Chapter 9

Sensing Bare Soil and Vegetation Using GNSS-R—Theoretical Modeling

Xuerui Wu and Shuanggen Jin

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1. Introduction

Once the reflected signals of GNSS constellations are thought to be errors and tried to remove from the direct signals, recently, however it was found new applications as GNSS-Reflectometry (GNSS-R) in the early 1990s[1]. By taking full advantages of these GNSS reflected signals, it has become a prosperous remote sensing technique. Different from the traditional remote sensing techniques, GNSS-R has its own unique features as:

1. Low cost and low power consumption: existing global navigation satellite constellations are a signal emission source and do not require the development of a dedicated transmitter. A corresponding GNSS-R receiver is required to receive the direct and reflected signals. Compared with conventional radar and microwave remote sensing radiometers, the GNSS-R sensor in complexity, size, weight and cost is reduced by about an order of magnitude onboard aerial or satellite remote sensing platforms;
2. Microwave band: GPS L_1, L_2C and L_5, GALILEO E_1, E_5, Beidou B_1, B_2, B_3 and GLONASS G_1 are working in L band, which have the nature of strong penetration and are suitable for monitoring soil moisture, vegetation and surface thawing condition as well as ocean surface characteristics;
3. High time resolution: GNSS satellites transmit signals continuously, and a GNSS-R receiver can receive multiple navigation satellites' signals in the field of view, so the time resolution GNSS-R are higher;
4. High spatial resolution: if a GNSS receiver is installed on the ground, the radius of GNSS-reflected signals is about 50m, while for the airborne GNSS-R, the spatial resolution are about km scale related to the aircraft height and surface roughness, so the spatial resolution of GNSS-R remote sensing is higher;

5. GNSS-R can perform positioning using the direct signal with self-position and self-timing ability, which is beneficial to the positioning, timing and geographic information system. Meanwhile, it is also easy to carry out a wide range of soil moisture and vegetation observation network;

6. Multi angle: the incident zenith angles of GNSS constellations are in 0~90 degrees and their azimuth angles are in 0~360 degrees, so the multi-angle observation becomes one of the significant advantages for GNSS-R remote sensing;

7. Multi polarizations: different from linear polarizations of radar and radiometer, the direct signals transmitted by GNSS satellites are RHCP, and its polarizations are changed after reflecting from the surface, so it is possible to receive multi polarizations (LR, RR, HR, VR);

From the above observation characteristics, GNSS-R remote sensing is a new multi-discipline between microwave remote sensing and satellite navigation. If we make fuly use of GNSS-R observational characteristics, more potential applications are explorled, such as sensing the soil moisture, vegetation and ocean surface characteristics, which has important application values and milepost sense with integration and development of microwave remote sensing and satellite navigation technology.

2. Applications of GNSS-R

According to the observed surface, GNSS-R applications have extended from ocean, land to ice and snow [2].For the ocean surface, when the sea surface roughness increases, the reflected waveforms have lower amplitudes, and therefore GNSS-R can be used to detect intermediate sea surface roughness according to the distorted waveforms [3]. Since the permittivity of reflected surface is sensitive to the polarimetric measurement, GNSS-R can be used to monitor the salinity and the temperature of ocean surface [4]. As for snow and ice surface, GNSS-R has the ability to detect its permittivity, texture, or substructure [5]. It has also been proposed to sense the parameters of soil moisture and vegetation with GNSS-R. Currently three kinds of aspects are performed:

2.1. Quantitative retrieval with Interference Pattern Technique (IPT)

The IPT technique over land surfaces have been successfully developed for retrievals of surface topography, vegetation height and vegetation-covered soil moisture [6]. A ground-based instrument named Soil Moisture Interference-pattern GNSS Observations at L-band (SMI-GOL) Reflectometer has been used in their field campaigns since 2008[6]. The instrument measures the inference of the direct and reflected GPS signals instantaneously, and the received power is a function of the elevation angles. It should be pointed out that the polarization of the antenna is Vertical polarization (V-pol). Using the number and position of the minimum amplitude oscillations (notch), the geophysical parameters (surface topography, vegetation height and vegetation-covered soil moisture) can be retrieved. According to their reports, good quantitative retrieval results have been achieved [6]. Recently, a dual-polarization SMIGOL (PSMIGOL) has been designed [7] as an extension of SMIGOL. Different from SMIGOL, the extended PSMIGOL has two antennas, one is H polarization and the other one is V polarization [7]. This instrument has improved the accuracy of soil moisture retrieval [7].

