Simulation of Sea Clutter at Low Grazing Angles

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Keywords: Coherent sea clutter, Low grazing angles, Statistical models, Shape parameters.

Abstract. An algorithm is presented in this paper to generate correlated coherent sea clutter with high credibility. It can be considered as a high credible simulation result when we generate sea clutter at a condition exactly similar to the measurement condition based on empirical models developed from the measured data. A large number of measurement studies have been taken at low grazing angles and some empirical models have been obtained from these measurements. The paper lists some classical measurement data and their amplitude distribution models. The mean clutter reflectivity and the amplitude distribution of sea clutter is greatly influenced by the grazing angle. This paper discusses the method to choose a suitable empirical model by the value of grazing angle. By analyzing the range of grazing angle in each measurement condition, the paper displays the relationship between grazing angle and the shape parameter of the related amplitude distribution model. Correlated random sea clutter variates according to the proposed algorithm is generated. The statistical goodness of fit tests on the estimated results is performed to determine the accuracy of the random numbers.

Introduction

The modelling and simulating of coherent returns from sea surface is required to evaluate the performance of radar throughout its design and development cycle. With a good knowledge of the nature and behavior of sea clutter, realistic returns can be applied to achieve the performance required by the radar users. Sea clutter is a result of complex interaction between incident electromagnetic waves and sea surface. Its characteristics vary according to the radar parameters, such as frequency, polarization and grazing angle, and the sea conditions, such as wind speed, wind direction and wave height. A number of statistical properties are used to characterize the sea clutter: the normalized RCS, the amplitude distribution, the spectrum of the clutter returns, and the spatial correlation properties.

The normalized RCS, which also referred to as the mean clutter reflectivity, is defined as the RCS per unit area of sea surface illuminated by radar. The commonly used normalized RCS models are GIT [1] and TSC [2]. These models are mainly based on empirical measurements and observations. They provide a good estimate on the values of NRCS in different conditions. As the instantaneous echo power varies about the mean clutter intensity, the amplitude variation of sea clutter is defined as the amplitude distribution which is characterized by the pdf of the returns. The commonly used amplitude distribution models are: Rayleigh [3], Log-Normal [4], Weibull [5] and K-distribution [6]. The spectrum of the returns, which also means the temporal correlation properties, describes the amplitude fluctuate properties vary with time. The spatial variation of clutter returns from two separate patches of the sea is characterized by the spatial correlation properties. The realistic modelling of clutter involves incorporating the correlation information into the joint probability density function of clutter sample.

It is known that the grazing angle has great influence on the statistic characteristics of the sea clutter. As the clutter amplitude statistics have long-tails at low grazing angles, much of the analysis and modelling of sea-clutter has been undertaken at low grazing angles to achieve the best detection performance against small targets. This paper explains some of the typical measurement studies, mainly focuses on the detailed experiment conditions and its corresponding amplitude statistic distribution. A sea clutter simulation algorithm with a high credibility is presented in this paper. The
main idea of the algorithm is to simulate sea clutter by choosing the appropriate empirical model based on its measurement conditions.

**Characteristics of Sea Clutter**

**The Normalized RCS Models**

The normalized RCS describes the complex nature of the average echo intensity changed with radar parameters and environmental parameters, such as frequency, polarization, grazing angle, wind speed, wind direction and wave height. The commonly used models for mean clutter reflectivity are GIT and TSC. The model coefficient changed with frequency. From necessity, we only talk about the model values above 10 GHz in this paper.

The GIT model is developed by the Georgia Institute of Technology. It is a function of grazing angle, radar frequency, wind speed, average wave height, look direction and polarization. GIT model covers the frequency band from 1 GHz to 100 GHz, and the grazing angle from 0.1° to 10°. The model value is averaged at the upwind, crosswind and downwind direction. GIT model is a function with three factors: 1) multipath and interference factor $A_l$; 2) wind direction factor $A_u$; 3) wind speed factor $A_w$. The clutter scattering coefficient of GIT model is:

$$
\sigma_{VV}^0 (\text{dB}) = \sigma_{HH}^0 (\text{dB}) - 1.38 \ln (h_w) + 3.43 \ln (\lambda) + 1.31 \ln (\phi) + 18.55
$$

(1)

$$
\sigma_{HH}^0 (dB) = 10 \log_{10} (5.78 \times 10^{-6} \phi^{0.547} A_l A_u)
$$

(2)

where $\phi$ is the grazing angle in radians, $h_w$ is the average wave height in meters.

