DEVELOPMENT OF SPACEBORNE SOOP REFLECTOMETRY MODEL FOR COMPLEX TERRAINS

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ABSTRACT

Following the launch of multiple global navigation satellite system (GNSS) reflectometry (GNSS-R) missions, the Signals of Opportunity (SoOp) method has proven to be a powerful tool for geophysical parameter retrieval for land applications such as soil moisture. Having demonstrated the feasibility of the SoOp techniques at P- and S-band, the development of SoOp measurements beyond the GNSS frequency regime is highly anticipated. The SoOp Coherent Bistatic (SCoBi) model and simulator, developed in 2017 and open-sourced in 2018, has been made available to provide multi-frequency, fully polarimetric SoOp simulations for ground-based applications through the joint use of analytical wave theory and distorted Borne approximation to evaluate land contributions from multilayer dielectric profiles composed of soil moisture, vegetation, and surface roughness effects. This paper describes the advancement of SCoBi from a ground- and airborne-based model to a spaceborne model. This extension allows for fully polarimetric, complex delay-Doppler map (DDM) simulations through evaluation of the coherent superposition of electric fields emerging from a grid of oriented facets. The model generates a grid of facets by determining the geometry of contributing elements from digital elevation models, with each element providing its contribution under a flat-earth assumption. This module will enable the analysis of fully polarimetric scattering from frequencies available across the ultra-high frequency (UHF) regime.

***Index Terms*—** Signal of Opportunity, discrete scatterer, UHF, land applications, forward model, surface topography

1. INTRODUCTION

Physical models play a leading role in understanding the physical mechanisms involved in bistatic scattering from space and identifying surface features mainly contributing to the observed signal. They also enable the study of landscape variations under user-defined configurations to conduct uncertainty analysis to determine optimal cases for specific applications/missions. With these goals in mind, we have developed a generalized, fully polarimetric forward model: the SoOp Coherent Bistatic Scattering (SCoBi) model [1]. It is a robust framework which allows for the modeling of many SoOp system variables and scattering surface parameters. The SCoBi model is publicly available and has been designed to be highly configurable to allow for additional modeling features [2]. The model has been successfully applied to forest [1], agricultural fields [3], and root-zone SM studies [4, 5].

The SCoBi model was originally developed for ground-based and low-altitude instruments to support field experiments. However, in the case of spaceborne geometries, the reflected signals emanate from a much larger area, and the impact of Earth curvature and topographic relief needs modeling consideration. The modeling topography in bistatic scattering from space has been studied for Global Navigation Satellite System Reflectometry (GNSS-R) applications in recent published works [6–9]. For instance, Gu et al. [8] studied the electromagnetic scattering of random rough surfaces superimposed on many levels of elevations using the Kirchhoff integral as first-principle. Zhu et al. [9] applied a physical patch model for faster computation of the Kirchhoff integral. Campbell et al. [7] developed a Digital Elevation Models (DEM)-based model for GNSS-R measurements of a bare surface in the geometric optics limit of the Kirchhoff approximation. Dente et al. [6] presented and validated an upgraded version of previously developed model (called the Soil And VEgetation Reflection Simulator (SAVERS)), suitable to simulate GNSS-R signals received by space-borne sensors. Distinct from aforementioned methodologies, this upgraded SCoBi model generates ”complex” delay-Doppler map (DDM) to investigate coherence. As of writing, a modeling tool that simulates non-GNSS SoOp signals from land surfaces does not exist in the literature. The simulation of complex DDMs is important in particular for NASA's SigNals of Opportunity: P-band Investigation (SNOOPI) on-orbit demonstration of remote sensing using P-band SoOp as it is designed to produce observables, based upon the correlation of direct and reflected signals, allowing the estimate of the complex reflection coefficient (magnitude and phase) at the surface.

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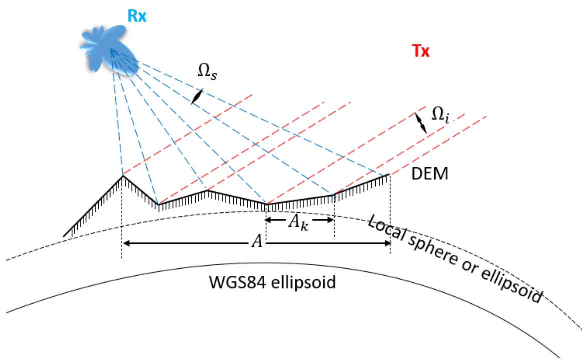

Fig. 1. The illustration of spaceborne SoOp configuration over topographic relief. DEM consists of a rectangular grid with elevation assigned to each grid point. Unique surface features can be assigend to each facet, depending on the land cover type.

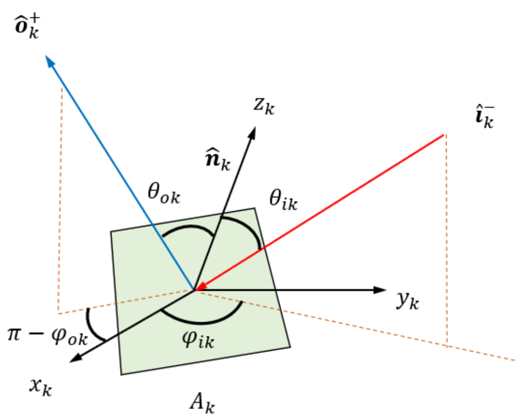

Fig. 2. Facet configuration.

