Relationship Between Bistatic Radar Scattering Cross Sections and GPS Reflectometry Delay-Doppler Maps Over Vegetated Land in Support of Soil Moisture Retrieval

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ABSTRACT

This paper presents the application of a coherent bistatic radar scattering model from vegetated terrains and the extension of the model to circularly polarized incident wave cases for GNSS signals. It will then present an analysis relating the bistatic scattering Radar Cross Sections (RCS) of vegetated land cover to the customary Delay Doppler Maps (DDMs) resulting, e.g., from GNSS reflectometry (GNSS-R) observations. This step is key in being able to use GNSS-R data in soil moisture retrieval algorithms. While some analyses exist for this purpose for scattering from sea surface, such analysis has not been carried out specifically for vegetated land surface. The proposed model and methods are envisioned to be applied to the airborne GNSS Reflectometer Instrument for Bistatic SAR (GRIBSAR) project currently under development, as well as to the CYGNSS mission.

Index Terms— Coherent bistatic radar scattering model, RCS, Delay Doppler Map, GNSS-R, GRIBSAR

1. INTRODUCTION

Soil moisture is a critical variable in studying the global ecosystems, and monitoring the interactions between land and atmosphere. Soil moisture measurements on global and local scales contribute to many areas of human concerns such as weather and climate forecasting, flood prediction, drought analysis, crop productivity evaluation, and human health. Thus, it is essential to advance dependable soil moisture retrieval methods [1]-[3]. Development of bistatic retrieval techniques and receiver systems give us the possibility to use the existing signals of opportunity (SoOP), such as signals transmitted by GPS/GNSS and TechDemoSat-1 (TDS-1). The basic measurement from these sources is the Delay-Doppler Map (DDM) [4]. To be able to use these observations for quantitative soil moisture retrieval, we need to convert the DDMs to the more familiar scattering cross sections. In previous works, we presented a coherent bistatic forward scattering model at L-band and P-band for various

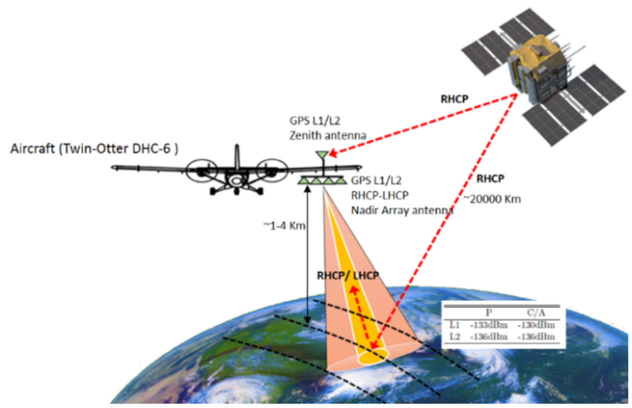


Fig. 1. GNSS Reflectometer Instrument for Bistatic Synthetic Aperture Radar (GRIBSAR), which is capable of receiving the GPS signal in direct and specular paths. The direct path signal and scattered signal in specular direction are captured by Zenith antenna (RHCP) and RHCP-LHCP Nadir Array antenna, respectively.

terrain types including forests [3]. This model is built on its mono-species backscattering model counterpart, and comprises three main scattering mechanisms that include the direct bistatic scattering from ground, bistatic scattering from the vegetation layer, and double bounce bistatic scattering from trunks and branches**.** Consequently, the total bistatic scattering RCS of vegetated terrain is computed by superimposing the three stated scattering contributions. This model produces co-pol (σ_{HH} , σ_{VV}) and cross-pol (σ_{HV} , σ_{VH}) radar cross sections for linearly polarized incident waves [3]. The bistatic scattering model can be extended to include Right-hand Circularly Polarized (RHCP) incident wave cases (Fig. 1) by an analysis parallel to [5], especially for the case of GRIBSAR where both RHCP and LHCP receivers are planned. The linearly polarized received signals (σ_{RH}, σ_{RV}) from RHCP incident wave scenarios can be derived by using the radar cross sections predicted by the polarimetric bistatic scattering model ($\sigma_{RH} = \sigma_{HH} + \sigma_{VH}$, $\sigma_{RV} = \sigma_{VV} + \sigma_{HV}$) [5], [6].

