A forward scattering and propagation model for Antarctic ice sheet investigations

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Summary A forward scattering and propagation model has been developed with the primary intent to investigate the feasibility of sounding the Antarctic ice sheet using a spaceborne radar system. The use of the model is also envisaged for support and interpretation of airborne ice sounding or ground penetrating radar (GPR) data. In principle, the model could also be used to support planetary radar sounding missions, for example, including those for Mars. The model computes the time-pulsed backscattered response from a very large 3D volume which includes a series of user-defined gridded layers representing the ice surface, bedrock, intermediate ice layers and other possible material that may be found within the ice, e.g. volcanic ash. Earth curvature, large-scale topography, undulations or sastrugi are taken into account in the elevation of each elementary grid cell. Presented simulation results are compared with actual data (GPR or airborne radar sounder data) in order to demonstrate the overall validity and functionality of the model. The model architecture is such that it allows input description of both the ice sheet and instrument characteristics ranging from very simple (for demonstration) to very complex (for the expert users).

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Introduction

Currently, remote sensing of the Earth from space is usually limited to a thin superficial surface layer. However many issues related to climate change studies, Earth resources or risk monitoring require information over a greater range of depths below the surface. Radars operating at low frequencies offer, under certain circumstances, the possibility of imaging through weakly conductive material down to the bed(rock). Airborne and ground based radar campaigns in the Antarctic have shown that not only the bed beneath 4.5 km of ice can be sounded but also sedimentary layers can be imaged and followed. However, to model global ice sheet dynamics and mass balance (accumulation of snow and losses through melt and iceberg calving) over longer periods (100 to a few 100'000 years), it is mandatory to have a complete coverage of the Antarctic and Greenland ice sheets with observations of homogeneous quality, which can be best accomplished using a spaceborne platform. The forward scattering and propagation model described in this paper forms a significant contribution towards the assessment of the overall feasibility for a spaceborne ice sounder and the possibility that this data can be inverted to extract parameters for the identification of ice layers and the determination of the bedrock depth under different temperature and surface roughness regimes.

The science questions being asked by the climate and glaciological communities, which such a satellite mission could help answer, broadly fall under the topic areas described in (Rommen et al., 2004) which are briefly recalled here:

1) Better estimates of ice sheet thickness and topography are needed for more accurate assessments of different glaciological contributions to the total ice discharge to the ocean. The resulting mass balance drives a major part of the sea level variations. Furthermore, the retrieval of internal horizons and isochrones can be used to assess historical variation in ice sheet snow accumulation, and thus can be correlated to the historical variation in sea level.

2) The understanding of the connection between the Earth's paleo-climate and past evolution of the Antarctic ice-sheet: Using ice-core dating and coupled climate/ice-dynamical modeling, the past evolution of the ice-sheet is analysed. In such analyses, large climate events are identified and their effects on the ice-sheet evolution are examined. There is also the un-answered question of the origin of the Antarctic ice-cap in the history of the Earth and its reversibility. The study of the past evolution also provides some degree of validation to the ice-dynamical model.

3) Understanding the present evolution of the ice-sheet as a function of the past and present climate forcing: The Antarctic ice-sheet is in a transient state due to the Holocene warm wave event, some 11,000 years ago. Thus, the understanding of the present evolution can only be gained through the use of the ice-dynamical model driven by the climate forcing from the past to the present time. The ice-dynamical model is validated by using wide variety of observations available today and in the near future by those from the proposed satellite mission.

4) Predicting the future evolution of the ice-sheet: A prediction of the future evolution of the Antarctic ice-sheet requires a thorough understanding of its dynamics under past, present and future climate forcing due to its very slow response time. The key tool to be used for this prediction is the ice-dynamical model, validated through the observations of the paleo-climate and present day evolution of the Antarctic ice-sheet.

