STUDIES OF TERRAIN SURFACE ROUGHNESS AND ITS EFFECT ON GNSS-R SYSTEMS USING AIRBORNE LIDAR MEASUREMENTS

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ABSTRACT

Analyses of GNSS-R data sets have revealed the occasional presence of coherent signals over land areas. Studies have been conducted of modeling such returns using classical scattering theories that consider the geometry, the frequency band, and surface parameters as inputs. The surface roughness is a crucial parameter that is not widely available from ancillary sources. This paper presents a comparison of roughness statistics derived from Digital Elevation Maps (DEMs) having different spatial resolutions, and shows the importance of having a high-resolution DEM in order to resolve small scale roughness. This is particularly important when modeling reflected signals over very flat surfaces where coherency can be significant.

Index Terms— Surface Roughness, GNSS-R, Lidar, Reflectometry

1. INTRODUCTION

In the past decade, interest in GNSS-Reflectometry has significantly grown following the launch of TDS-1 [1] in 2014 and the 8 small-satellite constellation of the CYclone Global Navigation Satellite System Mission (CYGNSS) [2] in 2016. Analysis of data sets from these missions reveals the presence of coherent reflected signals over both land and ocean scenes in some cases [3]-[5]. A coherent return occurs when contributions from many points on Earth's surface arrive with similar phases and therefore add constructively. Many investigations have been conducted to model land coherent returns using classic scattering theories such as Physical Optics. These theories consider several parameters as inputs such as the geometry, the frequency used, and surface descriptions. The surface is usually characterized by a root mean square (RMS) height of surface roughness that is derived in some studies using Digital Elevation Models (DEMs). The Shuttle Radar Topography Mission (SRTM) DEM [6] is currently a standard DEM used for describing the surface in scattering modeling theories, as the SRTM provides a global DEM with a spatial resolution of 30 m in the +/- 60 degree latitude range.

The GNSS wavelength measured is 19 cm and coherent returns are expected to be significant only over very flat areas where the RMS height is of the order of a few centimeters (for example over inland water bodies) [7]-[8]. Analyses of the SRTM DEM demonstrate that such flat areas do not exist over typical land surfaces. However, this conclusion is impacted by the coarse horizontal and vertical resolution of the SRTM DEM, as clear coherent returns have been observed in CYGNSS reflected signals in a small set of inland locations that do not appear to be associated with inland water bodies. This demonstrates the need to obtain more accurate measurements of the land surface RMS height, which can be achieved using a local airborne Lidar survey.

This paper reports an investigation of the impact of terrain surface roughness on GNSS-R returns using airborne Lidar measurements. To perform this analysis, Lidar data acquired during an airborne Lidar survey over the San Luis Valley, Colorado is used; the dataset was collected to support the land cal/val activities of the CYGNSS mission. The next Section describes the Lidar survey, and the importance of the high-resolution of Lidar DEM is highlighted in Section 3. Section 4 then investigates the relationship between the surface roughness and coherent returns over land surfaces.

2. LIDAR SURVEY

Terrain surface roughness can be estimated from airborne Lidar measurements. The analysis presented in this paper uses airborne Lidar data acquired by Survey And Mapping, Inc. (SAM) in May 2020 over the San Luis Valley, Colorado as shown in Figure 1.

The black box outlines the area of the Lidar survey that was chosen as it receives frequent CYGNSS coverage having a

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high Signal-to-Noise-Ratio (SNR). The surveyed area represents a parallelogram of 77 km (North to South) by 33 km (West to East). This area is particularly of interest for the CYGNSS mission as it also contains two cal/val sites (red areas on the map) that were instrumented with soil moisture sensors in order to calibrate and validate soil moisture products derived from CYGNSS measurements over land.

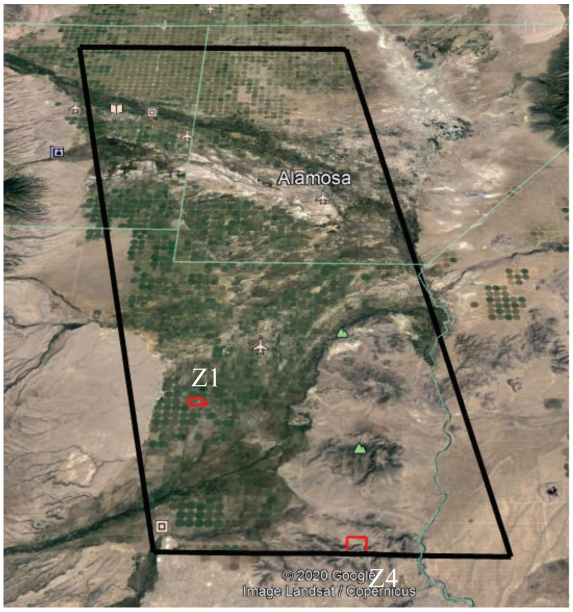

Figure 1: Lidar survey over the San Luis Valley, CO

From the Lidar measurements, three products were derived: a 30 cm DEM, a 10 cm gridded DEM, and the full backscatter waveforms. In this preliminary study, only the 30 cm DEM is analyzed. The vertical accuracy of the Lidar data as reported by SAM is about 5 cm. The accuracy of this data set in the presence of low vegetation remains under evaluation.