2.2. Qualitative analysis using GPS multipath information

The multipath of GPS signals was thought as errors for positioning and timing, although it cannot be fully removed. However, the multipath is sensitive to environmental parameters: near surface soil moisture [8], vegetation [9], snow and ice [10]. Therefore, it is an efficient method for these geophysical parameters detections. The geodetic GPS receiver records the coherence of the direct and reflected signals. Its geometry is shown in Figure 1.

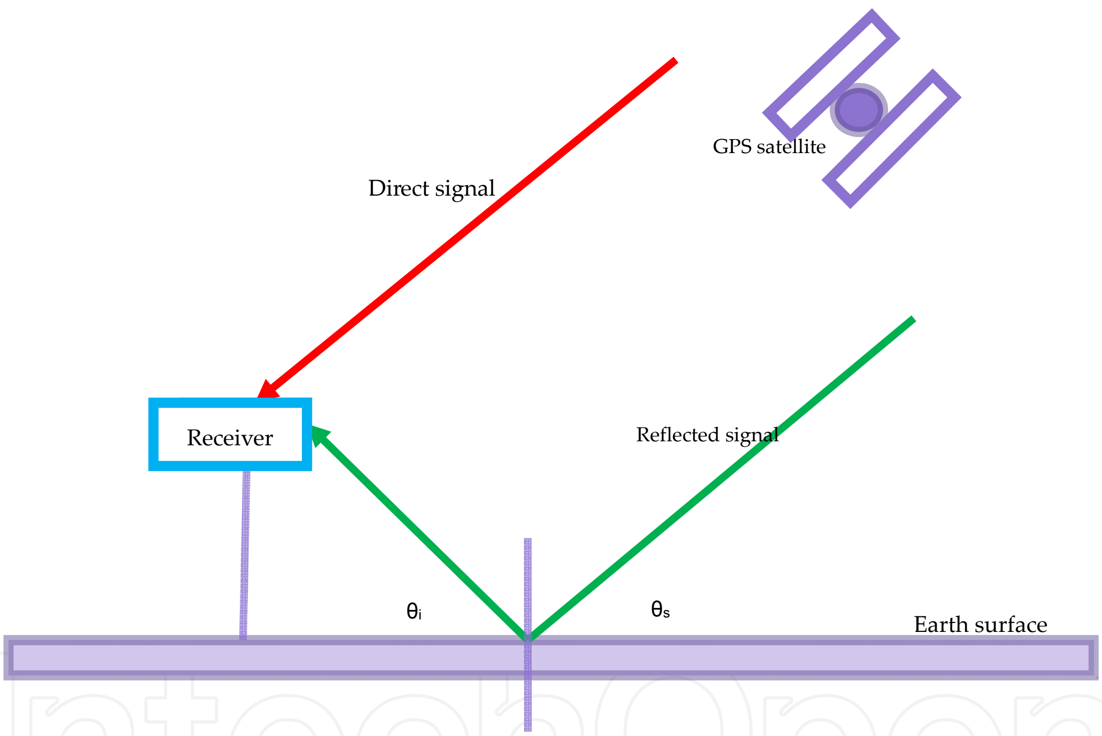

Figure 1. Scattering geometry of multipath signals. The red line represents the direct signal; green line is the reflected signal. The received power by a geodetic receiver is the coherence of direct and reflected signals at the specular directions: $\theta_s = \theta_i$, θ_s is the scattering angle, θ_i is the incidence angle, and there is no consideration for the azimuth angles.

