X-Band high range resolution radar measurements of sea surface forward scatter at low grazing angles

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***Abstract*—Radar measurements of a radar calibration sphere test target suspended in sea surface multipath propagation conditions are reported. Wideband measurements together with high range resolution (HRR) processing were employed to resolve the direct reflection component and sea surface reflected multipath components of the received signal. The temporal correlation characteristics of the resolved single bounce multipath signal component are investigated, which shows that a strong temporal correlation in the sea surface forward scatter component exists. Based on this measurement, we propose a temporal correlation extension to an existing low-angle propagation model, together with a correlation filter structure to realize the correlation extension in computer simulation.**

***Index Terms*—radar multipath, sea surface forward scatter, temporal correlation.**

I. Introduction

Low-angle radar tracking has plagued radar designers for several decades [1]. Several low-angle radar tracking solutions that have been proposed [2], [3] rely on models of the multipath propagation over the sea surface. The performance of such solutions is highly dependent on the quality of the propagation models used [4]. Despite the apparent need for accurate models, a widely accepted signal model of realistic low grazing angle sea surface forward scatter is not available in the open literature. The aim of the current work is to improve the realism of existing sea surface multipath models.

In low-angle radar tracking the surface reflected multipath signal components are usually unresolved in the angular, range and Doppler dimensions due to radar resolution constraints. Hansen *et al.* made use of an ultrawideband radar to make high range resolution (HRR) measurements of sea surface forward scatter [5] in which the authors were able to resolve the direct and multipath (both single and double bounce) components of the received signal. In the present work, HRR processing was used to obtain high enough range resolution to separate the direct and multipath components of the received signal in order to investigate the characteristics of the sea surface forward scatter component.

A surface is considered to be rough if the Rayleigh's criterion, namely

$$\sigma_h \sin\psi_0 > \frac{\lambda}{8}, \quad (1)$$

is satisfied, where λ is the wavelength, ψ_0 is the angle of incidence and σ_h is the standard deviation of the normally distributed surface height of the ocean. Reflection from a rough surface can be separated into specular (coherent) and diffuse (incoherent) components. The specular component of the reflected electromagnetic wave is defined as originating from within the first Fresnel zone. This means that any reflection point which results in a path length difference of less than $\lambda/2$ relative to the nominal reflection point will contribute to the specular reflection component. Any reflection point which results in a phase difference of more than $\lambda/2$ is assumed to be incoherent relative to the nominal reflection point. The voltage sum of all such paths at the receiver is referred to as the diffuse reflection.

The development of the rough surface specular reflection coefficient is reviewed in [6]. The diffuse reflection power can be found by using the model presented by Barton [1]. This model predicts the power densities of the diffuse component in range, azimuth, elevation and Doppler and is still cited as the standard method of predicting the diffuse reflection power in low-angle radar propagation.

For the development and performance prediction of modern radar processing algorithms it is required to accurately model both the amplitude and phase information of the multipath signal. The signal model presented by Blair and Brandt-Pearce [7] is a potential candidate because it includes specular and diffuse reflection terms with their respective phase terms. In their model the diffuse reflection coefficient is assumed to be Rayleigh distributed with uniformly distributed phase. This implies that the diffuse reflection component is temporally uncorrelated. However, measurements reported by Lo *et al.*

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[8], [9] indicated strong temporal correlation. As will be shown, the measurements presented in this paper confirm the strong temporal correlation in the diffuse reflection component. Based on the temporal autocorrelation function (ACF) estimated from the current measurements, we propose an extension to the multipath signal model of Blair and Brandt-Pearce.

II. Test Setup

An X-band measurement radar overlooking the sea was used to make wideband measurements of a 25 cm diameter radar calibration sphere suspended above the sea surface.

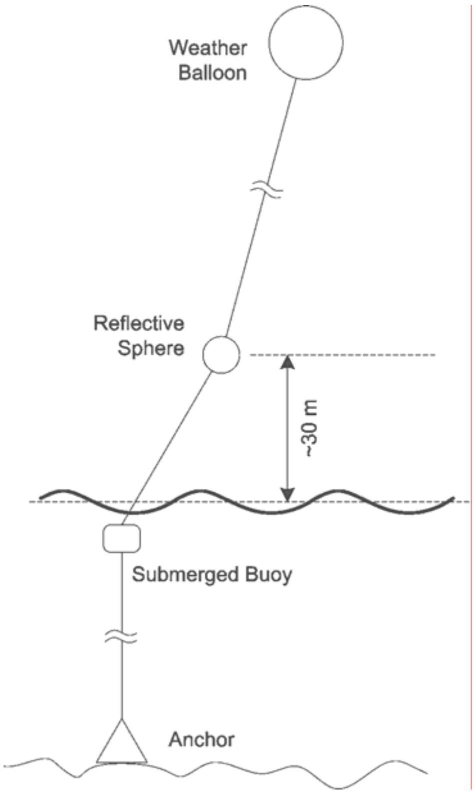

Figure 1 – Test setup used during the measurements.