3. IMPORTANCE OF HIGH-RESOLUTION DEM

Scattering theories require knowledge of surface roughness to model GPS reflected signals over land. Figure 2 presents a comparison between the SRTM DEM at 30 m resolution and the DEM acquired during the Lidar survey over the San Luis Valley. DEMs at the CYGNSS cal/val sites Z1 (top figure) and Z4 (bottom figure) are shown in Figure 2. The plots on the left are the DEMs at 30 cm spatial resolution that were acquired during the Lidar Survey. The column in the middle is the same DEM downgraded to a 30 m resolution for comparison with the SRTM DEMs shown in the right column. The Z1 site consists mainly of flat agricultural sites whereas the Z4 site includes more topography. From the comparison of Figure 2, it can be seen that SRTM DEM is close to the Lidar DEM downgraded to 30 m resolution where large topography is observed (at Z4), while larger discrepancies are observed over the flatter Z1 area. These differences will cause differences in the surface RMS height and therefore in model predictions. Note the vertical accuracy

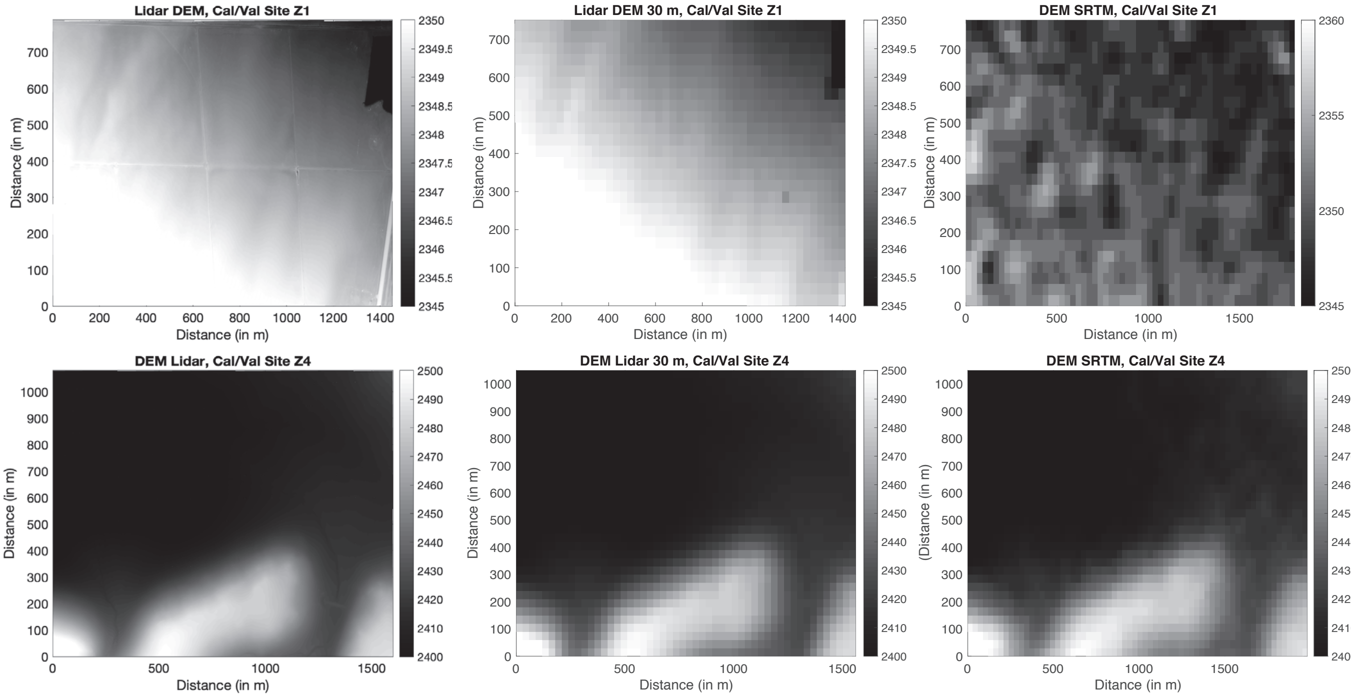

Figure 2: DEM at the cal/val sites: Z1 (top figures) and Z4 (low figures). The DEMs were produced using: the 30 cm Lidar measurements (left), DEM downgraded to 30 m resolution (middle) and SRTM DEM at 30 m resolution (right)

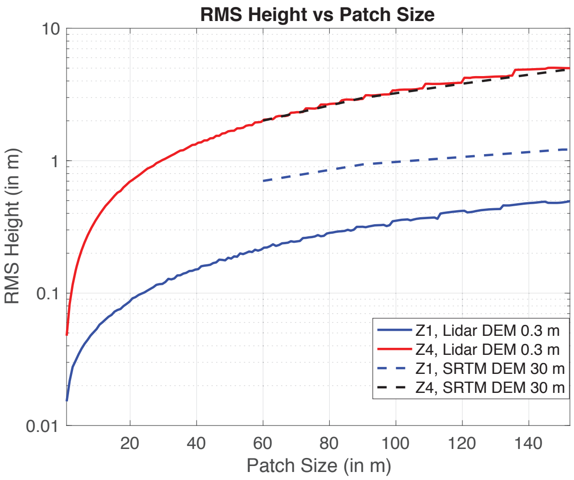

Figure 3: RMS height as function of patch size for the two Cal/Val Sites using Lidar measurements (bold lines) and SRTM DEM (dashed lines)

of the SRTM is stated as 3.5 m [9], clearly indicating the challenges of using it to describe smaller scale roughness.

