International Journal on Emerging Technologies 10(4): 266-272(2019)

ISSN No. (Print): 0975-8364
ISSN No. (Online): 2249-3255

Estimation of Sea Clutter Parameters for Long Range using STFT

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(Received 02 September 2019, Revised 01 November 2019, Accepted 09 November 2019)
(Published by Research Trend, Website: www.researchtrend.net)

ABSTRACT: Sea clutter is the back scattered signals from the sea surface. Sea clutter is an undesired signal and interferes with the radar's ideal functioning, often the cause of false detections, and has dynamic nature. The radar system scientists needs to understand the clutter characteristics in order to develop exact signal processing technique and predict operational performance in different maritime conditions, and maintains low false detections, CFAR. Radar Signal Processing has the ability to estimate and model the spectral characteristics of sea clutter for achieving effective detection and tracking the targets on the surface of sea and gives CFAR. In this paper STFT technique along with Gaussian window function is used for the generation of successive Doppler spectra of real time measured sea clutter data. This paper aims for developing a high frequency resolution technique for modeling the spectral characteristics of clutter, estimating the clutter intensity, Clutter to Noise Ratio (CNR), and clutter attenuation in all Range gates 1 to 96 for real time data. And also predicted mathematical estimators are developed for the variation of CNR, Clutter intensity and clutter attenuation as a function of range. These mathematical models are helpful for estimating the sea clutter parameters as a function of range, which are required for radar surveillance in maritime environment.

Keywords: Sea clutter, Clutter to Noise Ratio (CNR), High frequency resolution, Doppler frequency, Doppler bin, Clutter Intensity (CI), Clutter Attenuation (CA), Constant False Alarm Rate (CFAR), Short Time Fourier Transform (STFT), Gaussian window, Radar Signal Processing (RSP).

I. INTRODUCTION

Exact sea clutter mathematical models are very much helpful for radar Scientists all through the design and development of radar systems [1]. The mathematical models for the sea clutter are essentially required in the Radar Signal Processing (RSP), for detecting and tracking of simple and complex targets in the maritime domain. The sea clutter was modeled as a Gaussian compound model, specifically the compound K-distribution model [2]. There are several problems with detecting and tracking the targets of Gaussian-compound models were presented in the literature [3, 4]. The mathematical methods which are presented so far generally depend upon estimating the covariance matrix of the radar sea clutter returns and then developed an optimum detection method that gives a Constant False Alarm Rate (CFAR) at various levels of information about sea clutter and target statistics. The improvement on such detection methods requires exact models of the Doppler frequency of clutter that can allow perfect implementation and interpretations [5, 6].

Walker discussed a method of characterizing the average Doppler spectra, based on the Gaussian-distribution parameters of the sea clutter power spectral density (PSD) [2, 6]. These components, with different mean Doppler shift frequency, spectrum width, and amplitude, were associated with three different scattering mechanisms (Bragg, whitecap, and burst). But as it is, this procedure does not describe the short term transient variations in the Doppler shift spectra, which establish non-Gaussian clutter intensity parameters in the Doppler frequency spectrum extremes, and this characteristic introduces the problems when trying to set detection thresholds to give a CFAR [2, 3, 7]. This obviously non stationary characteristic of sea clutter modeling the Doppler shift spectrum by a covariance matrix of the momentarily component that is calculated by averaging over a long time period may not estimate perfectly its speckle variations [8, 9]. Mathematical procedure for modeling the clutter relies upon the K-distribution compound model for clutter intensity parameters. It is characterized that sea clutter intensity is confined more to center bins of the Doppler shift spectrum, and estimates clutter intensity at every Doppler frequency bin as a function of time. Estimating the Clutter to Noise Ratio (CNR), clutter intensity and clutter attenuation in each range gate, and analyzing the variation in clutter parameters as a function of range. It builds up the thoughts discussed in [8, 9]. Sea clutter parameters are estimated in [8, 9] is restricted to only one range gate data, method suffers with low frequency resolution, and limited to short range, this leads to wide clutter spectrum with low clutter intensity estimation. Sea clutter modeled with high frequency resolution, but limited to one range cell [10]. In this paper work carried out for long range all 1 to 96 range gates, with high spectral resolution in comparison with [8, 9].

