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Impact of Orthogonal, Pseudorandom Radar Waveforms in Estimating the Backscatter Frequency Correlation Function

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Abstract

To determine the biomass of a forest, a synthetic aperture radar (SAR) could be used to measure the frequency correlation function (FCF) of backscatter to estimate the average canopy height. An FCF capable SAR must measure the target backscatter at several frequencies simultaneously. This will require transmitters with orthogonal waveforms to maintain a low system complexity. Circularly shifted m-sequences are proposed as suitable waveforms. Their limitations and some solutions are discussed. Their ability to correctly estimate the FCF is also assessed through a computer simulation. As an example, it is shown that a maximal length sequence with 2047 chips can reasonably estimate the FCF of a target in the presence of clutter.

1 Introduction

Radar is an established tool for observing many physical processes. Its utility in monitoring forests is of special interest because forests play an important role in both the water and carbon cycles. Since forests act as carbon reservoirs, an extensive amount of work has been done to estimate the amount of carbon or biomass that may be stored in them. An important parameter that is needed for estimating biomass is the tree or canopy height [1].

Synthetic aperture radars (SARs) could become much more capable tools for estimating canopy height if they could additionally measure the complex frequency correlation function (FCF) of radar backscatter. The FCF is a measure of how similar the radar backscatter is over a small frequency range of the same target.

Measuring a target's backscatter at several frequencies simultaneously is a significant difficulty in designing a SAR which can measure the FCF. This necessitates the use of several transmitters which transmit waveforms that are quasi-orthogonal to each other. A maximal length sequence (m-sequence) is a type of pseudorandom noise (PN) code that could be used to achieve orthogonal waveforms. This paper provides a preliminary investigation on how accurately the FCF could be measured when m-sequences are used for the transmit waveforms and discusses some practical issues in using those waveforms in a SAR. It will be shown that shifted m-sequences could accurately estimate the FCF because of their cross-correlation properties, if the practical issues are resolved.

This paper is organized as follows: the first section gives a brief explanation of the FCF, m-sequences, and practical considerations in using m-sequences in a SAR; the next section discusses the method used for assessing the impact of m-sequences on estimating the FCF; the third section is a presentation of the results; and the fourth section presents conclusions from this investigation.

2 Background

2.1 Frequency correlation function

The FCF is a metric that can characterize a target's backscatter over a small frequency range. Suppose a radar illuminates a distributed target and measures the backscatter with several frequencies that are very close to the center frequency (f_0). The backscatter will be approximately independent of the illuminating frequency, or

$$\langle |E(f)|^2 \rangle \cong \langle |E(f_0)|^2 \rangle, \tag{1}$$

where $E(f)$ is the backscatter random process. It can be approximated as a stationary random process under the above assumption that the illuminating frequency is close to the center frequency. This means that the covariance of $E(f)$ is only a function of the frequency shift

$$C(f_1, f_2) = \langle E(f_2) E^*(f_1) \rangle = C(f_2 - f_1). \tag{2}$$

The complex FCF of this process is then defined as the normalized covariance function

$$R(\Delta f) = C(f_2 - f_1) / \langle |E(f_0)|^2 \rangle, \tag{3}$$

which has both magnitude and phase [2]. In practice, the covariance function is approximately characterized from several independent sample measurements at different frequency points. In this case, the correlation becomes a summation.

The FCF is primarily affected by the spatial structure of a target rather than any frequency-dependent material properties. It has been shown by Sarabandi and Nashashibi that the FCF can be used to estimate the thickness of a random medium [2]. This property of the

FCF could be very useful for estimating the average height of a forest.

2.2 Orthogonal m-sequences

A maximal length sequence is a type of PN binary sequence. It can be created using a shift register with appropriately connected taps between the register output and individual flip-flops in the register. A shift register with m flip-flops can create an m-sequence that is $N = 2^m - 1$ bits, or chips, long. A defining characteristic of an m-sequence is that every combination of m bits, except for the zero vector, will be represented just once as a window m bits long is shifted along one period of the m-sequence. It is in this sense that the sequence is "maximal." The properties of m-sequences are well known [3]. One useful property of m-sequences for radar pulse compression is that an m-sequence's autocorrelation sidelobe level approaches $1/N$.

