RECENT PROGRESS ON FORWARD SCATTERING MODELING FOR GNSS REFLECTOMETRY

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ABSTRACT

A geometric optics limit of the Kirchhoff approximation is widely used for modeling the bistatic radar cross section of the ocean surface. The question of practically acceptable accuracy of this approximation for GNSS-R applications remains open. In this paper we use more accurate approximation, the small slope approximation to assess the validity of the geometric optics model. Here, we present the results of calculations of the bistatic radar cross section for L-band circular polarization signals using both the geometric optics model and the small slope approximation. Another issue addressed in this paper is the sensitivity of the modeled bistatic radar cross section to wind direction. Two semi-empirical surface spectral models are employed and in- and out-of-plane geometries are considered. Also, using the small slope approximation we investigate the sensitivity of the azimuthal angle dependence of the bistatic radar cross section to wave fetch.

***Index Terms*—**Bistatic radar scattering, Global Navigation Satellite Systems (GNSS), GNSS reflectometry, ocean waves, wind.

1. INTRODUCTION

Both space-borne and airborne reflectometry rely on modeling the bistatic radar cross section (BRCS) of the ocean surface. Currently, a geometric optics limit of the Kirchhoff approximation (KA-GO) is widely used for this purpose. While this approach demonstrated its robustness for evaluation of the effect of surface roughness on received reflected waveforms, or delay-Doppler maps (DDM), the question of practically acceptable accuracy of this approximation for GNSS-R applications remains open. This issue is especially important when assessing the wind speed and altimetric retrievals by employing the forward scattering modeling the GNSS reflected signals. In this paper we use more accurate approximation, the small slope approximation (SSA) [1], [2], to assess the validity of the KA-GO approximation. It is known that the KA-GO requires a mean-square slope (MSS) model which is either based on a L-band limited elevation spectrum of the ocean surface [3], [4] or on an empirical mean square slope (MSS) data derived from calibrated GNSS-R measurements [5]. There is a certain degree of discrepancy between spectral and empirical MSS approaches due to an uncertainty in the "cutoff" wave number for the former approach, and due to a significant scatter in calibrated data for the latter approach. Also, the GO-KA generally does not account for diffraction effects which may manifest itself in the trailing edge behavior of the reflected waveform. The deficiencies of the KA-GO can also lead to incorrect description of the BRCS for out-of-plane scattering [6]. At the same time, the SSA approach does not require the "cutoff" wave number because it employs the entire elevation spectrum without splitting it on large-scale and small-scale components. It takes into account the mentioned above diffraction effects, although, similarly to the KA-GO, it requires the ocean roughness to have small slopes (< 0.2-0.4). Here, we present the results of calculations of the BRCS for L-band circular polarization signals using both the KA-GO and the SSA to assess the applicability of the KA-GO models.

An important issue in ocean scatterometry and GNSS reflectometry is a measurement of near-surface wind direction. Here we investigate the dependence of the bistatic radar cross section modeled with the SSA on the azimuthal angle with respect to wind direction for in- and out-of-plane geometries. These calculations are based on two semi-empirical surface spectral models [7], [8]. Also, using the SSA we investigate the wind direction sensitivity of the bistatic radar cross section to wave age, or fetch.

2. THE BISTATIC RADAR CROSS SECTION IN SMALL SLOPE APPROXIMATION

There are two approximations of the SSA, the SSA of the 1st order and the more accurate approximation, the SSA of the 2nd order. Practice shows that the SSA of the 1st order,

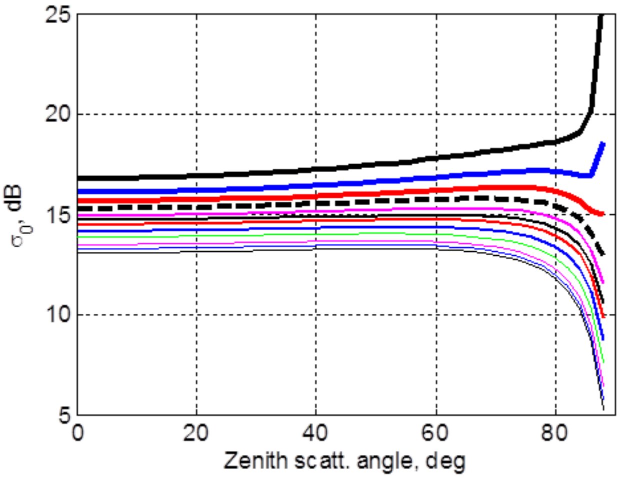

Fig. 1. LHCP BRCS calculated using the KA-GO based on the spectral-derived MSS.