In this paper we have estimated the three important clutter parameters as a function of range in narrow Doppler spectrum with high intensity and CNR due to high frequency resolution. Section II of this paper presents the significance of the problem of estimating the Doppler spectrum of sea clutter bands and spectrum band of noise. Table 1 in section II presents the specifications of real time clutter data sets provided by the Council for Scientific and Industrial Research (CSIR). Section III highlights about importance of Short Time Fourier Transform (STFT). Section IV presents mathematical analysis of clutter using real data set and the methodology used for generating progressive Doppler shifted frequency, as a function of time period, by using STFT with the Gaussian window. Finally, it shows that how a continuous time series coherent clutter data can be used for mathematical modeling of sea clutter. This methodology takes minimum time for processing and for generation of successive Doppler spectrum, and results high spectral resolution in the estimation of sea clutter modeling parameters, in comparison with techniques discussed in the literature [7, 8].

II. DOPPLER FREQUENCY SPECTRUM OF SEA CLUTTER

The mathematical modeling analysis carried out on the data set collections of individual range bins, provided by the Fynmeet radar, Council for Scientific and Industrial Research (CSIR), South Africa are tabulated in Table 1. The vertical polarized radar with a frequency of 6.9 GHz, a Pulse Repetition Frequency (PRF) f_r, of 5 kHz, and Pulse Repetition Time (PRT) T_r of 200µ seconds, range resolution (ΔR) of 15 meters, and an antenna azimuthal angle half power beam width of 1.8 degree are considered for collecting the data [11]. Sea cluttered data set measurements were stored as radar reflected signal in-phase and quadrature phase parts of the clutter combined with noise scattered signals from a number of range regions. In the present case, the data onto CFA17 from all range cells (96) are processed and analyzed. And each clutter data set consists of 197520 samples of complex time series of data measured and recorded within the time interval of 39 seconds, with the sampling frequency(f_r). The real time sea clutter recording conditions indicated in these data sets is a mixed nature of various wind and wave directions, with the radar normally looking into the waves but with a crossing wind, is compulsorily different, looking at a direction of about 45 degrees, to the propagation of wave and the direction of downwind. Successive spectra in terms of time and frequency were estimated for this data set. The meaning of CFA is as follows: 'C' stands for clutter, 'F' indicates as fixed operating frequency and 'A' indicates as 6.9 GHz constant operating frequency. Table 1 consist of various CSIR clutter data sets, but CFA17 data set is adopted here for estimating and analyzing the sea clutter parameters as the function of range. Tracking range of 3000 m is considered from the measuring specifications of the data set, grazing angles indicates the altitude of measurement system, and range resolution is the progressive distance between two adjacent range gates. Sea waves height indicates the state of sea (sea state 4), and recording time is the total time taken for data measurement [11, 12].

Table 1: CSIR Data bands.

Data set	Range (m)	Graz. Angle (Deg.)	Resolution (m)	Significant wave height (m)	Total time period (sec.)
CFA-17	3000	1.23	15	2.48	39
CFA-14	3000	1.23	15	2.48	39
CFC-17	3000	1.27	15	2.2	32
CFC-14	3000	1.23	15	2.2	32

III. SHORT TIME FOURIER TRANSFORM (STFT)

The Short-Time Fourier Transforms (STFT), is a Fourier transformation technique used to determine the sinusoidal frequency and phase knowledge of local components of a sea clutter information signal as it is changing dynamically as a function of time. But in general the procedure adopted for determining STFT is to divide a long time period the signal into shorter segments of equal size and then evaluating the Fourier transforms independently into each smaller section. This process generates the Fourier spectrum of each shorter segment and improves the resolution of frequency. One then normally plots the varying frequency spectra as a function of time. Here STFT is applied to get the frequency and time information of sea clutter data. In case of continuous-time signals, the function $x(t)$ to be converted is compounded by a window function which is non-zero for short periods of time. The Fourier transforms (single-dimensional function) from the generated signal is considered as the window slid along with the time axis, appearing in a two-dimensional (Time and angular frequency) representation of the information. The STFT of the signal $x(t)$ as shown in Eqn. (1), time and frequency transformations are expressed in Eqn. (1).