A set of quasi-orthogonal transmit waveforms can be created from one m-sequence by circularly shifting it to make another sequence. That sequence can be circularly shifted again to make yet another sequence until the required number of sequences is reached. This coding scheme was utilized by Jumani and Sarabandi for lunar imaging from a terrestrial multi-static SAR [4]. The cross-correlation between the original sequence and its circularly shifted version is similar to the autocorrelation of the original sequence. However, as seen in Fig. 1, there are points, or "images," of high correlation that appear at the lag which is equal to the shift amount. These images can negatively impact pulse compression and need to be taken into consideration when using m-sequences for orthogonal coding.

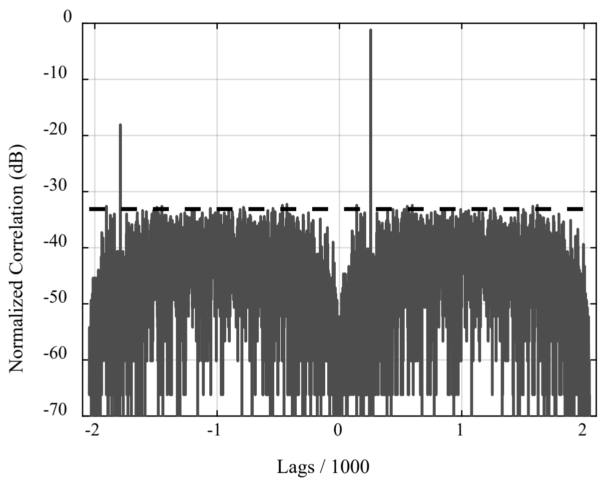

Figure 1. The cross-correlation between a 2047-chip m-sequence and another version of itself circularly shifted by 256 chips. Two peaks of high correlation, or images, can be seen at lag 256 and -1,791. The dashed lined is the theoretical sidelobe level of $1/N$ for the autocorrelation of an m-sequence composed of 1's and -1's.

2.3 Airborne SAR using m-sequences

Circularly shifted m-sequences could be used to achieve quasi-orthogonal transmit waveforms in an airborne SAR application with a few modifications. According to Jumani and Sarabandi, N transmitters can be assigned unique m-sequences for pulse compression without contamination from cross-correlation images if

$$N = \left\lfloor \frac{\tau_p}{T_D} \right\rfloor, \tag{4}$$

where τ_p is the time duration of the entire transmit pulse and T_D is the two-way delay time (or depth) of the target [4]. Consider a typical scenario for a side-looking SAR as illustrated in Fig. 2, where distances are derived from the operating parameters of NASA's UAVSAR [5].

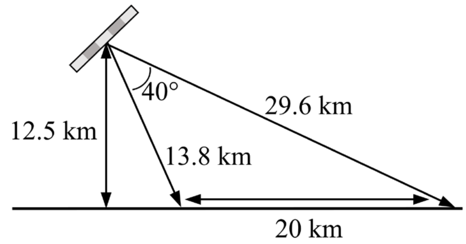

Figure 2. Representative SAR imaging dimensions viewed from the front or rear of an airborne SAR platform. A phased array scans a 20 km swath using multiple beams to segment the swath. The incident angles of the 13.8 km and 29.6 km rays are 25° and 65° respectively.

The target depth in Fig. 2 is the difference between the nearest and farthest points in the swath. In this case, the target depth is 15.8 km with a 105 µs two-way time delay. To use 5 transmitters, the total pulse duration would need to be above 525 µs to avoid corruption from a different transmitter. This presents a problem, though, because echoes from the closest points on the ground will begin to arrive at the radar after only 92 µs.

