THE IMPACT OF RAIN ON L1 GNSS-R RADAR SCATTERING CROSS-SECTION

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ABSTRACT

Current GNSS-R systems for ocean surface wind measurements usually operate at the all-day all-weather L-band frequencies. Though L-band signals can penetrate through clouds and precipitation, under heavy precipitation the various impacts of rain on the measurement need to be accounted for. Impact of rain on the microwave bistatic radar cross-section is not a well understood phenomena. In this work we attempt to improve our understanding of the measured radar cross-section under precipitation using the CYGNSS measurements and propose a forward model that accounts for a combined wind-rain interaction in the forward scattering direction.

Index Terms— CYGNSS, GNSS-R, rain, radar cross section

1. INTRODUCTION

Earth remote sensing using reflected GNSS signals is currently an emerging trend especially in ocean surface wind measurements primarily due to its all day/all weather capability. Unlike the existing scatterometer missions, GNSS-R uses L-band navigation signals that can penetrate through clouds and rain [1]. Rain may have a negligible impact on the transmitted signal in terms of path attenuation at this wavelength. However, there are other effects due to rain, such as change in surface roughness, enhanced winds due to downdraft outflow etc., which can be observed in these measurements [2] [3].

L band scatterometry measurements are sensitive to wind driven gravity-capillary waves - thus the bistatic radar cross-section can be used as a measure of near surface winds. However, the presence of rain may also cause a number of effects which can affect the measurements. Alterations of the surface roughness conditions by the rain need to be accounted for. The impacts of wind at shorter wavelengths have been carefully characterized in prior studies [4] [5]. Also, many previous studies have done extensive experiments on the impact of rain on radar backscatter [6] [7] [8]. Currently there are no careful observation-based characterizations of the impact of rain on radar forward scatter, which is the nature of operation of GNSS-R missions. In this work we try to understand the impact of rain on L band forward scatter signals using the measurements of Normalised Bistatic Radar Cross Section (NBRCS) by the CYclone Global Navigation Satellite System (CYGNSS).

CYGNSS is a small satellite GNSS-R mission selected by NASA's earth venture program. It carries a passive receiver called the Delay Doppler Mapping Instrument (DDMI) that maps the received reflected GPS signals from the Earth's surface into delay-doppler space. This 2D representation of the received signal is called a delay-doppler map (DDM) of the forward scattered signal. The specular point is the point of shortest propagation distance on the surface from the GPS transmitter to the CYGNSS receiver and has the highest power scattered in the forward direction. Each DDMI outputs 4 DDMs per second which are compressed and sent to the ground resulting in a total of 32 sea-surface measurements produced by the CYGNSS constellation per second [9].

This paper is organized as follows. Section 2 describes the dataset used for this analysis; Section 3 describes the physical mechanism of the rain impact on the water surface. Section 4 briefly describes the Double Difference DDM approach to observe the rain signature in CYGNSS measurements. Section 5 discusses the various possible effects that can be isolated from each other and finally the paper concludes with a description of next steps in this direction.

2. DATA DESCRIPTION

In this analysis we use the CYGNSS science quality release V2.1 data from 18th March 2017 (DOY 77) to 3rd October 2017 (DOY 276) which contain measurements from all the 8 CYGNSS observatories over 200 days. The CYGNSS Level 1 data contains the received surface signal power DDMs and the NBRCS, derived by inverting the forward model as described in [10]. These geolocated DDMs are matched at the specular point to the reanalysis products of 10m referenced ocean surface wind speeds provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) as a ground truth for wind. The ground truth source used for precipitation is the Integrated Multi-satellitE Retrievals for GPM (IMERG) Level 3 V05B Half Hourly Final Run gridded data product with a spatial resolution of 0.1x0.1 deg [13]. This is matched to the CYGNSS Level 3 resolution of 0.2x0.2 deg spatial resolution and 60 mins temporal resolution.

The CYGNSS data are filtered for stringent quality measures and only those data that have a very high antenna

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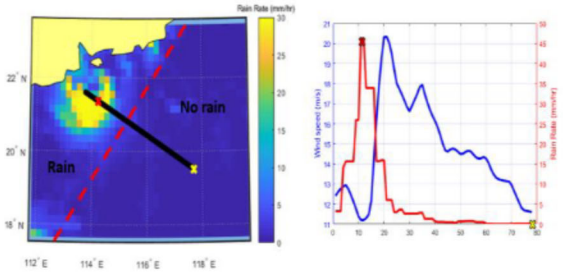


Fig. 1. CYGNSS track over a large rain cell showing the impact of rain.

gain (>10dB) are used for our purposes. The total number of samples is ~ 10^8 thus statistically significant conclusions can be derived from this dataset. The co-located precipitation measurements have a maximum precipitation of ~ 50 mm/hr, which provides a good dynamic range of precipitation to perform this analysis.