$$\text{STFT}\{x(t)\}(\tau,\omega) \equiv X(\tau,\omega)=\int_{-\infty}^{+\infty} x(t)w(t-\tau)\, e^{-j\omega t}\, dt \quad (1)$$

$w(t)$ is the Window function, $x(t)$ is the information signal which is to be transformed into time and frequency, τ and ω are the time and angular frequency respectively [12, 13]. This transformation work is carried out by using Gaussian window function.

IV. ANALYSIS OF SEA DATA

Short Time Fourier Transform (STFT) with Gaussian window function and weighting with α = 2.5 were used for computing successive Doppler spectra of a typical radar time domain signal, $x(t)$. In this analysis Fig. 1 plots the Power Spectral Density (PSD) of the clutter data of "CFA17 One Range gate", consist of 197520 samples, for 1543 successive spectrum (39.50 sec), for a Fast Fourier Transform (FFT) of length $(L = 128)$, over the central 5000 Hz of Doppler spectrum, with the center frequency as 0 Hz. The sea cluttered intensity varies as a function of time and its spectral characteristics are often best described by the ideal K-distribution compound model.

The Doppler spectrum pulse width also changes as a function of time, with frequent extreme Doppler variations along with the time axis. The sea clutter Doppler spectrum is observed as asymmetrical in shape, with a nonzero mean Doppler frequency. These natural characteristics highlights the complexity of the relationship between the clutter intensity modulation and the form of the frequency Doppler spectrum, the former is characterized by the swell structure of the surface of the sea, and the second one is additionally affected by the local gusting of the wind on the sea surface and by the natural scattering process. However, despite of this complexity, it ought to be noted that the modulated compound Gaussian method continues to be applicable within the frequency domain and has a direct impact on the performance of coherent radars in the same way as it does on non-coherent radars operational performance [6, 12].
The K-distribution compound was used for modeling the clutter data [14, 15]. The Clutter to Noise Ratio (CNR), Compound K-distribution shape parameter (v) of the clutter, intensity of clutter at each Doppler bin was estimated using standard signal processing techniques [16]. The power spectra, which is, shown in Fig. 1 with Gaussian window function, attenuation constant of α = 2.5, is further used to estimate and analyze the changes of clutter spectrum shape, intensity of clutter at different range bins with more accurate frequency resolution and Doppler shift centroid [17, 18].

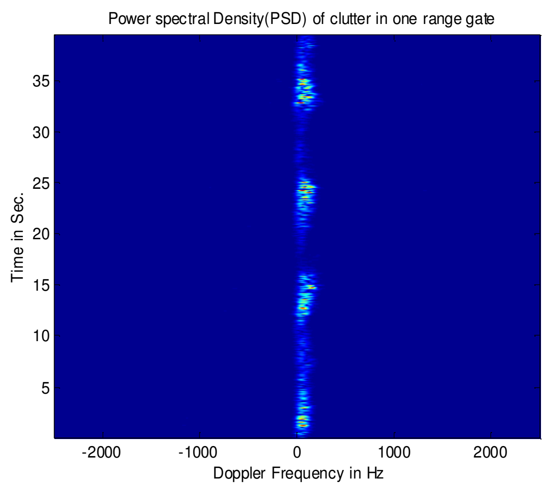

Fig. 1. Power Spectral Density (PSD) of CFA17, at One Range gate; fr = 5000Hz, FFT length L=128, α=2.5, Gaussian Window function.