Model architecture

The full capability and complexity of the model is best explained using the flow chart depicted in Figure 1. The input 'radar system parameters' allows full description of the end-to-end radar system such as operating frequency, duty cycle, polarisation, peak power, antenna gain diagram, etc., etc. The user is able to select either to use a simple set of parameters to define the topography, or to enter a digital elevation map (DEM), for all medium descriptions (i.e., air/ice interface, internal ice layers and bed conditions). The 'facet generation' module generates an ensemble of facets (each characterised by position, surface area, normal vector and complex radar scattering cross-section), which is electromagnetically equivalent of the input ice-sheet topography wherein each surface/layer is represented by a sub-ensemble of facets. The 'propagation path, antenna gain and radar cross-section calculations' module forms the heart of the simulator, which computes the following parameters:

- determination of the propagation path between the radar and a facet, with due account of the Fresnel refraction effect at the ice-surface;
- determination of the corresponding two-way propagation delay;
- determination of the antenna gain along the propagation path;
- determination of the complex reflected and refracted signal at the ice-surface as a function of the incident wave polarization (for both the transmission and reception paths);
- determination of the incidence angle at the facet;
- determination of the complex radar cross-section of the facet as function of incidence angle and polarization;
- determination of the Doppler shift associated with the facet

The 'echo calculation for a facet' module computes the radar-echo from a facet, using the propagation parameters as determined by the 'propagation module'. This is computed through complex scalings, time-delaying and phase-setting