The vertically polarized radar antenna was positioned approximately 20 m above the mean sea level (AMSL). The reflective sphere was suspended approximately 30 m AMSL at a range of 2430 m from the radar using a weather balloon and a submerged buoy anchored to the sea bed. A drawing of the setup is given in Figure 1.

The angular separation between the sphere and balloon was sufficient to suppress the return from the balloon by more than 30 dB. The measurements were made in relatively calm conditions, estimated to be between sea state 1 and 2.

During initial testing of the test setup it was found that even if the buoy is partially submerged, the upper surface of the buoy still caused a clutter return to be observed. The buoy was thus submerged by approximately 0.5 m.

Stepped frequency measurements over a wide RF bandwidth were continuously recorded for several minutes. The number of frequencies and frequency step rate used resulted in a wideband sweep period of 20 ms. HRR profile data was obtained from the stepped frequency measurements by applying standard synthetic range profiling (SRP) techniques. A range resolution of approximately 10 cm was achieved which was sufficient to separate the direct and multipath components.

III. Method of Analysis

The recorded data was calibrated for HRR processing by correcting for the system's wideband point target response. This response was obtained by measuring the sphere and balloon setup used for the multipath measurements at a much greater elevation angle in order to avoid multipath interference. Each HRR profile was normalized by the amplitude and phase of the direct component to compensate for slight fluctuation in the radar cross section (RCS) of the sphere as well as the phase shift due to range migration. The single bounce multipath component was then isolated by estimating its delay relative to the direct component and extracting samples at this delay across all HRR profiles.

A signal model for the content of the single bounce multipath component can be obtained by using the multipath signal model presented in [7]. Based on their model, the direct and multipath components of the received signal can be expressed as

$$S = \alpha e^{j\phi}\Big(1 + 2ge^{j\Delta\phi}\left(\rho_S + \rho_d e^{j\phi_d}\right) + g^2 e^{j2\Delta\phi}\left(\rho_S{}^2 + \rho_d{}^2 e^{j2\phi_d}\right)\Big) \tag{2}$$

where α represents the amplitude and ϕ the phase of the direct component; g is the ratio of antenna gain in the direction of the surface reflection to the antenna gain in the direction of the target; $\Delta\phi$ is the phase shift associated with the path length difference between the direct and surface reflection paths (including the phase shift due to specular reflection from the sea surface, which is approximately 180°); ρ_S is the specular reflection coefficient and ρ_d and ϕ_d are the magnitude and phase of the diffuse reflection coefficient, respectively. The single bounce multipath component, normalized to the direct component, can therefore be written as

$$S_{sb,n} = 2ge^{j\Delta\phi}\left(\rho_S + \rho_d e^{j\phi_d}\right). \tag{3}$$

For a stationary target setup, only the diffuse reflection coefficient in this signal model is time dependent which permits an analysis of the temporal correlation properties of the diffuse reflection coefficient.

In order to test the validity of a temporally correlated diffuse reflection coefficient, a computer simulation of the single bounce multipath component was generated using the parameters of the measurement setup. Correlated Rayleigh samples, with an ACF based on the measured diffuse reflection ACF presented in [8], were used for the diffuse reflection coefficient. The ACF of the simulated single bounce multipath component was then compared to that of the measured data.

IV. Results and Discussion

The upper graph of Figure 2 shows an example of HRR profile data of the reflective sphere measured in multipath propagation conditions. The direct and multipath signal components (both single and double bounce) are clearly distinguishable in range. Note that the direct reflection from the sphere is at a closer range than the multipath reflections and has constant amplitude whereas the multipath signal components exhibit significant amplitude fluctuation. The envelope of the corresponding single bounce multipath component is shown in the lower graph of Figure 2.

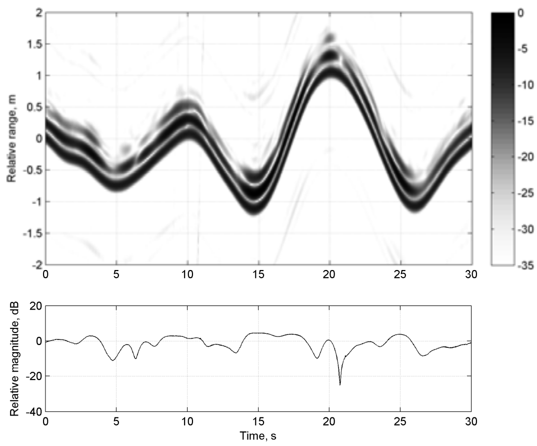

Figure 2 – High range resolution profile plot showing an example of the direct and multipath signal components of the reflective sphere measurements. The relative amplitude of the single bounce component is shown in the lower graph.