A. Clutter to Noise Ratio (CNR)
The noise content within the sea clutter data base was estimated at the extreme edge Doppler shift band of the power spectrum, far Doppler bins are assumed as free of clutter component. Minimum values of extreme outer bins is estimated as Noise power (p_n) in every range gate. Fig. 2 demonstrates the average power spectrum of clutter and noise in one range gate, approximated by taking the average of power spectra for the complete time record of successive Doppler spectrum. Two more similar echoes with less magnitude are also observed at Doppler shift frequencies around ± 1200 Hz as shown in Fig. 2 which is due to the artifact of the radar. Hence information at this particular frequency is neglected.

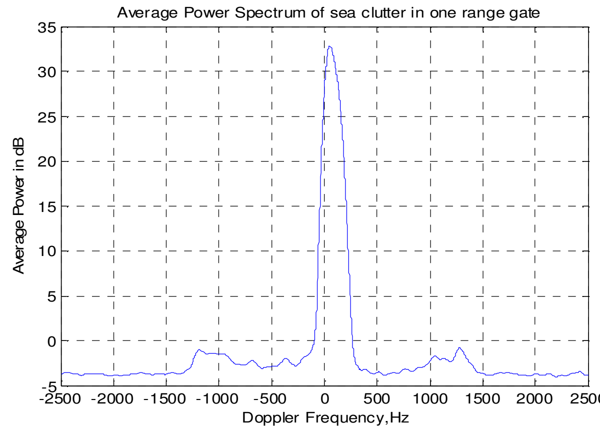

Fig. 2. Average power spectrum of sea clutter in one Range gate.

The information at the Doppler frequency bands from -2500 Hz to - 110 Hz and +280 Hz to +2500 Hz is estimated as noise component and this frequency bands is known as noise region. The existence of sea clutter is estimated in the frequency range of –110 Hz to +280 Hz, known as clutter band. Due to high accuracy in frequency resolution, exact the sea clutter component is estimated at narrow Doppler frequency band with high intensity. It is observed from the Fig. 2 that the sea clutter is confined effectively to central part of the spectrum with more clutter intensity at positive second Doppler bin, about +50 Hz. Equation for Clutter to noise ratios (CNR) is given in Eqn. (2).

$$\text{Clutter to Noise Ratio (CNR)} = \frac{\langle y \rangle - p_n}{p_n} \quad (2)$$

where 'y' is the combination of clutter and noise intensity estimated within the Doppler frequency range of -110 Hz to +280 Hz, and 'p_n' is thermal noise power estimated individually in every range gate of complete data set from outer bins.

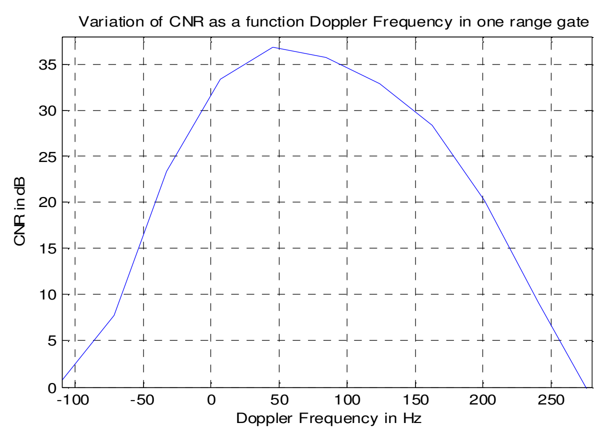

Fig. 3. Variation of Clutter to Noise Ratio (CNR) in dB of one Range Gate as a function of Doppler spectrum (f_d).

The Clutter to Noise Ratio (CNR) is estimated using expression (2) from the successive Doppler spectra of sea clutter in different individual Doppler bins of one range gate. Fig. 3 shows the graphical depiction of variation of CNR as a function of Doppler spectrum (f_d) in one range gate. It is observed from the Fig. 3 that Maximum clutter to noise ratio exists at second positive Doppler bin.