3. RAIN EFFECTS ON CYGNSS MEASUREMENTS

The impact of rain needs to be carefully analyzed for accurate wind retrieval from scatterometer radar return measurements. Approximately 5% of Earth's surface is covered by rain [6] and rain, being an important geophysical phenomenon, needs to be accounted for.

A rain drop hitting the water surface can cause 3 major types of surface deformation – crater, crown and stalk. First a cavity with a crown is formed which then changes into a vertical stock of water that finally subsides to generate rings of gravity capillary waves [8]. The dominant features in this process with respect to microwave signals are the stalks and the ring waves. Stalks are said to impact radar returns at grazing angles and, for other oblique incidences, ring waves are said to be the dominant factor [11]. Apart from the roughening effect on the surface, heavy rain can also push down the air column, creating an outflow of air radially away from the down draft region that can further increase the surface roughness.

Fig.1 shows a sample CYGNSS track over a large rain cell. Note in this case that the wind is suppressed at the region of heavy precipitation and there is a surge of wind just outside the rain cell. The plot on the right is the matchup precipitation and wind information along the track. The peak rain rate recorded in this track is 46.5mm/hr. This example demonstrates that rain not only increases the surface roughness but can also dampen the roughness induced due to wind.

4. DOUBLE DIFFERENCE DDM APPROACH

The double difference DDM approach is proposed here to analyze the impact of rain on the CYGNSS NBRCS. For the track shown in Fig.1, the measured CYGNSS power DDM

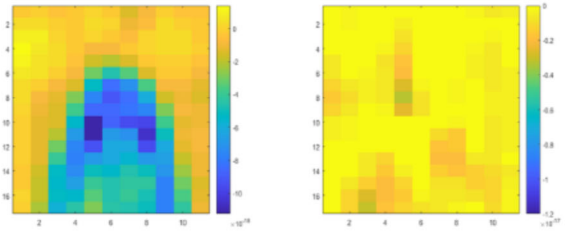


Fig. 2. Double Difference power DDM between peak rain and no rain (left). Double Difference power DDM between adjacent no rain samples (right).

is compared with a model of the power DDM derived by the End-to-End CYGNSS simulator for the same geometry of the satellites and sea state [9]. This forms the first difference of the double difference. This difference removes any fixed offsets in the simulator relative to actual measurements. The second difference is performed of the first difference under peak precipitation and the first difference under zero precipitation, at two difference locations along the track. This double difference is used to assess the impact of rain in the measurements.

Fig.2 shows the result of the double difference between rain and no rain on the left. There are a number of interesting features. First, the double difference shows that the impact of rain is in the glistening zone around the specular point and the power received at the specular point is reduced under rain condition as compared to no rain.

Note that the samples chosen for difference (shown with a cross in Fig.1) have similar wind speed (between 11-13 m/s) hence the difference can be assumed to arise from the rain alone. Second, the double difference yields a magnitude of the same order as the power received (~10^-18 W) which shows that the rain effect cannot be neglected.

The double difference on the right is a benchmark which is calculated between 2 adjacent no rain samples. In this case, we see the effects of noise only, as a measure of the repeatability and stability of the measurements. There are no distinct feature seen. This double difference approach shows that there is a measurable impact of rain on the received power. However one must also keep in mind that the samples are separated considerably in space, hence there is a possibility that other sea state conditions may be different.

4.1. Combined surface roughness spectrum

It is observed through the double difference approach that the impact of rain on the measurement is significant. We next attempt to account for the rain effect in the forward model. The current CYGNSS forward model uses the empirical Katzberg surface roughness spectrum [14]. To better represent the effect of rain, we combine the Elfouhaily omnidirectional wind-wave spectrum with the dominant ring wave spectrum in [6].

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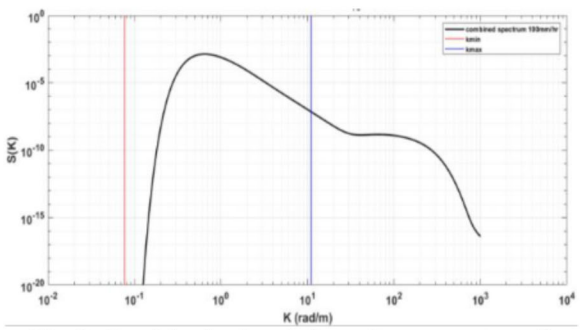


Fig. 3. Combined rain-wind roughness spectrum for wind = 3m/s and rain = 10 mm/hr

Fig. 3. Represents the combined spectrum which includes both the effects of wind driven and rain induced surface roughness. The roughness spectrum is integrated between the wavenumbers kmin and kmax shown in red and blue respectively to derive the mean square slope (mss). The result suggests that this combined spectrum has negligible impact on mss due to rain. The upper cutoff wavenumber is dervied from [10] which is applicable to a strong diffuse scattering regime. The improved bistatic radar equation proposed in [12] suggests that rain effects on surface roughness can be observed only for very low wind speeds (<3 m/s) where the scattering phenomena shifts from strong diffuse scattering to coherent weak surface scattering.