or the SSA1 suffices for calculations of the left-hand circularly polarized (LHCP) BRCS of the L-band signal in the forward scattering regime. For calculations of the right-hand circularly polarized (RHCP) BRCS and for a wide-angle scattering regime the more accurate SSA2 is required. The SSA1 gives the expression for the bistatic radar cross section (BRCS) σ_0 in the form of a 2D surface integral similar to that obtained in the Kirchhoff approximation but with a more accurate pre-integral factor [1], [2]; generally, the integral cannot be evaluated by the stationary phase method.

We performed SSA1 calculations of the left-hand circularly polarized (LHCP) BRCS σ_0 along the nominal specular direction and compared it with the corresponding BRCS based on the KA-GO models for a range of incidence angles and winds.

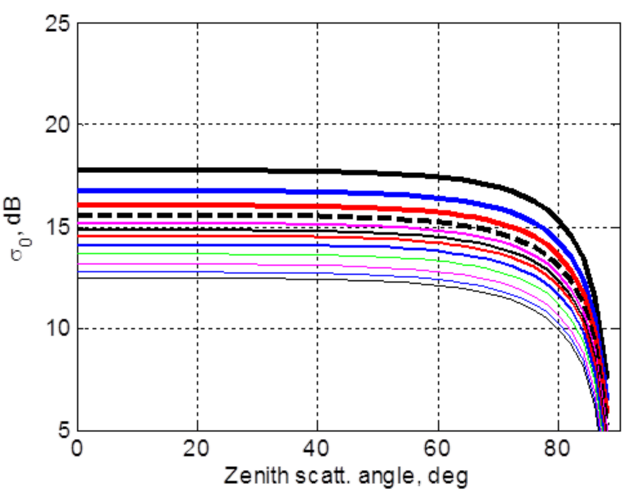

Fig. 2. LHCP BRCS calculated using the KA-GO based on the empirically-derived MSS.

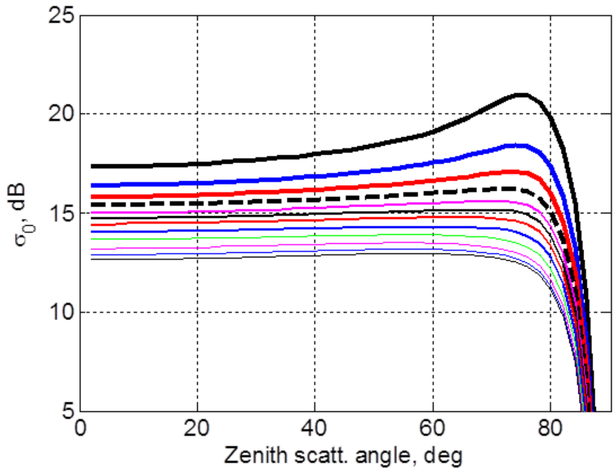

Fig. 3. LHCP BRCS calculated using the SSA1.

Here, in Fig. 1, we present the results obtained with the KA-GO model, using an MSS based on the Elfouhaily et al. spectrum [7] and a cutoff frequency from [4]. Fig. 2 depicts the results obtained with the KA-GO model using the empirical MSS model from [5]. In Fig. 3 we presents curves for σ_0 calculated with the SSA1 and the Elfohaily et al. spectrum. Each plot has twelve curves. The top seven curves correspond to wind speeds U_{10} from 4 to 10 m/s. The rest are for the wind speed of 12, 15, 20, 25, 30 m/s. This dependence on wind speed reflects the fact that increased wind produces a stronger surface roughness which, in its turn, decreases scattering in a specular direction. One can see that σ_0 behaves differently for every of these models at scattering angles larger than 60°-70°. It should be remembered that all these models are not valid at large scattering angles. Usually, in aircraft and space-borne GNSS-R missions this range of angles is avoided. It should be noted that the empirical MSS model [5] was built on GPS reflection data obtained for low incidence/scattering angles, < 45°, therefore, it might not reflect the actual behavior of the scattering at larger angles. At the same time, all three models demonstrate a quite similar levels of the BRCS over wind speeds for scattering angles below 45°.