2.3. Microwave scattering theoretical study

The transmitted sources are the GNSS constellation, while a special GNSS-R receiver or an out-of-commercial geodetic GPS receiver is the corresponding receiver, which forms a typical bistatic/multistatic radar working mode. Therefore its scattering mechanisms should be studied carefully. Ferrozoli et al [11] have used an electromagnetic model to deduce the theoretical response of vegetation, and found that different with the monostatic radar, the vegetation showed a decreasing trend with increasing biomass, and it may allow retrieving the biomass using the GNSS-R remote sensing technique.

3. Bare soil and vegetation scattering models

3.1. bare soil surface scattering model

If the surface is smooth enough, a smooth surface reflectance models can be used to describe the scattering surface properties. The commonly used randomly rough surface scattering models are KA (Kirchhoff Approach), SPM (Small Perturbation Method), IEM (Integrated Equation Model) and the further improved AIEM (Advanced Integrated Equation Model) models [12][13], see Table 1. If the Kirchhoff model is under the stationary phase approximation, it is commonly known as the geometrical optics model, which is best suited for very rough surfaces. If it is under the scalar approximation, it is also known as the physical optics model, which is suitable for intermediate scales of roughness. The small perturbation model is suitable for surface roughness scales with short correlation lengths.

<table>
<tr><th>Models</th><th>Roughness scope of application</th><th></th></tr>
<tr><td>GO</td><td>$s>\lambda / 3$, $l>\lambda$, & $0.4<m<0.7$</td><td rowspan="2">$kl>6; l^2>2.76s\lambda$</td></tr>
<tr><td>PO</td><td>$0.05\lambda<s<0.15\lambda$, & $m<0.25$</td></tr>
<tr><td>SPM</td><td>$ks<0.3$, $kl<3$, & $m<0.3$</td><td>else</td></tr>
</table>

Table 1. Roughness scope of application for GO, PO and SPM

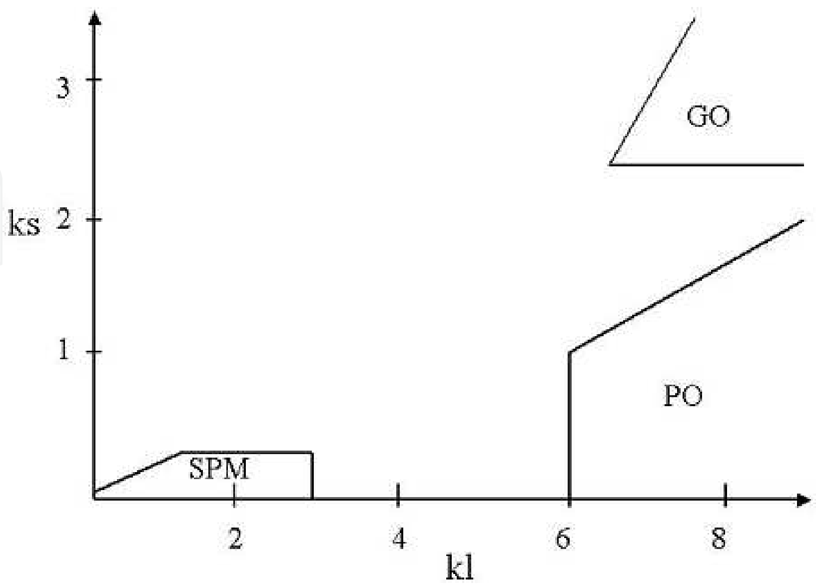

Figure 2. Scope application of random roughness surface scattering model

As we can see from Figure 2, the roughness scopes of the three surface models are not continuous and do not conform the surface roughness of continuous changes of the real world, and therefore it is needed for a roughness scope with more extensive surface scattering model based on the AIEM model and its improvement. In order for GNSS-R applications, the scattering model should be able to calculate bistatic scattering.