This paper outlines the development of an upgrade to the current SCoBi model and simulator. The upgraded model will enable spaceborne simulation and analysis of SoOp signals across ultra-high frequency (UHF) regime. A simulation study comparing the response of two SoOp frequencies over varying topography will be presented.

2. FORMULATION

This spaceborne implementation of SCoBi builds upon the model's architecture by incorporating topography and full DDM processing. The primary focus of this extension is to enable analysis with respect to topographical relief, spherical Earth surface scattering, and incoherent contributions from surface roughness effects. The key features of the SCoBi model and developments are (1) to supply phase information for raw data investigations, (2) the ability to simulate heterogeneous scenes including mixed vegetation, water bodies, and topographic relief, and (3) to provide a formulation based on an open-sourced physical SoOp model which can contribute to the reproducibility of scientific efforts, technology validations, and replicability of our simulation studies.

In order to maintain phase and amplitude from the underlying Earth surface, the original SCoBi formulation, which works on a single plane wherein the transmitter and receiver are aligned along the x-axis and the z-axis represents the Earth surface normal at the specular point, communicates with the vector formulation of the transmitter, receiver, and specular point system in an earth-centered, earth-fixed (ECEF) coordinate system. From the ECEF frame, Earth's topography can be determined along a WGS84 ellipsoid through pairing with a DEM. The simulation region for a given configuration is determined by creating an equally-sized grid centered on the specular point that is dependent on the bistatic geometry and antenna pattern as shown in Fig. 1. The grid itself is composed of facets which form equally-sized square elements when projected onto the plane that is tangent to the specular point's normal vector with respect to the underlying local ellipsoid, determined as the elevation above the WGS84 ellipsoid at the specular point. With respect to the facet center, surrounding DEM grid centers provide aspect and slope angles which can be used to transform the facet into a coordinate system compatible with the original SCoBi formulation [1]. Since the absolute phase (complex electric field) of the received signal is preserved in SCoBi, the received total reflected signal will be a coherent superposition of contributions from each facet as is done in [10]. The relative orientation of the facet receiver geometry is explicitly included through the polarization basis rotation matrices. The change in local incidence/scattering angle due to change in surface slope and polarization mixing due to tilting out of the plane of incidence can also be accounted within the SCoBi framework. In addition, Doppler is another source of phase shift, and the coherent nature of the SCoBi model is suitable to handle complex DDM calculations.

These features would be useful for not only providing realistic simulation results over most Earth terrain from spaceborne geometries, but also for determination of spaceborne SoOp instruments' spatial resolutions that vary depending on the nature of scattering. It is, thus, important to identify contributing Fresnel zones and the scattering mechanism not only to determine the footprint, but also to arrive at physical observables that are suitable for inversion. The analysis of the physically consistent model predictions will be used to investigate the modeling deficiencies of the physics-based model in detail.

3. SIMULATION SETTINGS

The initial simulation study presented in this paper will analyze the distinct response of land surfaces with respect to multiple frequencies. In this study, GNSS signals (1575.42 MHz) and P-band signals (240 – 380 MHz) will be analyzed to visualize what unique features can be seen in both existing GNSS-R datasets such as TDS-1 and CYGNSS as well as forthcoming P-band datasets such as SNOOPI. Two surfaces of varying topography will be used for analysis. The GNSS response will be compared to measured DDMs from NASA's CYGNSS L1 datasets.

Two sample DEMs representing an area of low topography and moderate topography will be used for analysis of the dual-frequency response to L- and P-band signals at RL polarization (a right-hand circularly polarized transmitter and left-hand circularly polarized receiver.) The simulation scene will take place over the midwestern United States. The full, complex DDM of the simulation scene will be generated, and the resulting coherent and incoherent response will be segregated using the methodology described in Section 2. Additionally, the simulated L-band DDM will be compared to physically measured DDMs taken from CYGNSS observations. For comparing L-band and P-band simulated DDMs, the simulation scene will make use of interpolated 1-arcsec (≈30m) Shuttle Radar Topography Mission (SRTM) DEMs available for the United States (https://doi.org/10.5066/F7PR7TFT). For comparison with CYGNSS DDMs, this DDM will be regridded to 300m. Contributions which potentially stem from surface heterogeneity will be identified using the Moderate Resolution Imaging Spectroradiometer Land Cover Type (MCD12Q1; https://lpdaac.usgs.gov/products/mcd12q1v006/).

4. CONCLUSIONS

As research interest in SoOp for land applications increases, the need for comprehensive modeling tools becomes more pronounced. This study will showcase an initial simulation study using an enhanced, spaceborne-capable upgrade of the SCoBi model. This SCoBi extension will enable DEM implementation, topography analysis, and "complex" DDM simulations. Distinct from existing methodologies in the literature, this upgraded SCoBi model uses a novel approach for calculating the response from land surfaces that preserves amplitude and phase. Individual contributions from each simulated facet is determined in its own local coordinate system, and the received signal's amplitude and phase is preserved through a coherent summation of the complex fields emerging from each facet. The incoherent contributions of the surface are determined through Monte Carlo simulations of the simulation scene's topography. This approach for modeling SoOp interaction with land surfaces is expected to be the first fully polarimetric, anaytical wave theory-based method available in the literature that is applicable for UHF frequencies. Preliminary results of the multifrequency response to sample topography will be presented.

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