$A_l$ is a theoretically derived factor used to characterize the multipath and interference effects:

$$
A_l = \sigma_e^4 / (1 + \sigma_e^4)
$$

(3)

$$
\sigma_e = (14.4 \lambda + 5.5) \phi h_w / \lambda
$$

(4)

$A_u$ describes the variation due to aspect angle between the antenna and sea direction:

$$
A_u = \exp \left[ 0.25 \cos \theta (1 - 2.8 \phi) \lambda^{-0.31} \right]
$$

(5)

where $\theta$ is the radar look direction relative to the upwind direction angle in radians.

$A_w$ describes the variation due to wind speed and wave height:

$$
A_w = \left[ 1.94U / (1 + U / 15.4) \right]^{1.91 \lambda^{0.03}}
$$

(6)

where $U$ is the value of wind speed.

The TSC [7] model is developed by the Technology Service Corporation and is based on a fit to data compiled by Nathanson [3]. It is a function of grazing angle, radar frequency, Douglas sea state number, wind aspect angle and polarization. TSC model covers the frequency band from 0.5 GHz to 35 GHz, and the grazing angle from 0.1° to 90°. The model value is an average of the upwind, crosswind and downwind. TSC model is a function with three factors: 1) low grazing angle factor $G_l$; 2) wind direction factor $G_u$; 3) wind speed factor $G_w$. The sea clutter scattering coefficient is:

$$
\sigma_{HH}^0 (dB) = 10 \log_{10} \left( 1.7 \times 10^{-5} \phi^2 G_l G_u G_w \right) \left( 3.2808 \lambda + 0.05 \right)^{1.4}\n$$

(7)

$$
\sigma_{VV}^0 (dB) = \sigma_{HH}^0 (dB) - 1.05 \ln (8.225 \sigma_i + 0.05) + 1.09 \ln (\lambda) + 1.27 \ln (\sin \phi + 0.0001) + 10.945
$$

(8)

where $\phi$ is the grazing angle in radians, $\sigma_i$ is the standard deviation of sea surface height in meters.

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\( G_i \) is a parameter related to the grazing angle and multipath effect:

\[
G_i = \sigma_i^{1.5} / (1 + \sigma_i^{1.5})
\]

\( \sigma_i = (3.2808\sigma_z + 0.25)4.5416\phi / \lambda \) \hspace{1cm} (9)

\( \sigma_z = 0.03505S^{0.95} \) \hspace{1cm} (10)

where \( S \) is a parameter of the Douglas sea state.

\( G_e \) is a parameter used to characterize the effect of wind direction:

\[
G_e = \begin{cases} 
1 & , \phi = \pi / 2 \\
\exp \left( \frac{0.3\cos \theta \exp(-\phi / 0.17)}{(10.7636\lambda^2 + 0.005)^{0.2}} \right) & , \phi < \pi / 2 
\end{cases}
\]

\hspace{1cm} (12)

\( G_w \) is a factor used to characterize the effect of wind speed:

\[
G_w = \left[ (1.9438U + 4.0) / 15 \right]^4
\]

\hspace{1cm} (13)

\( A = 2.63A / (A_2A_3A_4) \) \hspace{1cm} (14)

\( A_1 = \left[ 1 + (\lambda / 0.00914) \right]^{70/11} \)

\hspace{1cm} (15)

\( A_2 = \left[ 1 + (\lambda / 0.00305) \right]^{70/13} \)

\hspace{1cm} (16)

\( A_3 = \left[ 1 + (\lambda / 0.00914) \right]^{70/3} \)

\hspace{1cm} (17)

\( A_4 = 1 + 0.35Q \)

\hspace{1cm} (18)

\( Q = \phi^{0.56} \)

\hspace{1cm} (19)

Figure 1 shows the comparison of these three models at a frequency of 15 GHz, HH and VV polarization. The sea state \( S = 2 \), which has a wind speed about 5.4 m/s and an average wave height about 0.32m. The look direction is upwind and the grazing angle is changed from 0.1° to 10°.

![NRCS with grazing angle (VV polarization).](image)

From Figure 1 and Figure 2, we can see the normalized RCS increased with the grazing angle in both VV and HH polarization. The normalized RCS at VV polarization is higher than at HH polarization. The curves of GIT model and TSC model are of same trends. For grazing angles greater than 1°, the GIT and TSC models are in substantial agreement. While, for lower grazing angles, the
TSC model has values greater than the GIT model. This is in consistent with the conclusion presented in [7]. What’s more, the TSC model contains some measured data about the effect of the evaporation duct on the sea surface. We can choose the TSC model when the grazing angle is lower than 1°.

Figure 2. NRCS with grazing angle (HH polarization).

Amplitude Distribution

The probability density function of Log-Normal distribution is:

\[ p(x) = \frac{1}{\sqrt{2\pi \eta_x}} \exp \left[ -\frac{\ln^2(x/\mu)}{2\eta^2} \right] \] (20)

where is the voltage envelope of clutter returns, \( \eta \) is the standard deviation of the underlying normal distribution and \( \mu \) is the median value of the log-normal distribution.