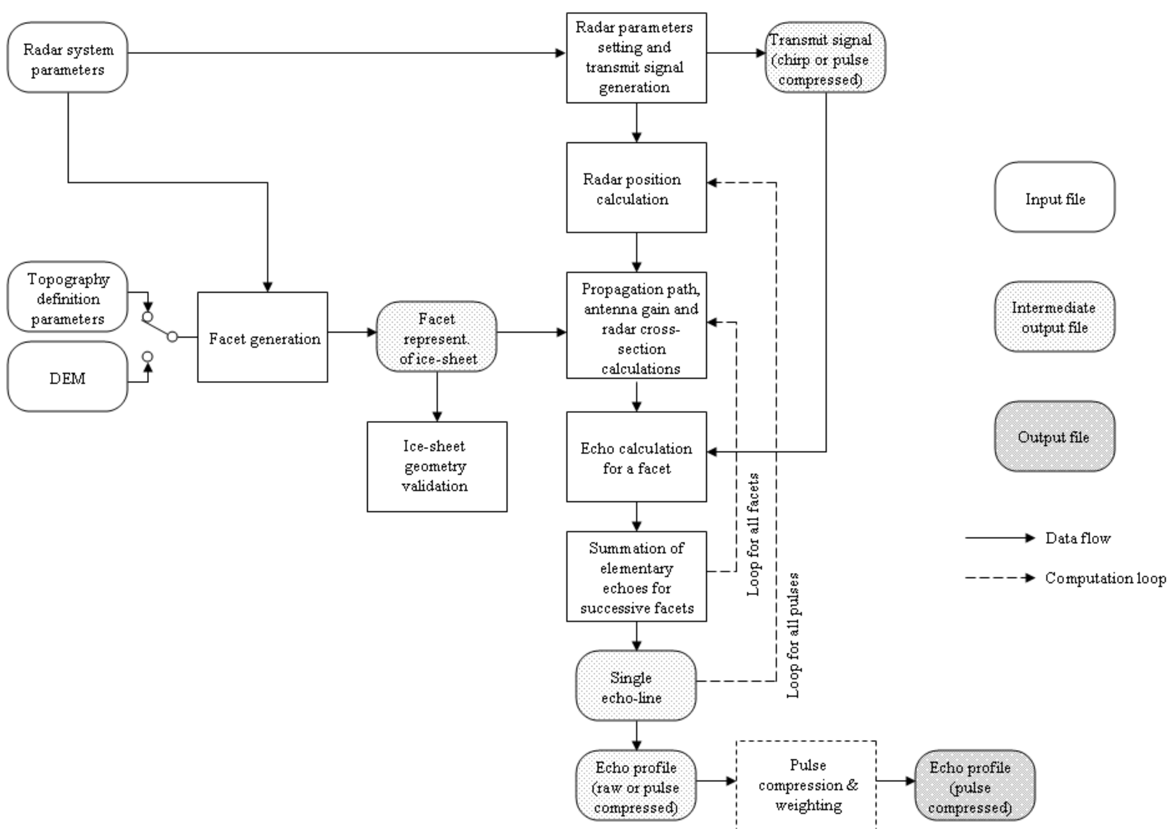

Figure 1. EM model flowchart

of the transmit signal with due account of Doppler shift. The carrier frequency is taken into account in the phase-setting. The result is an elementary echo appropriately placed within an echo-window. A computation loop is implemented in order to calculate the time-resolved echoes for all facets that once summed provide a single echo line. The process can be repeated to arrive to the echo profile (raw or pulse compressed), containing all echo-lines collected during a simulation run (from t = 0 to t_{final}). In cases where a compressed pulse was used as a transmit signal, the resulting echo-profile would be final. When a chirp transmit signal was used, then the echo-profile would be raw.

Model implementation

Each possible scattering surface (air/air interface, volcanic ash deposit layers, ice layers, bedrock/ basal condition) is described by a grid of adjoining planar facets. The number of facets and their size can be defined by the user – thus setting up the overall simulation domain - , taking into account the validity region for the dimensions of the individual facets, which is constant across the simulation domain. The topography of the terrain is described by the height and orientation of the facets. For example, a series of facets can be set up to follow the contours of an undulating sine wave, a flat plane, or a specific user defined topography.

In addition to the topography, each facet has its roughness defined by its RMS height and its correlation length.

The impinging wave on the first interface (the air/ice interface) will interact with these surface facets. For each facet the contribution backscattered to the radar is calculated, using the Kirchhoff approximation, taking into account the orientation, polarisation and roughness parameters. Also the amount of radiation penetrating into the ice volume is calculated, again taking into account the orientation, polarisation and roughness parameters. The transmitted wave into the ice sheet propagates downwards using a ray-tracing technique and interacts with internal layers encountered. The user can define as many layers as required at different depth. Each layer between the air/ice interface and bed has a complex permittivity defined by the user.

For the purpose of limiting the computational complexity, the volume between two consecutive layers is considered as homogeneous and is only responsible for the extinction and phase shift of the radar return for the areas in between the layers. This assumption together with the ray tracing from the air/ice interface to a given layer is believed to be valid for the largest portion of the Antarctic ice sheet where the intermediate layers are very weak reflectors and do not significantly affect the downward-propagating wave.