4.2. CYGNSS NBRCS observations

From the discussions so far it is clear that the presence of rain is correlated with a change in the forward scattering signal. However the induced surface roughness due to impacting drops is not significant at higher wind speeds. The CYGNSS measurements of NBRCS in Fig. 4 show that the effect of rain is visible even at higher wind speeds. This suggests that the additional surface roughness is not caused by the drop impact on the surface but rather may be due to the outflow of down draft air causing excess local winds relative to the non-raining case.

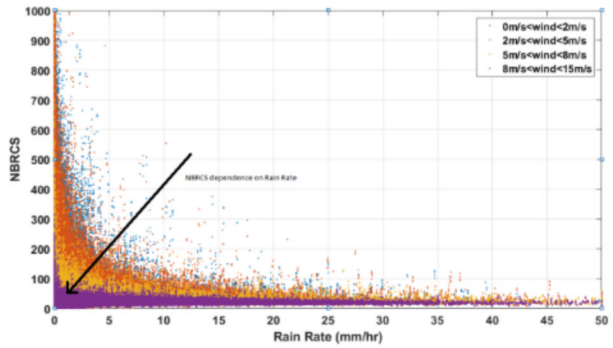


Fig. 5. Dependence of NBRCS on Rain rate for different wind speeds.

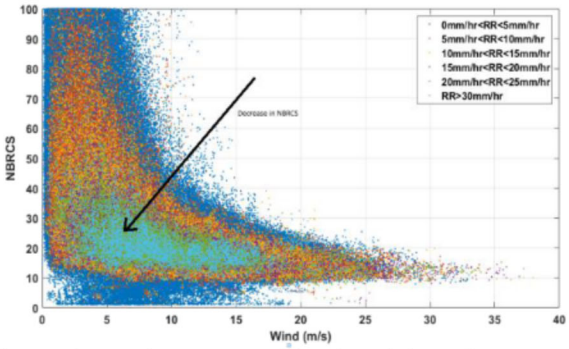


Fig. 4. Change in NBRCS with rain. Higher rain rates are generally associated with lower NBRCS due to outflow winds near convective downbursts.

Fig. 4 represents the dependence of NBRCS on wind. As rain rate increases, the excess wind causes a drop in NBRCS. This effect is visible up to a wind speed range of 15 m/s, above which the wind generated roughness dominates and the excess wind effect due to rain is not visible. Fig. 5 is a plot of NBRCS w.r.t rain rate for different ranges of wind speeds. At lower wind speed ranges, there exists a strong dependence of NBRCS on rain rate as the drop impact on water surface causes a significant change to the surface roughness as suggested in [12]. With slightly higher wind speed ranges the rain induced excess downdraft winds become visible in the form of a reduction in the magnitude of NBRCS. For wind speeds > 15 m/s, the dependence of NBRCS on rain becomes negligible as the wind forcing, independent of rain, dominates the rain effect.

5. DISCUSSIONS

The GNSS-R weak scattering model in [12] suggests that the surface roughness due to rain will be visible only for winds less than 3 m/s. However, observations show a sensitivity due to the excess winds in the presence of rain up to a wind speed of 15 m/s. We hypothesize that the dependence on rain rate at winds greater than 3m/s is an outcome of the down draft and outflow winds associated with convective downbursts of rain. It should however be noted that other effects like swell have not been considered here.

Another advantage of L-band bistatic measurements is that the reduction in NBRCS due to excess local winds caused by rain can be separated from the reduction in NBRCS due to the surface roughening effect from the rain impact.

6. CONCLUSION

In this work we have attempted to bound the impact of rain on the forward scatter radar cross-section using CYGNSS measurements. We have co-located ECMWF wind and GPM IMERG precipitation information with the CYGNSS

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observations. There is a detectable change in the forward scattering signal associated with the presence of rain. We note that the impact roughening by rain dominates at lower wind speeds and the effect of excess winds exist up to a wind speed of 15 m/s in the NBRCS measurements. This also suggests that there is a possibility to measure the excess rain induced wind in the L-band GNSS-R measurements.

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