2. CIRCULAR/LINEAR BISTATIC MODEL

As mentioned in previous section the proposed bistatic scattering model has 3 major categories of contribution, which are described below. We have previously reported on the conversion between linear and circular polarization combinations on transmit and receive [6].

2.1. Direct Ground Bistatic Scattering

For the terrains with small surface roughness the combination of Small Perturbation Method (SPM) and Kirchhoff Approximation or KA (for computing the scattering in specular direction) are used [3]. This analytical method gives an approximate full bistatic solution, and benefits from low computational cost. Moreover, for the cases where the k. s>0.3 (k is wave number and s is the standard deviation from average surface roughness) the Stabilized Extended Boundary Condition Method (SEBCM) is used in lieu of SPM. SEBCM [7] is a numerical method, which is for full bistatic scattering calculation in all directions all in one shot. However, the computational cost of this method is significantly higher than SPM.

2.2. Vegetation Volume Scattering

In the proposed bistatic model trunks and branches are modeled as vertical and randomly oriented dielectric cylinders, respectively. The probability density function (pdf) considered for branches orientation is $sin^2\alpha$ and α is the deviation angle from the vertical line. At first the scattering matrix for a randomly oriented cylinder is determined and then converted to its corresponding stokes matrix. The computed stokes matrix is then multiplied by the pdf of cylinder orientations and averaged over all cylinder tilts [3].

2.3. Double Bounce Bistatic Scattering

The trunk-ground and branch-ground bistatic scattering matrices are computed by cascading the scattering matrices of cylindrical distributions and ground rough surface. As mentioned in 2.1 either SPM + KA or SEBCM is used for the calculation of bistatic scatteing matrix from randomly rough surface. Therefore, the total double bounce stokes matrix can be derived from computed double bounce scattering matrix.

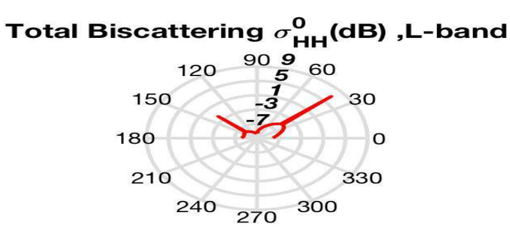
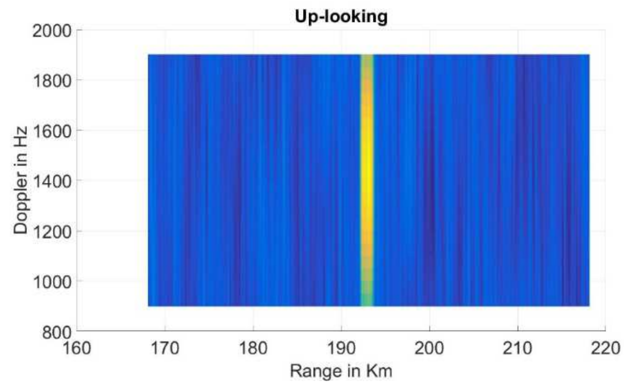


Fig. 2. Polar plot depiction of bistatic RCS for the plane of incidence

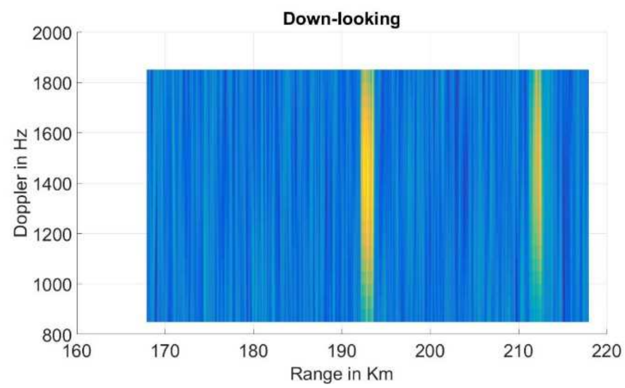
An example of model simulations for a woody savanna landscape is shown in Fig. 2.