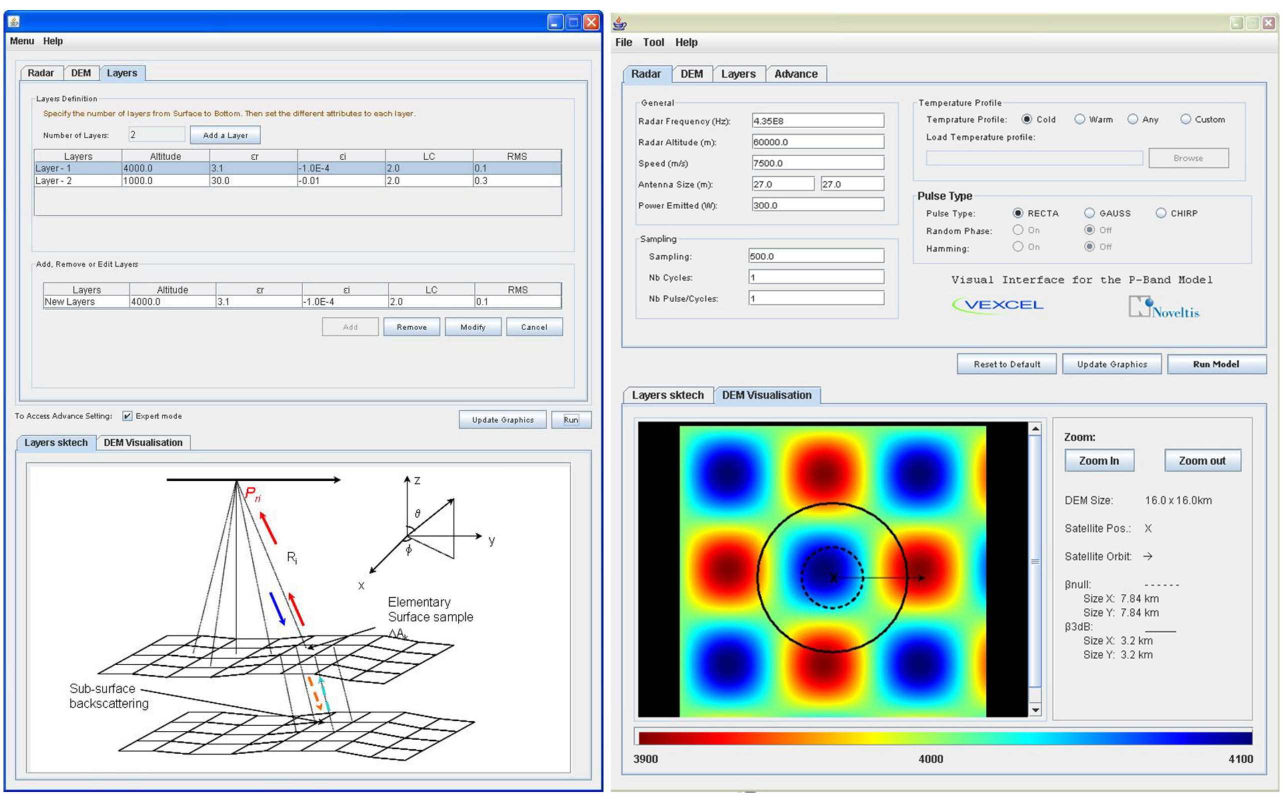

Figure 2. The algorithm user-interface, showing the definition of two interfaces with roughness parameterisation (left image) and the radar input parameters and DEM visualisation (right image).

As has been described in literature, the AC-conductivity of Antarctic/Arctic ice is basically dependent on 2 factors: the temperature and the impurity concentration. The conductivity (and thus the attenuation) is greatly impacted by the temperature of the ice sheet. Therefore, to calculate the overall wave attenuation throughout the ice sheet thickness, aspatially dependent temperature profile, from which an attenuation profile is calculated, can be input in the model. There are a range of satellite and radar parameters that can be defined by the user. These include: the satellite altitude, velocity, antenna dimension, radar transmit power, PRF, radar bandwidth, antenna gain, polarisation, pulse type (rectangular, Gaussian or chirp). The model output consists of the complex electromagnetic field as recorded at the receiver output at baseband as a function of time, which can be examined in a variety of ways. A train of pulses for a moving satellite can be simulated, so that additional processing techniques can be applied to the returned time resolved echoes that include Doppler information.

Preliminary results

As the model is currently undergoing final steps of validation, a number of consistency checks have been performed including the absolute level of the echo power and convergence analyses for increasing number of facets for a given scenario (quantitative analyses), and to examine the behaviour of the model for increasing complexity of topography and surface roughness (qualitative). Returns from subsurface layers (including bed) arrive with the correct delay and amplitude. Therefore, it can be concluded that the model is reliable with respect to power consideration and geometry. The model is capable of calculating results both from a single pulse (Figure 3) and from a sequence of pulses stacked as a radio echogram (Figure 4). For this preliminary test, the speckle effects usually present in echo-signals have been switched-off.