The probability density function of Weibull distribution is:

\[ p(x) = \frac{1}{\eta_x} \left( \frac{x}{\eta_x} \right)^{p-1} \exp \left[ -\left( \frac{x}{\eta_x} \right)^p \right] \] (21)

where \( x \) is the voltage envelope of clutter returns, \( p \) is a parameter that relates to the skewness of this distribution. \( \eta \) is the scale parameter decided by echo power of radar sea clutter.

The probability density function of \( K \) distribution is:

\[ p_k(x) = \frac{2b}{\Gamma(v)} \left( \frac{bx}{2} \right)^{v-1} K_{v-1}(bx) \] (22)

where \( x \) is the voltage envelope of clutter returns, \( v \) is the shape parameter and \( b \) is the scale parameter.

Correlation Characteristics

The temporal correlation of sea clutter describes the correlation between pulses and for a symmetrical sea clutter spectrum that can be represented by a Gaussian function. The spectral width is related to standard deviation of the clutter speed which is determined by the wind speed. The Doppler shift is determined by the relative speed between radar and waves. The Gaussian spectrum can be found:

\[ G(f, s) = \exp \left\{ -\frac{(f - f_s)^2}{2s^2} \right\} \] (23)

where \( f_s \) is the doppler shift, and \( s \) is the spectral width.
The spatial correlation of sea clutter is defined as the cross correlation between the two adjacent patches of the sea in the radical dimension. An experimental spatial autocorrelation function is presented by Watts [8]:

\[ r(m) = \exp(-Lm / \rho) \tag{24} \]

\[ \rho = \frac{\pi}{2} \frac{U^2}{9.18} (3\cos^2 \theta + 1)^{1/2} \tag{25} \]

where \( m \) is the index number of the separate patch of sea surface covered by radar. \( \rho \) is the correlation length of the sea surface and is taken to be a length characteristic of wind waves, given in terms of wind velocity \( U \). \( \theta \) is the angle between the line of radar sight and the wind direction.

### Simulation of Sea Clutter Returns

#### The Choice of Amplitude Distribution

Nathanson [3] summarized the measured backscatter values of sea clutter from about 60 experiments. They cover a range of different grazing angles including \( 0.1^\circ, 0.3^\circ, 1.0^\circ, 3.0^\circ, 10^\circ, 30^\circ \) and \( 60^\circ \). The pulse width is widely ranged from 0.5 us to 10 us. The radar is operated at UHF, L, S, C, X, Ku and Ka band. Nathanson found that sea clutter obeys the Central Limit Theorem and has Rayleigh distributed amplitude statistical properties for large illuminated patch sizes and higher grazing angles (\( > 10^\circ \)).

It is found that with the decreasing of grazing angles, the clutter distribution develops a heavier tail than Rayleigh distribution. The log-normal distribution is proposed yields a good description of some experimental data obtained from high-resolution radars at lower grazing angles. The amplitude distribution of sea clutter from a Ku-band MIT radar [9] is considered as log-normal distribution. The data were collected at a sea state of 3. The grazing angle is ranged from \( 1^\circ \) to \( 5^\circ \). The shape parameter of log-normal distribution changed with grazing angles. The value decreased from 0.72 to 0.48 as the grazing angle increased from \( 1^\circ \) to \( 5^\circ \) [10].

Schleher [11] proposed the Weibull distribution based on the measured data from John Hopkins University. The data were obtained from a Ku-band horizontal polarized radar with a pulse width of 0.1 us and a beam width of \( 5^\circ \). The grazing angle is changed from \( 1^\circ \) to \( 30^\circ \). The paper shows that the measured data are good fitted to the Weibull distribution. The value of shape parameter increases with grazing angle. It increases from 1.160 to 1.783 as the grazing angle increases from \( 1^\circ \) to \( 30^\circ \).

Jakeman and Pusey [12] proposed the K distribution of sea clutter amplitude at two low grazing angles of \( 1^\circ \) and \( 1.5^\circ \). They explained the physical properties of sea clutter and noted that the K distribution consists of two components: the local power and the speckle component. The data were gathered from an X-band radar with a pulse width of 0.07 us and 0.27 us, for both vertical and horizontal polarization. Another X-band high-resolution radar, Ingara [13], is proved has a K distribution amplitude statistical property at a low grazing angle of about \( 0.1^\circ \). The shape parameter of K distribution is suggested from 0.1 to 3 for a high-resolution radar with low grazing angles.