A more detailed study of the impact of the horizontal resolution on the estimation of RMS height was also performed. The area of interest was divided into patches of a specified size, and the RMS height was then computed for each patch and the results averaged over patches. This allows an analysis of the impact of the patch size on the resulting RMS height. Figure 3 presents the results of this analysis. The results show that the RMS height calculated from the Lidar Survey and the SRTM DEM are in good agreement for Z4 at patch sizes greater than ~ 60 m, but that the SRTM result significantly overestimates terrain roughness at Z1 as compared to the Lidar DEM. These differences are likely impacted by the much greater vertical errors in the SRTM.

4. COHERENT RETURNS OVER LAND

Figure 4 plots the predicted coherent reflection coefficient for CYGNSS as a function of the surface RMS height and incidence angle under the Physical Optics model. The rapid decrease in the coherent reflection coefficient for rougher surfaces shows that coherence is likely to be significant only when the terrain RMS height remains < ~ 5 cm within a significant fraction of the first Fresnel zone on Earth's surface.

From Figure 3, the Lidar DEM at both the Z1 and Z4 sites shows that the computed RMS height exceeds the ~ 5 cm level needed for significant coherence even after averaging over a 20 m patch. These results suggest that the received field is unlikely to have significant coherent contributions even for the relatively flat Z1 site. These results also suggest that any coherent returns in the San Luis valley are most likely to be associated with inland water bodies.

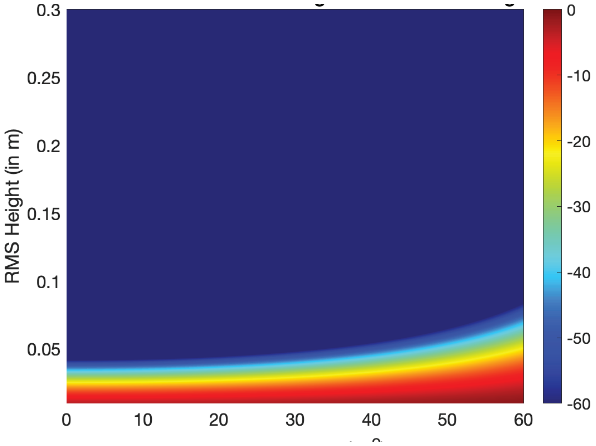

Figure 4: Coherent Reflection Coefficient Amplitude (dB) as a function of RMS height and incidence angle

In other locations, coherence appears to occur in areas where no water bodies can be identified. One such example where CYGNSS coherent reflected signals are observed is located near White Sands, New Mexico (Figure 5). The green dots shown represent coherent returns received by CYGNSS between January and June 2020. The region seems to be extremely flat (even flatter than the region near the Z1 site), and no water bodies are visible in optical imagery of the area.

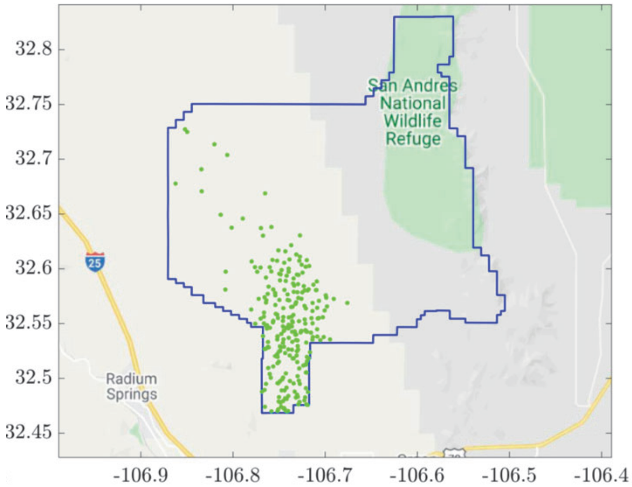

Figure 5: CYGNSS coherent returns observed between January and June 2020 near White Sands, New Mexico

High resolution Lidar data is of interest in this area in order to fully resolve small scale roughness to support the modeling of coherent reflected signals in this region. It is noted that even airborne lidar data may be insufficient to resolve "electromagnetic" scale roughness on horizontal and vertical length scales finer than ~ 1 m and ~ 5 cm, respectively, but that airborne lidar datasets remain useful for assessing the presence of roughness on larger "intermediate" scales.

Analyses of airborne lidar datasets for this region will be reported at IGARSS 2021.

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