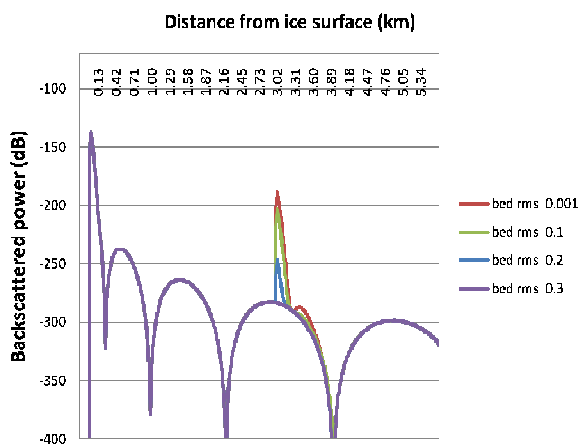

Figure 3. Varying echoes from the bedrock (3km) for varying roughness parameters.

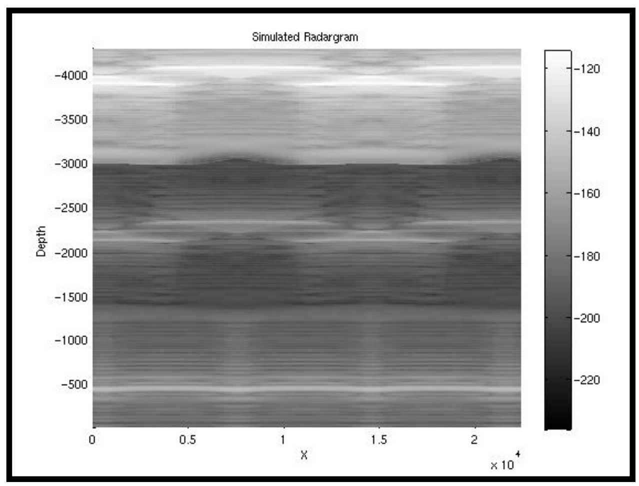

Figure 4. Stacked pulse echoes for a gentle undulating topography.

The shown results, when the effects of speckle included, do not take into account any additional processing and can thus be seen as the raw retrieved data including both coherent and incoherent components. This enables a wide variety of unfocused and focused SAR and other processing techniques to be examined, in order to increase the signal-to-clutter and signal-to-noise ratios as if it were real airborne or spaceborne radar echo sounding data.

Summary

In this paper, an overview has been given on a forward scattering and propagation model development representative for the Earth's ice sheets, especially tailored for the Antarctic case as a first attempt to evaluate the feasibility of a spaceborne ice sounder operating at UHF (435 MHz). In order to enable the large simulation domains (> 100 km × 100 km × 4 km), a number of assumptions had to be made in order to arrive to a computationally solvable 3D EM model. The computational effort is roughly proportional to the number of grid points (~5,000 grid points/second on a standard desktop computer). For the case of the Antarctic ice sheet, the assumptions are thought to be valid for radar frequencies used by airborne, GPR and future spaceborne ice sounders. In short the model's main achievements are the following:

- Compute the complex backscattered signal at the receiver output as a function of time;
- Be consistent with respect to the power conservation consideration;
- Compute coherently backscattering arriving from the different interfaces;
- Integrate the off-nadir echoes responsible of the surface clutter signal;

- Take into account the variation of the radar wave speed and refraction during the spreading of the pulse inside the ice layers using ray-tracing;
- Take into account the losses due to absorption and scattering in each layer encountered during the two-way propagation of the radar-pulse;
- Take into account the Doppler frequency-shift of the echo from each illuminated point simulated within the radar footprint to allow different processing techniques such as Doppler filtering;
- Inherent modularity to allow for future adaptations and evolutions;
- Allowance to model various geometries, including those that are the most representative of the Antarctica.

References

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