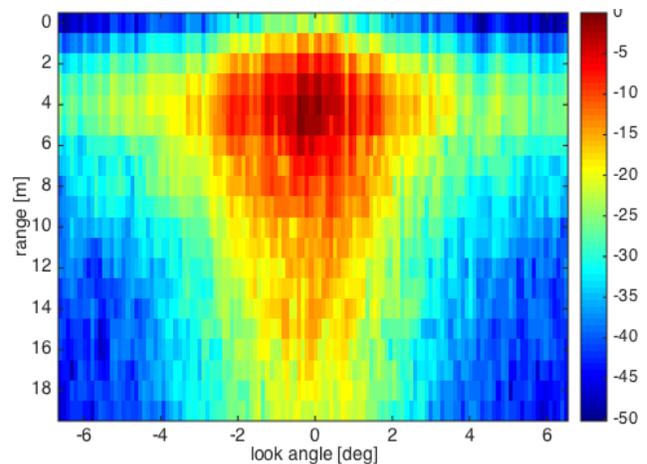
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