The temporal ACF of the single bounce multipath component, extracted from the measured data, is shown in Figure 3 together with the temporal ACF of the simulated signal. It is clear that there is significant temporal correlation in the single bounce multipath component. The temporally uncorrelated diffuse reflection coefficient used in Blair and Brandt-Pearce's multipath signal model, therefore, is not appropriate. It is also clear that the ACF used in the current computer model resulted in a simulated signal with temporal correlation properties similar to that of the measured signal. However, when compared to the temporal ACF presented in [8], the present data suggests a much longer correlation time.

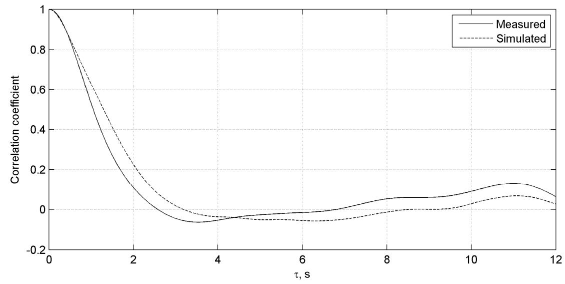

Figure 3 – Temporal autocorrelation functions for measured and simulated data.

This might be attributable to differences in sea states and prevailing winds. For the test setup used for these measurements the wind speed was less than 1 m/s resulting in an exceptionally smooth sea surface. The period of the swell varied between 9 seconds and 15 seconds, and the swell direction was approximately perpendicular to the radar's line of sight. This repetitive nature of the surface is thought to be responsible for the positive correlation value in Figure 3 at a time lag of 11 s.

V. Extension of Multipath Signal Model

Based on these results it is proposed to extend the multipath signal model presented in [7] by incorporating the temporal autocorrelation function

$$\mathrm{R}\left(\tau\right) = e^{-\frac{\tau}{\tau_d}} \cos\left(2\pi \frac{\tau}{T_o}\right) \tag{4}$$

with decay parameter τ_d and oscillation parameter T_o into the diffuse reflection coefficient. The values $\tau_d = 2.5$ s and $T_o = 1.7$ s were estimated from Figure 5 in [8]. From the measured data the values $\tau_d = 0.4$ and $T_o = 4.5$ were estimated which, when substituted into (4), results in an autocorrelation function with a longer correlation time.

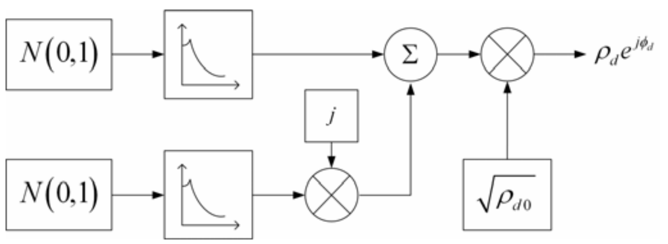

Figure 3 – Diagram of correlated diffuse reflection coefficient generator.

A correlated diffuse reflection coefficient can be realized using the correlated Rayleigh noise generator structure shown in Figure 3. The narrowband correlation filters are efficiently realized with IIR filters with the following z-transform

$$H(z)=\frac{1}{1-2K_1\cos(K_2)z^{-1}+K_1{}^2z^{-2}} \tag{5}$$

where $K_1=\exp(-T_S/\tau_d)$, $K_2=2\pi T_S/T_o$ and T_S is the sampling period. The Rayleigh parameter ρ_{d0} in Figure 3 is calculated using (11) in [7]. It should be noted that the structure for generating the diffuse reflection component is a generally applicable extension to the standard model. The values given in this section for the parameters for τ_d and T_o are however only valid for the specific combination of sea conditions encountered on the day the measurements were made. Future measurements have been planned which should extend the range of sea conditions and corresponding values of τ_d and T_o.

VI. Conclusion

High range resolution radar measurements of sea surface forward scatter have been presented that shows strong temporal correlation in the diffuse reflection component. This agrees with [8] which presents the only similar measurements reported in the open literature. Radar signal models of sea surface forward scatter found in the open literature do not incorporate this temporal correlation property of the diffuse reflection coefficient. Based on the close agreement between the autocorrelation function of simulated and recorded data, an extension to the multipath signal model presented by [7] is proposed. Finally, a correlated diffuse reflection coefficient generator is suggested to realize this temporal correlation property in computer simulation.

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