Empirical Doppler and Temporal Models of the S-band Backscattering from Forest

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***Abstract*—This paper presents an analysis of the temporal characteristics of the electromagnetic wave backscattered from wind-influenced forest at low grazing angles. The data were collected at the US Air Force Stockbridge Test Site in Stockbridge, New York during the last week of August 2017 using portable, high-power S-band radar. We show that the data are in good agreement with the Narayanan, Lacaze, and Billingsley temporal and Doppler models.**

***Index Terms*—Radar clutter, Doppler spectrum, decorrelation time, forest.**

I. INTRODUCTION

Backscattering from wind-influenced forest are distributed into a spectrum through the Doppler effect. This phenomenon has strong implications for various radar systems and applications, e.g., moving target indication, space-time adaptive processing, and other Doppler signal processing techniques [1-4].

To understand the characteristics of temporal phenomena, numerous studies of backscattering from a forest using measurement data have been published. Wong described the decorrelation of backscattering from trees using a random collection of rotating dipole scatterers [1]. Narayanan incorporated a wind speed parameter in Wong's model and compared with the X-band measurement data for different tree types [2]. In addition, Lacaze introduced a simple decorrelation time model based on random propagation time theory [3] and demonstrated a good fit with the measurement data described in [2]. Furthermore, Billingsley analyzed and modeled the power spectral density to understand the wind effect on Doppler spectra of the backscattering from trees [4].

In this paper, we present an analysis of the temporal behavior of the S-band backscattering data collected from forest with mixed coniferous and deciduous trees. The range-Doppler map was generated and the range values were aligned with the forest spatial profiles. In addition, existing empirical models of the decorrelation time and Doppler spectra are discussed and compared with the measurement data.

II. DATA COLLECTION

An experimental study was designed and implemented to collect backscattering data from mixed coniferous and deciduous trees with an S-band radar (3.195 GHz). The radar system transmitted an LFM waveform with a 15 MHz bandwidth corresponding to Δr = 10 m down range resolution and PRF of 1 kHz. A dish reflector antenna with a beamwidth of $\phi_B = 5^\circ$ was used for both transmitting and receiving the vertically and horizontally polarized signals. The antenna was mounted on an approximately 30 m tower. We calculated the grazing angle, α_T, based on the antenna pointing direction towards the center of the illuminated area and the local terrain slope from the digital terrain data [5]. The grazing angle, α_T, varied from 2.6° to 4.2° during the campaign. We collected the data for roughly 1 second, which provided approximately 1,000 temporal samples.

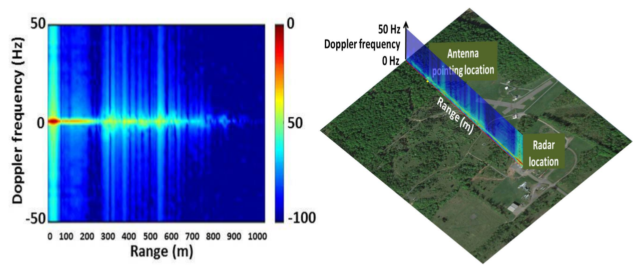

Fig. 1: S-band backscattering range-Doppler map

III. TEMPORAL ANALYSIS

The Doppler spectra of the radar reflections from the forest are estimated using the modified periodogram. To suppress the sidelobes of the Doppler spectra, the window sequence weights of the periodogram are applied in the time domain to the measured data. The range-Doppler map can be generated by using the modified periodogram again along the range samples. Figure 1 shows the VV polarized range-Doppler map, which is normalized by the maximum intensity. The range-Doppler map shows that the Doppler features tend to be symmetric with respect to the zero-Doppler line. In addition, the range-resolved Doppler features are well aligned with the forest spatial profiles. The data were registered using the geodesic coordinate information from our GPS- and IMU-based antenna pointing system. The strong backscattering returns and broad

Doppler spectral width are observed at the edge of the forest where an open field gives a way to tall trees.

For the quantitative temporal analysis and empirical model study, the autocorrelation functions were also computed using the slow-time samples. The decorrelation time of backscatter can be obtained by measuring the time when the envelope of the autocorrelation function decays to $\frac{1}{e}$.