3.2. Vegetation scattering model based on radiative transfer equation model

The Michigan Microwave Canopy Scattering model (MIMICS) [14] is based on the first-order solution of the radiative transfer equation for monostatic radar systems of a tree canopy, which is treated as a composition of a crown layer, a trunk layer and a rough-surface ground boundary. As for the crown layer, needles and/or branches are represented as dielectric cylinders, disks are represented by leaves, while the trunks are treated as large vertical dielectric cylinders of uniform diameter.

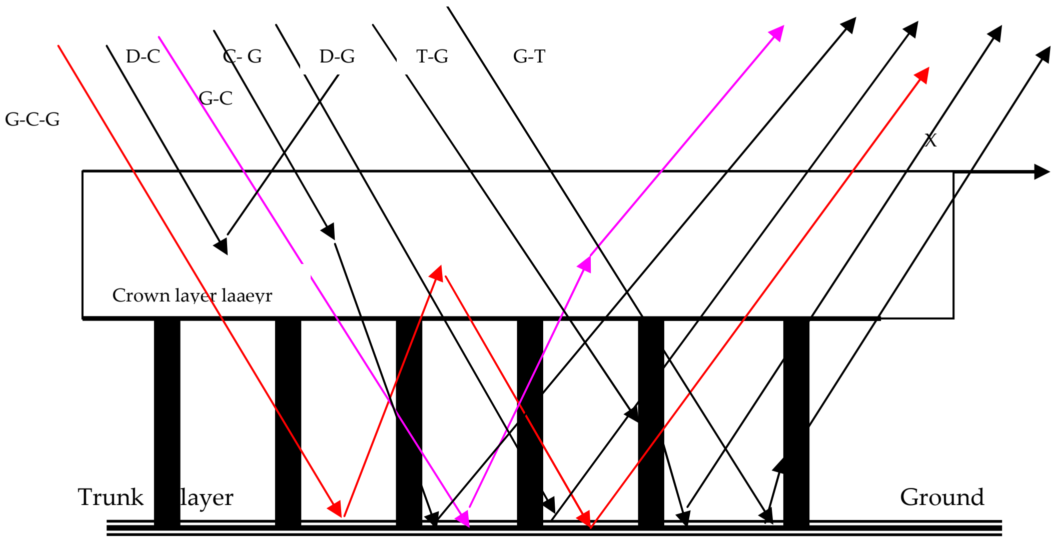

Figure 3. Scattering mechanisms in the first-order Bi-mimics solution based on RT theory, including G-C-G(ground reflection and crown scattering and ground reflection), C-G(crown scattering and ground reflection), DC(direct crown bistatic scattering), G-C(ground reflection and crown scattering, G-T(ground reflection and trunk scattering), DG(direct ground), and T-G(trunk scattering and ground reflection). The specular ground reflection is not shown here. Crown layer depth=d, Trunk layer depth=H [15].

However, MIMICS is insufficient for studying the bistatic RCS (Radar Cross Section) of vegetation. The following-on developed bistatic Michigan Microwave Canopy Scattering Model (Bi-Mimics) is a bistatic model [15], which is based on the original Mimics model, and referred as the bistatic Michigan Microwave Canopy Scattering Model (Bi-Mimics). Mimics and Bi-mimics models utilize an iterative algorithm to solve the radiative transfer equations [14,15]. There are eight scattering mechanisms in the first-order Bi-mimics model, including G-C-G (ground reflection and crown scattering and ground reflection), C-G (crown scattering and ground reflection), D-C (direct crown bistatic scattering), G-C (ground reflection and crown scattering), G-T (ground reflection and trunk scattering), D-G (direct ground), and T-G (trunk scattering and ground reflection). The specular ground reflection is not shown in Figure 3. The difference between the D-G and S-G scattering component is the surface scattering matrix. As for the D-G scattering mechanism, rough surface scattering matrix is used while considering for the attenuation of the incident and scattered intensity. However, the specular scattering matrix is used for the S-G scattering mechanism. More details for Bi-Mimics model is referred to the corresponding references [14, 15].