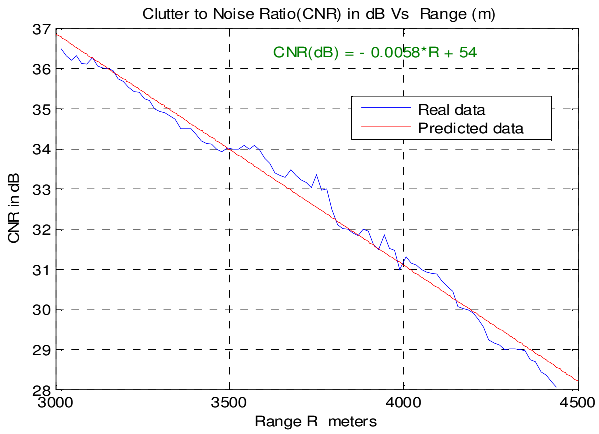

Fig. 4. Variation of Clutter to Noise Ratio (CNR) in dB as a function of Range (R) in meters, of CFA17 all Range Gates, (96), Range resolution (ΔR) = 15 m.

Sea clutter of measured data set CFA17 consist of 96 range bins, range resolution ((ΔR) is 15 meters, and tracking range is 3000 m. Maximum Clutter to Noise Ratio (CNR) in dB is estimated at the center band of clutter spectra for the time-series clutter data of all 96 range gates using Eqn. 2 for the minimum noise level (p_n), which is estimated from the far Doppler bins. Total range is calculated from equation (3).

R(m)=Tracking Range + Range resolution (ΔR)* No. of Gates (3)

Total Range (R) = 3000+15*96 = 4440 meters

$$\text{CNR}(dB) = -0.0058R + 58 \quad (4)$$

where "R" is Range in meters.

Fig. 4 shows the variation of clutter to noise ratio as a function of total range of all range gates. And it is observed from Fig. 4 and Table 2, which CNR in dB is linearly decreasing from range gate 1 to 96. The mathematical model (4) is developed for the estimation of CNR as a function of range.

B. Clutter Intensity Statistics

The clutter intensity component added with noise component ‹*y*› are given in equation (5), and it is estimated within the clutter band of -110 Hz to 280Hz.

$$\langle y \rangle = \frac{v}{b} + p_n \quad (5)$$

where (v) clutter is shape parameter and (b) is scale parameter. The graphical demonstration of sea cluttered intensity as a function of time for one range gate at second positive Doppler bin is shown in shown in Fig. 5. It is observed from Fig. 5 that maximum clutter intensity exists at second positive bin of the clutter spectrum, and clutter intensity is varying nonlinearly as a function of time.

Maximum values of Clutter Intensity is estimated at the second positive bin of clutter Doppler spectrum for the time-series clutter data set of all 96 range cells using Eqn. (5) within the clutter band and tabulated in Table 2. Total range is calculated from Eqn. (3).

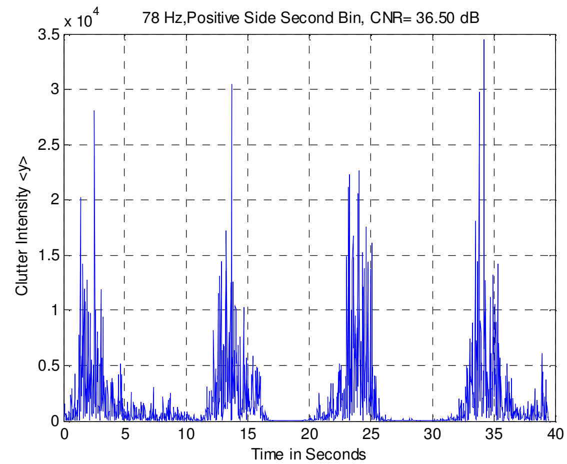

Fig. 5. Clutter Intensity as a function of time at positive second Doppler bin, i.e. at +78.125 Hz, CNR =36.50 dB.