The empirical amplitude distribution models and their shape parameters derived from the above measurements are shown in Table.1. The table displays the relationships among the grazing angle, the measured amplitude distribution and its related parameters.

| Grazing Angle | Amplitude Distribution | Shape Parameter |
|---------------|------------------------|-----------------|
| 0.1 ~ 10      | K distribution         | 0.1 ~ 3         |
| 1 ~ 5         | Log-Normal distribution| 0.72 ~ 0.48     |
| 1 ~ 10        | Weibull distribution   | 1.160 ~ 1.783   |
Test has been carried out to study the relationship between the grazing angle and the amplitude distribution model. As the grazing angle decreases, and for high resolution radars, the PDF of the clutter amplitude is found to exhibit long tails. The long tail of the distribution is crucial in setting target detection threshold in order to minimize both false alarms and missed detection. The Weibull and Log-Normal distribution are based on their agreement with experimental data. Unlike these two models, the K distribution is a physical and is derived from clutter scattering mechanism [14]. Meanwhile, the K distribution has the longest tail and can used at a grazing angle of 0.1°. As a result, the K distribution is the most appropriate model when the grazing angle is lower than 1°.

**Simulation Algorithm of Sea Clutter**

Based on the empirical models and their applicable conditions discussed above, an algorithm is proposed to simulate sea clutter by choosing the appropriate empirical model at different grazing angles. By setting the radar and sea conditions similar to the actual measurement conditions and utilizing the empirical amplitude distribution model achieved from measured data, the simulation result can be considered as a high credible result. The algorithm is aimed to achieve sea clutter with high credibility.

The range of simulating the clutter returns can be fixed as follow:

**Step 1** Input the radar parameters, sea conditions and viewing angles. Make sure the input parameters are similar to the measured specific radar and sea conditions.

**Step 2** Choose an appropriate NRCS model based on the value of grazing angle.

**Step 3** Choose an appropriate amplitude model based on the value of grazing angle.

**Step 4** Set the shape parameter value of the chosen amplitude model based on the empirical values displayed in Table 1.

**Step 5** Calculate the echo power according to the Radar Equation and estimate the scale parameters of the chosen amplitude model.

**Step 6** Generate the correlated random variates based on the chosen models. Test and verify the estimated clutter fitted with the theory models.

The simulation algorithm is displayed in Algorithm 1.

```
Algorithm 1 Sea clutter simulation algorithm

Input: grazing angle $\phi$, frequency, sea state;
Output: the correlated random clutter numbers;

Choose an appropriate normalized cross section model based on the grazing angle:

for $0.1^\circ \leq \phi < 1^\circ$
    do Choose the TSC model;
for $1^\circ \leq \phi \leq 10^\circ$
    do Choose TSC or GIT model;
Choose an appropriate amplitude distribution model based on the grazing angle:

for $0.1^\circ \leq \phi < 1^\circ$
    do Choose K distribution;
for $5^\circ < \phi < 10^\circ$
    do Choose K or Weibull distribution;
for $1^\circ \leq \phi \leq 5^\circ$
    do Choose K, Weibull or Log-Normal distribution.

Set the shape parameter for the chosen amplitude distribution model:

for K distribution
    do Set the shape parameter between 0.1 and 3;
for Weibull distribution
    do Set the shape parameter between 1.100 and 1.783;
for K distribution
    do Set the shape parameter between 0.48 and 0.72.

Calculate the echo power and estimate the scale parameter;
Generate the correlated random variates;

return the correlated random numbers.
```
Results and Verification

In this section, we adopt the simulation algorithm given in Section 3 to generate correlated coherent clutter based on the radar parameters and sea conditions setting at the beginning of the software.

The simulation results are showed in the following figures. Figure 3 shows the amplitude value of temporal-spatial correlated K distributed sea clutter [15]. Figure 4 shows the PDF curve of K distribution. Figure 5 and Figure 6 are the PDF curves of Weibull distribution and Log-Normal distribution respectively. From the estimated PDF curves in these figures, we can see the amplitude of the K distribution clutter performed more spikier than the other distributions as it has the longest tail and larger amplitude value which represent an exist of spiky clutter. The Log-Normal one follows behind. The Weibull distribution is less spiky for it is approaching a Rayleigh distribution when the value of shape parameter $p$ is 2.

As is shown in the figures, the estimated value and the theoretical value are good fitted. The simulated power spectrum is Gaussian spectrum and is consistent with the theoretical value.

Conclusion

A sea clutter simulation algorithm is developed to generate correlated random clutter variates. The simulation algorithm is based on the grazing angle to choose the appropriate models to generate correlated variates. The paper discusses the empirical models with the sea state, the geometry of radar system and radar parameters. A comparison of the PDF of the simulated clutter with the theoretical distribution PDF was done and shows good fit. The simulated correlated random clutter numbers can be used in radar signal processing procedures.
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