We investigated the wind dependence of σ_0 in more detail by calculating it for a narrow range of scattering zenith and azimuthal angles and for a fixed moderate incidence angle below 45°. We checked how predictions for σ_0 from all three models correspond to each other for scattering originated from the surface area limited to some number of delay zones. We found that while σ_0 is changing with the wind speed it does not appreciably change over the angles within the first delay zone. The discrepancy between curves for all three models are within 0.5 dB for wind speed

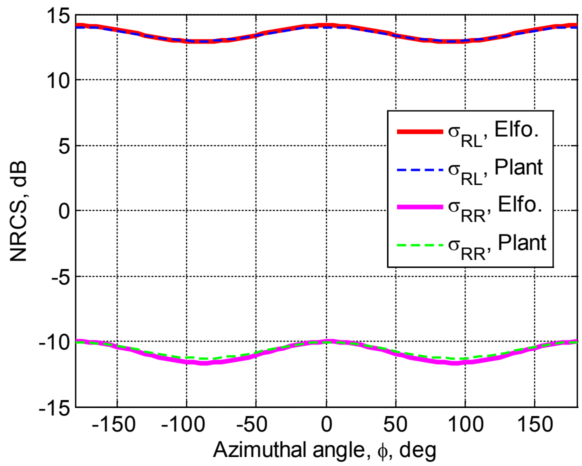

Fig. 4. Comparisons between LHCP (σ_{RL}) and RHCP (σ_{RR}) BRCS obtained with the SSA2 for two spectral models and the in-plane geometry.

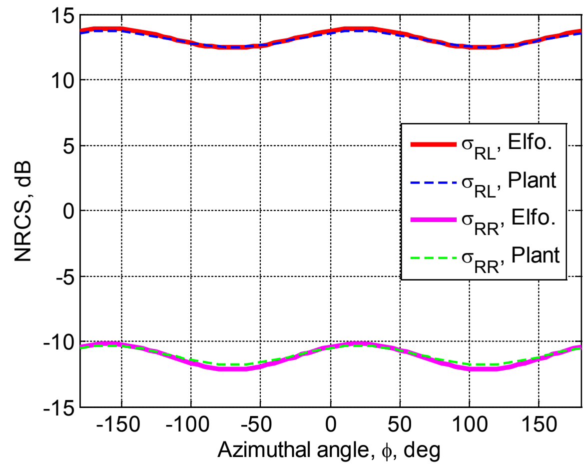

Fig. 5. Comparisons between LHCP (σ_{RL}) and RHCP (σ_{RR}) BRCS obtained with the SSA2 for two spectral models and the out-of-plane geometry.

below 15-17 m/s which is negligible given such adverse factors as speckle noise and natural wind speed variability that accompany real measurements. The discrepancy between the SSA curve and the curve based on the empirical MSS from [4] is less than 0.5 dB for the entire range of wind speeds used for this simulation, i.e. below 30 m/s.

3. SENSITIVITY OF BRCS TO WIND DIRECTION

Experiments with GNSS circularly polarized bistatic signals indicate that under favorable geometrical conditions they similarly to backscatter radars that use linear polarizations are sensitive to anisotropy of wind-driven waves [9], [10]. Here, we present the results of calculations for the bistatic NRCS as a function of azimuthal angle in order to look into sensitivity of scattered signals at circular polarizations to wind direction. We found that bistatic scattering exhibits a sensitivity to wind direction when the scattering direction does not coincides with the nominal specular direction.