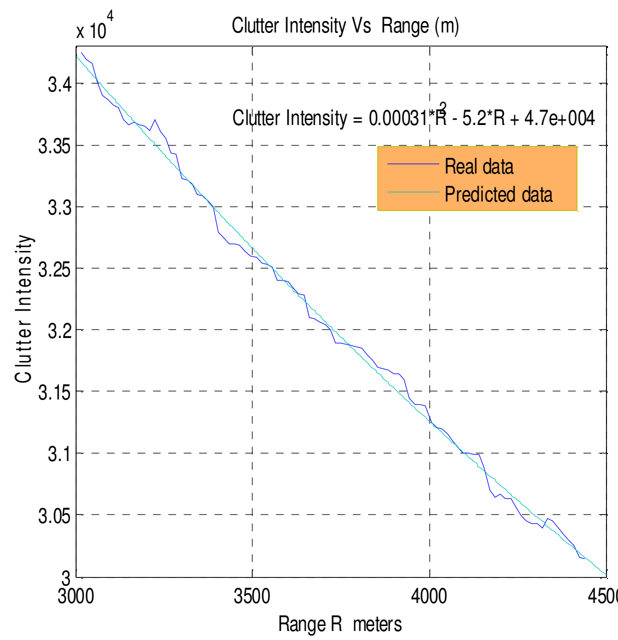

Fig. 6. Variation of Clutter Intensity as a function of Range (R) in meters, of CFA17 all Range Gates.

Fig. 6 demonstrates the variation in clutter intensity as a function of range of all range gates. And it is observed from Fig. 6 and Table 2 that Clutter intensity is decreasing as range is increasing. A second order mathematical model is developed for the estimation of Clutter intensity as a function of range is given in Eqn. (6).

$$\text{Clutter Intensity} = 0.00031R^2 - 5.2R + 4.7 \cdot 10^4 \quad (6)$$

Frequency resolution (Δf) can be calculated using Eqn. (7). Frequency band of each Doppler bin is 39 Hz.

$$\Delta f = \frac{\text{Sampling frequency}}{\text{FFT length}} \frac{f_s}{L} = 39.06 \text{ Hz} \quad (7)$$

C. Clutter Attenuation

The sea clutter attenuation is estimated at each range gate using Eqn. (8). The noise component is estimated from the outer Doppler bins.

Clutter Attenuation =10* $\frac{\log_{10}^{\text{Noise}}}{10^{-3}}$ dBm (8)

Fig. 7 illustrates the variation in clutter attenuation in dBm as a function of range for long ranges. And it is observed from Fig. 7 and Table 2, which clutter attenuation is increasing with increasing range. Second order Mathematical Eqn. (9) is developed for the estimation of Clutter Attenuation as a function of range.

Attenuation (dBm) = -2.7*10^{-7} R^2+0.007R+7.3 (9)

Estimated values of Clutter to Noise Ratio (CNR) in dB, sea clutter intensity and clutter attenuation in dBm of all range gates (96) from measured sea cluttered data set are shown in Table 2. Tracking range is 3000 meters and the spatial resolution (ΔR) is 15 meters.

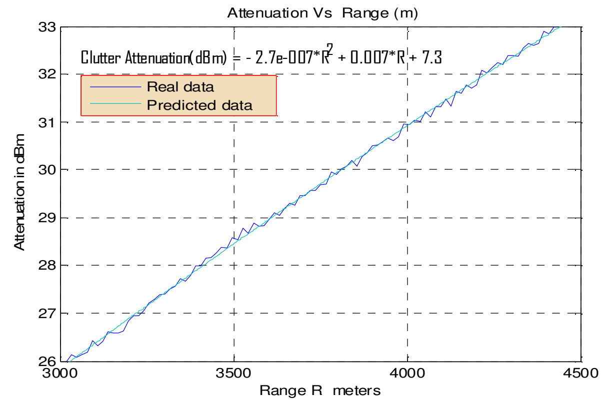

Fig. 7. Variation of Clutter Attenuation as a function of Range (*R*) in meters, of CFA17 all Range Gates.