A modification could be made to the SAR to overcome the limit on the maximum pulse length imposed by the closest scatterers on the ground. The SAR's receiver could use a multi-beam phased array to split the 20 km swath into smaller swaths. This would effectively reduce the target's depth because of the relationship between time delay and angle of arrival in this scenario. This solution has already been proposed by Krieger, et. al. [6] for multiple-input, multiple-output SAR (MIMO-SAR). Thus, to allow 5 transmitters in the scenario in Fig. 2, the sub-swaths would need to have a depth smaller than 18 µs so that a 90 µs transmit pulse could finish before the first echoes begin appearing.

3 Methodology

A simulation was constructed to evaluate the impact of using circularly shifted m-sequences in estimating a target's FCF. The simulation does this by calculating the radar backscatter from a simple target structure with a meaningful FCF, adding interference from clutter targets and adjacent transmit waveforms, estimating the target's backscatter by cross-correlating each m-sequence with the total response, and then computing an estimated FCF.

The target structure used is shown in Fig. 3. The radar scene is composed of a lossy dielectric sphere above an infinite dielectric ground plane. The scattering amplitudes of the target are calculated from the sum of four scattering components: (1) direct backscatter from the sphere, (2) bistatic scattering from the sphere to the ground, (3) bistatic scattering from the ground to the sphere, and (4) scattering off the ground plane to the sphere and then back to the ground plane. The last component can also be thought of as direct backscatter from the sphere's mirror image in the ground plane. The direct and bistatic scattering amplitudes from the sphere are calculated using verified codes that implement the closed-form Mie solution as formulated by Bohren and Huffman [7]. Scattering from the ground plane is assumed to be completely specular. Thus, the well-known reflection coefficients for s- and p-polarizations for a dielectric interface are used. This method of calculating the backscatter is an approximation that ignores multiple reflections between the sphere and the ground plane.

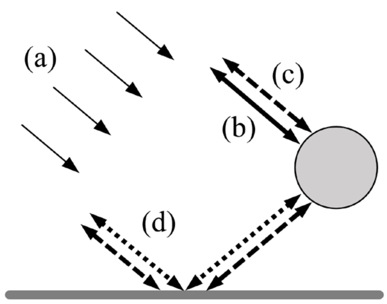

Figure 3. Simple scattering structure of a sphere above a ground plane when illuminated by a plane wave (a). There are four contributions: (b) direct backscatter from the sphere, (c) two bistatic sphere-ground reflections, and (d) backscatter from the sphere's mirror image in the ground plane.

The target's response to a radar pulse modulated by an m-sequence is computed in the following manner. First, if there are K transmitters, then K circularly shifted versions of one m-sequence are created and designated as $\mathbf{x}_k$, where the boldface indicates that $\mathbf{x}_k$ is a sequence of values or a vector (in this case it is a sequence of 1's and -1's). Second, the backscatter amplitude for each frequency E_k is computed such that $E_k = E(f[k])$, where $f[k] = f_0 - k\Delta f + B/2$, B is the bandwidth to sample, Δf is B/K, and f_0 is the center frequency. Third, the impulse response of the scene is created with

$$\mathbf{h}_k = E_k\delta[n - N_d] + \sum_{j=0}^{N_t-1} A_{j,k}\delta[n - N_j], \qquad (5)$$

where $\delta[n]$ is a Kronecker delta, N_t is the number of clutter targets, and N_d and N_j are the sample delays of the target of interest and surrounding clutter respectively. The value of N_j is restricted so that the condition in equation 4 is met. It also further restricted from being close to N_d so that no clutter targets fall in the same resolution bin as the target of interest. The backscatter amplitude of the surrounding clutter targets $A_{j,k}$ are set to the same value for each k such that

$$A_{j,k} = \alpha \cdot \frac{|E_k|}{N_t} \quad \forall \ j, \qquad (6)$$

where α is an arbitrary scaling factor. Fourth, the total response of the scene is calculated by

$$\mathbf{y} = \sum_{k=0}^{K-1} \mathbf{x}_k * \mathbf{h}_k\,, \qquad (7)$$

where the asterisk $(*)$ denotes convolution. Equations 5 – 7 simplify the received radar signal in two respects. First, unlike a real radar transceiver, they do not explicitly modulate $\mathbf{x}_k$ onto the carrier frequency and then demodulate the response. Such a consideration is outside the scope of this paper. Second, the target's response to $\mathbf{x}_k$ may not be a simple convolution of $\mathbf{x}_k$ and a Kronecker delta scaled by the corresponding backscatter amplitude E_k. This is because $\mathbf{x}_k$ will have some bandwidth associated with it that $E(f)$ may vary over if it is large enough.