3. DELAY DOPPLER MAP (DDM) OVER LAND

This section presents a brief review of the method used to convert the scattered signal power DDM in Watts to the scattering RCS.



(a)



(b)

Fig. 3. An example of over water-land DDMs. The GPS direct path signal (navigation signal) is captured by up-looking (zenith) antenna (Fig. 3.a) at ~193 km, and the specular scattered signal is received by Down-looking (nadir) array antenna (Fig. 3.b) at ~212 km. The latter is used to convert the measurements to cross sections and compared against theoretical model predications.

In order to convert the measured reflected GPS signal power to normalized bistatic scattering RCS, first the radar equation is used to calculate the measured scattered power in each DDM bin. Then the land surface scattering area ($A_{T,f}$) at each delay Doppler bin is calculated (each of the DDM pixels in Fig. 3) [8].

$$A_{T,f} = \iint_A \Lambda^2_{T,x,y} \, S^2_{f,x,y} \, dxdy \quad (1)$$

Λ and S are responses of GPS signal in time and frequency domain. The next step in the conversion method is to calculate the bistatic scattering RCS ($< \sigma_{T,f} >$) for each bin of the DDM, as follows [8]:

$$< \sigma_{T,f} > = \frac{P_{T,f}^{g}\,(4\pi)^3 I_{T,f}\, L_{a1} L_{a2}}{P^T \lambda^2 G^T G_{SP}^R R_{SP}^{Total}} \qquad (2)$$

In equation (2), $I_{T,f}$ is used to consider the receiver losses, and $R_{SP}^{Total} = \frac{1}{(R^R)^2\,(R^T)^2}$, which is the total range loss from transmitter to land surface and land surface to the receiver at the specular point, and P^T and $P_{T,f}^{g}$ are the GPS transmitted signal power, and the total scattered power in Watts, respectively [8]. Ultimately after the bin by bin calculation of the effective scattering area and the bistatic scattering radar cross section the normalized bistatic scattering RCS (σ^0) of the DDM can be calculated:

$$\sigma^0 = \frac{\sigma_{total}}{A_{total}} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\sigma_{T_i,f_j}}{\sum_{i=1}^{N}\sum_{j=1}^{M}A_{T_i,f_j}} \qquad (3)$$

where, N and M indicate the DDM bins for delay and Doppler, respectively [8]. Moreover, σ^0 belongs to the set of normalized bi-scattering RCS: ($\sigma_{RH}^0, \sigma_{RL}^0, \sigma_{HH}^0, \sigma_{VV}^0, \sigma_{HV}^0, \sigma_{VH}^0$).

4. RETRIEVAL OF SOIL MOISTURE

The normalized bistatic scattering RCS (σ^0) may be circularly polarized or linearly polarized receive channels as a result of the reflection of the circularly polarized incident GPS/GNSS signals. Our bistatic radar scattering model is capable of calculating these combinations, and will be used here to predict the left-hand side of this equation for available polarization combinations. We use the model to calculate various polarization combinations for DDM pixels with a variety of land-cover types, including vegetated landscapes. Results of these simulations will be shown at the presentation. We use the model predictions in an inversion algorithm, parameterized for vegetation properties over the extent of the respective DDM pixels. The retrieval performance is first tested with synthetic data. Results of these synthetic experiments will be shown. We will then apply the method to sample data such as those available to us and shown in Fig. 3. In the future, we plan to apply this method to data from the GRIBSAR airborne system and data from the CYGNSS mission, provided validation locations with available ground truth can be identified.

5. SUMMARY

We have developed a coherent bistatic radar scattering model that includes the circularly polarized incident wave scenarios. The results are intended to be used for retrieving soil moisture from GNSS-R DDMs that have been converted to normalized cross sections at the specular point over land. The retrieval algorithm minimizes the difference between the normalized cross sections from DDMs and from the model predictions, thereby producing estimates of soil moisture. Simulation results for GRIBSAR will be shown, as well as limited results with measured GNSS-R data. The advantage of GRIBSAR data is that they include two receive channels (RHCP and LHCP), hence potentially allowing more accurate retrievals. This point will be demonstrated with examples during the presentation.

6. REFERENCES

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