In Fig. 4 comparisons are shown between SSA2 results for L-band LHCP BRCS (σ_{RL}) and RHCP BRCS (σ_{RL}). The curves are plotted as a function of the azimuth angle φ_{sc}, within the plane of incidence, for $\theta_{inc} = 45^\circ$ and $\theta_{sc} = 35^\circ$. We call this configuration the in-plane geometry. The wind direction is at 0 ˚.Two spectral models: one by Elfouhaily et al. [7], and another by Plant [8] are used here. One can see that these two spectral models produce almost identical results.

In Fig. 5 comparisons are shown between SSA2 results for L-band LHCP and RHCP bistatic cross sections for the out-of-plane geometry. Again, the curves are plotted as a function of the azimuth angle φ_{sc}, for $\theta_{inc} = 45^\circ$ and $\theta_{sc} = 35^\circ$. However, the direction of the scattered wave this time is taken out of the plane of incidence by 5˚. Again, two spectral models produce almost identical results It is interesting to note that for this geometry the direction of the maximum BRCS is 20 ˚ off the wind direction.

Fig. 6 depicts comparisons between LHCP BRCS (σ_{RL}) and RHCP BRCS (σ_{RR}) obtained with the SSA2 for Elfouhaily et al. model and the in-plane geometry for infinite and finite fetch of 100 km. Usually, for purposes of ocean scatterometry fetch of 100 km is considered as a proxy for infinite fetch. Results for ocean microwave backscattering for these two fetches would be identical. In the case of the L-band forward scattering one can see a discernible difference in pairs of curves both for LHCP and RHCP signals.

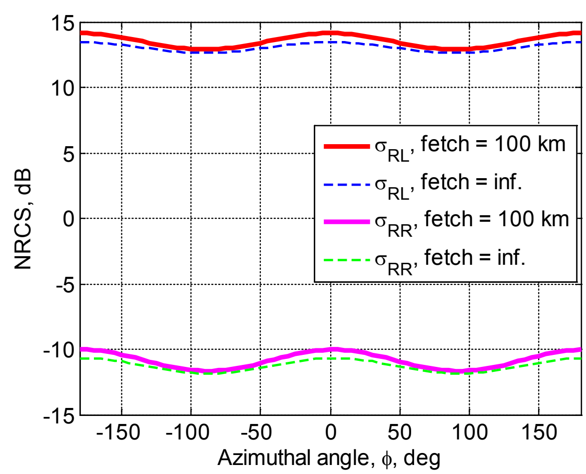

Fig. 6. Comparisons between LHCP (σ_{RL}) and RHCP (σ_{RR}) BRCS obtained with the SSA2 for Elfouhaily et al. model and the in-plane geometry for infinite and finite fetch.

4. CONCLUSION

We demonstrated here that for small deviations from the specular plane, LHCP σ_0 calculated with two version of KA-GO model is quite close to that one predicted by the more accurate, the SSA1 approximation. This case is more common for space-borne measurements when the calibrated correlation power collected from the narrow zone around the peak is the main observable. It might be not the case for the aircraft measurements where the observable includes the trailing edge of waveform, or the entire DDM.

Whereas the above considerations are applicable to global winds below 25-30 m/s for strong hurricane winds fundamental limitation of all above models can come into play. These could be a limitation of too steep, or even breaking, waves, or unavailability of elevation spectral models (similar to the Elfouhaily spectrum).

For hurricane conditions, a feasible wave-spectral model should include, apart from a local wind speed, also several other parameters such as a fetch, a distance from the hurricane center, the hurricane velocity etc. Currently, hurricane long-wave prediction models are available (such as WAVEWATCH III wave model [11]). Such model can provide us with a long-wave portion of the sea state spectrum (so called "fresh swell") in the area of hurricane.

More challenging would be a task to extend this model toward much shorter waves up to the cutoff frequency discussed above. To verify such an extended model available radiometric, scatterometric and GNSS-R data obtained in hurricanes can be used. The extended spectral model can be very useful for forward scattering modeling and evaluation of the performance and accuracy of the systems used in space-based missions such as CYGNSS [12].

Our modeling with the SSA shows sensitivity of GNSS reflected signals to the wind direction, however, only for directions away from the nominal specular direction. At the same time, there is no significant difference in azimuthal dependences obtained for the spectral models used. Simulations show some sensitivity of bistatic radar cross section to wave fetch.

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