Fifth and finally, the target's response to each transmitter is extracted by cross-correlating the total response with each of the unique transmitter waveforms, or

$$\mathrm{R}_k[m] = \sum_{n=0}^{N-1} \overline{y[n]}\mathrm{x}_k[n + m]\,. \qquad (8)$$

The magnitude and phase of R_k at the lag corresponding to the target's location is taken as the estimate of E_k and saved. The estimates of each transmitter are then arranged in an array and the normalized autocorrelation of the array is computed. This produces an estimate of the FCF that is then compared with the target's true FCF. The true FCF is found by calculating $E(f)$ at a finer frequency spacing and taking its autocorrelation.

4 Results

The methodology outlined in Section 3 was implemented in MATLAB and run on a PC desktop. Table 1 lists several important simulation parameters and the values to which they were set for the simulation. The center frequency was restricted to L-band because this band can easily penetrate forest canopies. The relative permittivities of the sphere and ground were chosen to be like the permittivities of wood and soil respectively. The sphere was also positioned above the ground plane at a height of about 15 m, which corresponds to the height of a deciduous tree. The number of transmitters was adjusted until the FCF estimates captured most of the variation in the true FCF.

Table 1. Simulation parameter values.

Description	Symbol	Value
Center frequency	f_0	1.5 GHz
Incident angle	θ_i	32°
Sphere height	h	$75\lambda_0$
Sphere radius	a	$0.4\lambda_0$
Sphere relative permittivity	ε_s	$5 + 0.05i$
Ground relative permittivity	ε_g	4
Number of clutter targets	N_t	792
Clutter amplitude factor	α	10
Chip period	T_c	1 μs
Number of chips	N_c	2047
Number of transmitters	N_{ch}	26
Frequency spacing	Δf	1.5385 MHz

The main result of the simulation is shown in Fig. 4. The simulated FCF estimates do not exactly match the value of the ideal, simulated FCF. This is to be expected because of the non-ideal orthogonal waveforms and additional clutter targets. However, the estimates do capture major variations in the FCF.

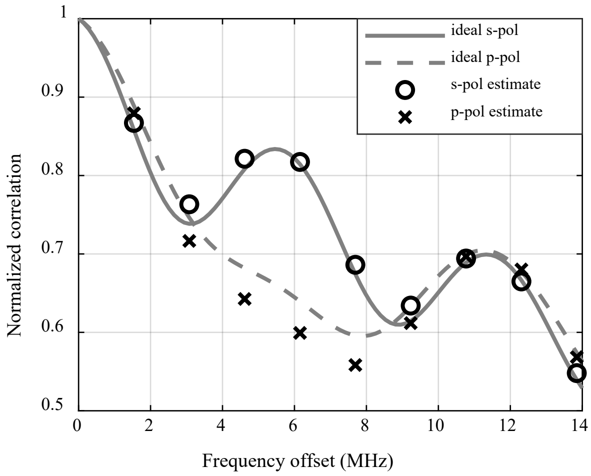

Figure 4. Ideal and estimated FCF's for the s- and p-polarizations.

5 Conclusion

We investigated a method for measuring the FCF with an SAR which required the simultaneous use of many transmitters to measure the target's backscatter across a range of frequencies. It was found that circularly shifted versions of an m-sequence could be used as orthogonal waveforms that would allow the target's responses to each transmitter to be separated at a receiver. This was possible if the swath that the SAR was imaging was divided into sub-swaths so that the pulse length of the SAR was many times longer than the pulse's two-way travel time through the sub-swath. The FCF estimated in this way showed agreement with the ideal FCF curve. This is a promising result which indicates that a practical airborne SAR could be designed which measures the FCF. An FCF-capable SAR could help measure the mean canopy height of forests.

6 References

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