Using the above-mentioned bistatic scattering models of bare soil (AIEM model) and vegetation (Bi-Mimics model), we can characterize their corresponding scattering properties in order for GNSS-R applications.

4. Scattering properties of different polarizations

To overcome the ionosphere effects, the transmitted signals of GNSS constellations are right hand circular polarization (RHCP). While its polarization changed after reflecting from the targeted surface. Its properties of circular and linear polarizations are studied in BAO-Tower Experiments [16], which used the receiver provided by the NASA Langley Research Center to track signals. There are four kinds of polarizations for the antennas: Horizontal, Vertical, Left Hand Circular Polarization and Right Hand Circular Polarization. The theoretical analysis showed that the received power was proportional to two factors: a polarization sensitive factor and a polarization insensitive factor, while the former one is dependent on soil dielectric properties and the latter one is related to surface roughness. However, this hypothesis is not confirmed in their BAO-tower measurement. The originally crude assumption of soil moisture homogeneity is the possible reason.

The polarization of a plane wave describes the shape and locus of the tip of the electric field-vector as a function of time. Polarization is of interest for GNSS-R remote sensing due to its potentially polarimetric and multipolarimetric measurements.

We can see from Fig. 4 that as for LR, HH and HR polarizations, their scattering properties are almost the same, while as for VR and VV polarizations, there is a dip as the incident angle at 70 degree and their scattering properties are very different from the ones of the other polarizations. From the above simulations, scattering properties at RR polarization are very different. Compared to the other polarizations, their scattering cross sections at the smaller incidence angles (from 10 degree to 55 degree) are the smallest one. When the incidence angle is between 70 degree and 80 degree, RR polarization is very similar to LR, HR and HH. The scattering cross section at RR polarization is larger than the one of VR and VV polarizations as the incidence angles are between 60 degree and 70 degree. We can use the dips at VV and VR polarizations for the soil moisture detections since they are related to the Brewster angle, which is very sensitive to soil moisture. In fact, the principle for soil moisture detections using IPT technique is to use the Brewster angle information.

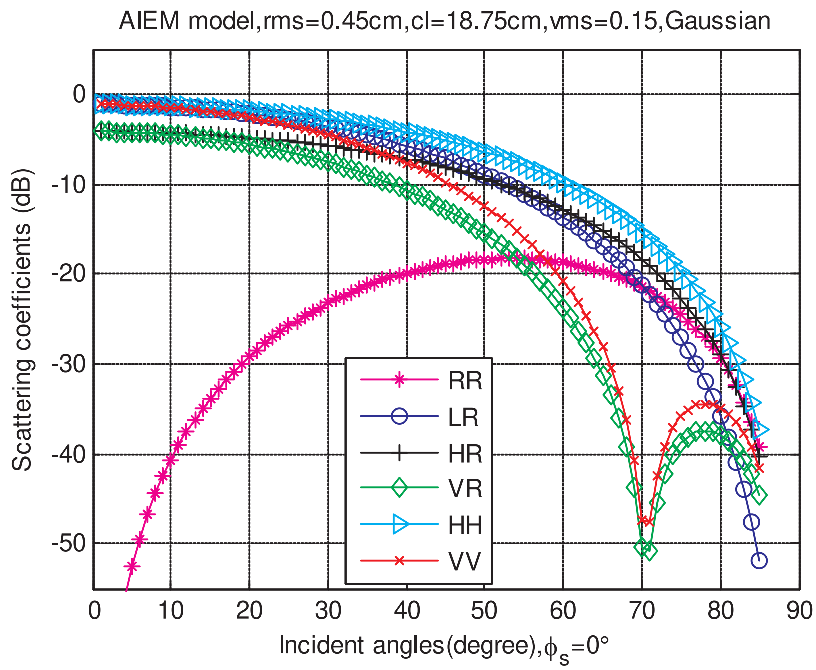

Figure 4. Scattering coefficients of linear pol and RX pol vs. incidence angles (vms=0.15).