Table 2: Estimated values of CNR, CI and CA.

Range gate No.	Range (meters)	CNR (dB)	Clutter Intensity (CI)	Clutter Attenuation (CA) (dBm)
1	3015	36.50	34250	25.99
2	3030	36.30	34200	26.13
3	3045	36.20	34167	26.09
4	3060	36.30	34010	26.14
5	3075	36.12	33900	26.19
6	3090	36.10	33875	26.43
7	3105	36.27	33827	26.33
8	3120	36.05	33801	26.42
9	3135	36.02	33705	26.62
10	3150	36.00	33670	26.59
11	3165	35.95	33685	26.59
12	3180	35.75	33670	26.64
13	3195	35.67	33650	26.83
14	3210	35.54	33620	26.96
15	3225	35.41	33709	26.95
16	3240	35.39	33609	27.06
17	3255	35.24	33552	27.21
18	3270	35.20	33441	27.30
19	3285	35.00	33421	27.39
20	3300	34.93	33226	27.41
21	3315	34.89	33217	27.50
22	3330	34.81	33186	27.56
23	3345	34.75	33100	27.73
24	3360	34.50	33090	27.67
25	3375	34.48	33045	27.79
26	3390	34.49	33000	27.99
27	3405	34.35	32800	28.00
28	3420	34.19	32750	28.14
29	3435	34.12	32700	28.16
30	3450	34.10	32695	28.25
31	3465	34.00	32690	28.38
32	3480	33.93	32645	28.36
33	3495	34.02	32600	28.56
34	3510	34.00	32590	28.53
35	3525	33.98	32550	28.78
36	3540	34.09	32540	28.67
37	3555	34.00	32514	28.89
38	3570	34.08	32406	28.83
39	3585	33.96	32400	28.84
40	3600	33.76	32390	28.96
41	3615	33.63	32340	29.10
42	3630	33.40	32300	29.05
43	3645	33.32	32290	29.19
44	3660	33.29	32100	29.30
45	3675	33.47	32090	29.26
46	3690	33.33	32070	29.46

47	3705	33.21	32050	29.45
48	3720	33.15	32000	29.57
49	3735	33.03	31900	29.58
50	3750	33.35	31900	29.69
51	3765	32.97	31880	29.71
52	3780	33.00	31875	29.95
53	3795	32.49	31860	29.90
54	3810	32.10	31850	30.03
55	3825	32.02	31800	30.07
56	3840	31.98	31750	30.19
57	3855	31.90	31700	30.08
58	3870	31.83	31690	30.26
59	3885	32.00	31680	30.37
60	3900	31.95	31650	30.50
61	3915	31.60	31640	30.51
62	3930	31.50	31600	30.59
63	3945	31.85	31450	30.66
64	3960	31.52	31400	30.61
65	3975	31.46	31390	30.70
66	3990	31.00	31380	30.96
67	4005	31.31	31256	30.95
68	4020	31.15	31206	31.02
69	4035	31.11	31200	31.02
70	4050	31.00	31156	31.20
71	4065	30.92	31100	31.09
72	4080	30.90	31050	31.32
73	4095	30.88	31006	31.31
74	4110	30.70	31000	31.46
75	4125	30.55	30996	31.33
76	4140	30.45	30990	31.64
77	4155	30.05	30890	31.59
78	4170	30.02	30700	31.76
79	4185	30.00	30650	31.71
80	4200	29.90	30670	31.76
81	4215	29.75	30640	32.07
82	4230	29.55	30630	32.01
83	4245	29.23	30556	32.15
84	4260	29.15	30490	32.23
85	4275	29.10	30450	32.20
86	4290	29.00	30430	32.39
87	4305	29.02	30425	32.39
88	4320	29.01	30400	32.37
89	4335	29.00	30470	32.55
90	4350	28.96	30450	32.64
91	4365	28.75	30400	32.60
92	4380	28.69	30337	32.64
93	4395	28.45	30300	32.88
94	4410	28.36	30256	32.82
95	4425	28.19	30156	32.99
96	4440	28.06	30150	33.00