IV. EMPIRICAL MODELS

A. Temporal decorrelation model

To estimate the decorrelation time of X-band backscatter, Narayanan modeled the autocorrelation function in [2] as

$$R(\tau) = \exp(-C_1^2 U^2 \tau^2)[\frac{2}{3} + \frac{1}{3}\cos(2C_2 U\tau)]^2 \quad (1)$$

where U is the wind speed in m/s, C_1 and C_2 are the decorrelation constants for different tree types in rad/m. We estimated the decorrelation constants using the least-square fit and found $C_1 = 0.4$ and $C_2 = 1.5$ for the wind speed of 3 m/s, which may depend on the mixture ratio of different tree types. Additionally, Lacaze's decorrelation model is expressed as

$$R(\tau) = \exp[-(\frac{\tau}{\tau_0})^\alpha] \quad (2)$$

where α is the slope and τ_0 is the decorrelation time [3]. To estimate $R(\tau)$, the decorrelation time, which was measured as being $\tau_0 = 233$ ms from the data, is used in (2). Similar to (1), we estimated the slop parameter using the least-square fit and found $\alpha = 1.7$ in this case. In [3], the value of α varies between 1 and 2. Figure 2 shows the comparison of the measured autocorrelation function with the empirical models. The fit of Lacaze's model is generally good up to a value of nearly τ_0. Narayanan's model follows overall slope of the measurement data. The results show that the empirical models developed for X-band returns can be applied the S-band backscattering from forest with mixed coniferous and deciduous frees.

B. Doppler spectrum model

The exponential spectral density for a forest is analytically expressed by Billingsley as

$$P(f) = \frac{r}{1+r}\delta(f) + \frac{1}{1+r}\frac{\lambda\beta}{4}\exp(\frac{-\lambda\beta}{2}|f|), -\infty < f < \infty \quad (3)$$

where λ is the wavelength of the carrier frequency, r is the dc/ac ratio, and β is the shape parameter. The dc/ac ratio, which is dependent on both wind speed and frequency, is empirically derived as

$$10\log_{10}(r) = -15.5\log_{10}(2.237U) - 12.1\log_{10}(f_0) + 63.2 \quad (4)$$

where f_0 is the carrier frequency in MHz. The value of β is independent of the frequency band from VHF to X-band. Using Billingsley's model, we estimated the spectral density and dc/ac ratio [4]. Figure 3 shows the normalized Doppler spectrum of the same data discussed in Figure 2 and the

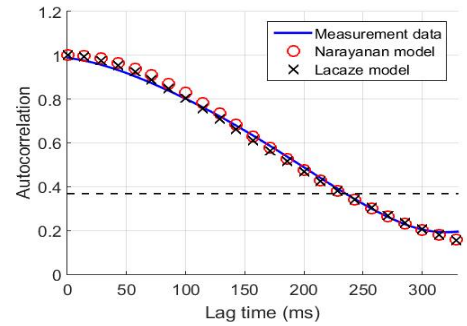

Fig. 2: Comparison of the estimated autocorrelation function and empirical models for a specific location

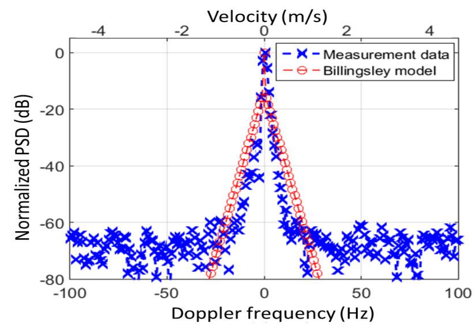

Fig. 3: Comparison of the estimated Doppler spectrum and empirical model

model with $\beta = 12$ in light wind condition [4]. The value of r is approximately 8 dB. The comparison shows that the Billingsley model slightly overestimates the Doppler behavior in this case.

V. CONCLUSION

The results presented have shown that the forest profiles may significantly influence the peak and width of the Doppler spectra of the S-band backscatter returns from forest. In addition, we have estimated the decorrelation time and Doppler spectrum and compared with the empirical models. The comparison shows that the decorrelation models developed for the X-band backscattering can also be applied to S-band backscattering. Furthermore, the Billingsley model agrees with the data generally well with a slight overestimation of the Doppler relative to the measurement data.

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