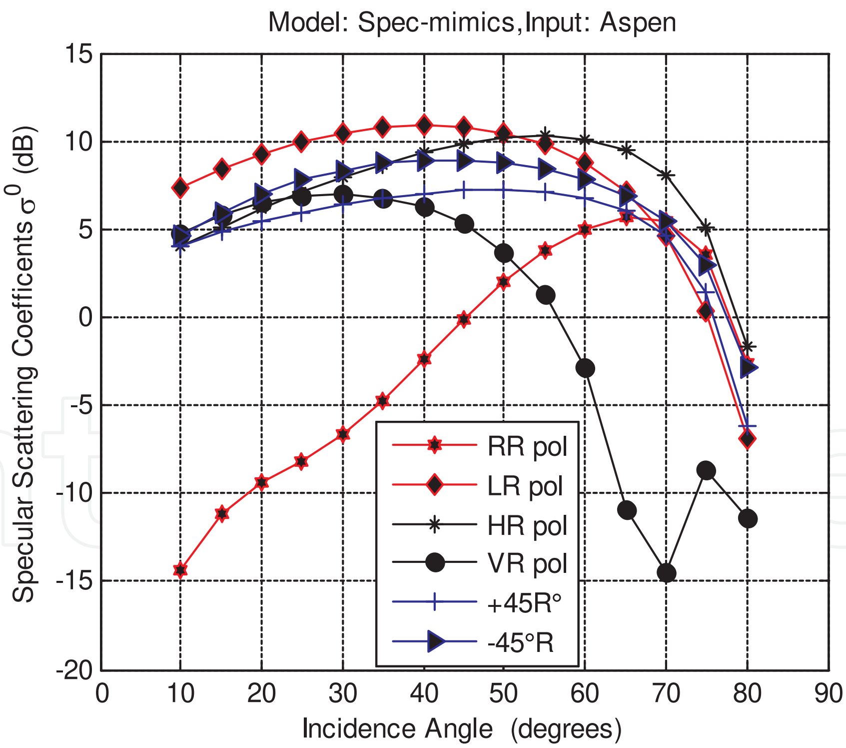

Figure 5. Specular scattering at XR polarizations versus incidence angles.

As for vegetation, the Bi-Mimics model at the specular direction (here referred to as Spec-Mimics model) is used to study its polarization scattering properties. We can see from the above simulations that the scattering trends for LR,-45R,+45R and HR are very similar, while they increases slowly when the incidence angle is between 10 degree and 40 degree and then decreases slowly as for the incidence angles between 50 degree and 80 degree. When the incidence angles are between 50 degree and 80 degree, the scattering cross sections of HR polarization is a little larger (2~3 dB) than the other polarizations (LR,-45R,+45R and HR). As for RR and VR polarizations, if the incidence angles are smaller than 52 degree, the scattering cross sections at VR polarization is larger than the ones at RR polarization, while the trend is just opposite when the incidence angles are larger than 52 degree, and there is also a dip for the incidence angle of about 70 degree.

5. Conclusion

Sensing soil moisture and vegetation with the new developed GNSS-R remote sensing technique is interesting and attractive for the scientific community. However, most of the present works are concentrated on the experimental analysis and the assumed feasibility. This chapter gives a brief review of the current status for GNSS-R soil and vegetation study, and then the scattering models of soil and vegetation are addressed. To make fully use of GNSS-R signals, polarization properties of the electromagnetic wave should be studies carefully. Using the wave synthesis technique, the scattering cross sections of any combination of transmit and receive polarizations for bare soil and vegetation are illustrated. For the apparent changes of waveform from the corresponding GNSS-R receiver, Vertical polarization antenna is preferred for the following on retrieval.

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Author details

Xuerui Wu[1,2,3*] and Shuanggen Jin[1]

*Address all correspondence to: xrwu@shao.ac.cn

1 Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China

2 Department of Environment Resources and Management, Chifeng College, Chifeng, Inner Mongolia, China

3 Space Star Technology Co., Ltd, Beijing, China

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