V. RESULTS AND DISCUSSION

In this section estimated clutter parameters are presented. The particular real time recorded sea clutter data set of CFA17 is provided by CSIR, South Africa, adopted here for processing and analysis. This data set consists of 197520 samples of sea clutter data in each range gate. There are total 96 range gates in the data set, here all the 96 range gates are considered for processing and analysis. Fig. 1 shows the Power Spectral Density (PSD), of one range gate, which displays the power of clutter and noise. Fig. 2 illustrates the average power spectrum of clutter and noise, and it gives the clutter Doppler band from –110 Hz to +280Hz, excluding this band, other band of Doppler shift frequency is referred as noise band. Clutter to Noise Ratio is estimated in each Doppler bin, Fig. 3 demonstrates the variation of CNR as a function of Doppler shift frequency within the clutter band.

Noise level is estimated from the extreme Doppler spectrum. Clutter to Noise Ratio, clutter intensity, and clutter attenuation at each range gate are estimated using the models developed. The estimated values are summarized in Table 2. Fig. 4 gives the variation of clutter to noise ratio of sea clutter as a function of range of all range gates, it is observed from Fig. 4 and Table 2, CNR is linearly decreasing with increasing range, and a mathematical model (4) is developed for the estimation of CNR as a function of range. This method gives improved frequency resolution in comparison with methods given in [8, 18]. Fig. 6 illustrates the variation in clutter intensity as a function of range for long range. And it is observed from Fig. 6 and Table 2, that Clutter intensity is decreasing with range, and predicted second order mathematical Eqn. (6) is developed for the estimation of Clutter Intensity as a function of range.

Fig. 7 shows the variation in clutter attenuation as a function of range, and it is observed from the Fig. 7 and Table 2, that Clutter attenuation is increasing with range. Predicted second order Mathematical Eqn. (9) is developed for the estimation of Clutter Attenuation as a function of range.

Table 3: Root Mean Square Error (RMSE) between Real data and Modeled data.

Estimated parameter	RMSE	Order of predicted Model Equation
Clutter to Noise Ratio(CNR) in dB	0.4003	First order
Clutter Intensity(CI)	115	Second order
Clutter Attenuation(CA) in dBm	0.087	Second order

Table 3 shows the root mean square error between real data and predicted data, and minimum error is observed between these two data sets. Predict model equations for clutter parameters are best fit to the real data.

VI. CONCLUSION

Several parameters related to sea clutter are estimated using STFT, based on a time-varying Doppler spectral intensity of clutter with a Gaussian shape. Parameters estimated in the model are the overall CNR, clutter intensity and clutter attenuation as a function of range for all range gates (1 to 96) of data set i.e. long distance. And predicted mathematical equations are developed for the estimation of CNR, clutter intensity and clutter attenuation in terms of range. This method was tested on other clutter data sets and also for spectra of longer time intervals. It has given consistent results in all cases with improved frequency resolution, and it is able to reproduce the same characteristics that observed in real time data set.

VII. FUTURE SCOPE

This method should be extended for modeling the variation of Doppler shift frequency as a function of range, and also work can be extended towards improving the spectral resolution.

ACKNOLEDGEMENT

Exact modeling the spectral distribution of sea clutter is essential to ensure excellent target detection and tracking accuracy in the maritime environment. This is a challenging area for research due its significance in navigational radar surveillance. In this area still subject to considerable research and discussion. All above key points motivated us to do research in this area. The authors would like to thank to the Council for Scientific and Industrial Research (CSIR), South Africa for providing real time recorded sea clutter data which is used in this research paper and for their generous support in this work.

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How to cite this article: Vemula, Gurumurthy and Kakarla Subba Rao, (2019). Estimation of Sea Clutter parameters for Long Range using STFT. *International Journal on Emerging Technologies*, *10*(4): 266–272.