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A coherent, CW, X-band, dual-frequency radar has been used to detect stationary targets in the Chesapeake Bay. It is shown that by multiplying returns at two frequencies and averaging, sea clutter is suppressed. If the decorrelation of the two clutter returns is greater than that of returns from a stationary target, the signal-to-clutter ratio of the two-frequency system is shown to be greater than that of a comparable single-frequency radar.

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CONTENTS

DETECTION OF STATIONARY TARGETS IN SEA CLUTTER USING A CW DUAL-FREQUENCY RADAR*

INTRODUCTION

Target detection using dual-frequency radars has been considered by several authors in recent years. It has been shown by Skolnik [1] to be infeasible for frequency-agility applications when several targets are considered. Hsiao [2] has shown that a dual-frequency MTI system which mixes power returns at the two frequencies is not superior to a single-frequency system. Finally, Kroszczyński [3, 4] has given a basic theory for a two-frequency MTI system and has analyzed its efficiency assuming that both target and clutter returns at the two frequencies are uncorrelated.

Recently, a CW, X-band, dual-frequency radar, designated the Delta K Radar, has been constructed at NRL's Chesapeake Bay Division for the purpose of studying the effect of waves of several meters wavelength on the sea-clutter return. One result of this study has been to show that for a sufficiently large radar footprint, the sea returns at the two frequencies are decorrelated down to very small frequency separations. This agrees with previous studies [5, 6] using pulsed systems which found that sea clutter at two frequencies is decorrelated when the frequency separation exceeds the reciprocal pulse width. This fact suggests the possibility that sea clutter could be reduced if the output of a radar system were the product of fields at two different frequencies rather than the square of a single return. Thus if target returns at the two frequencies were correlated to some degree, an improvement in signal-to-clutter ratio over a single-frequency system could be achieved. To test this concept, several small targets were successively placed in the water inside the footprint of the Delta K system, and the return signals were processed to see if such improvement could be obtained. It was found that some improvement did indeed occur. This report details the target-detection experiments leading to this conclusion. The Delta K system was also found to be very successful in obtaining information about long ocean waves. These oceanographic experiments, however, will be reported elsewhere.

THEORETICAL CONSIDERATIONS

To shed more light on the anticipated signal-to-clutter improvement, let us assume that we have been able to separate radar returns from two coherent transmitted signals at different frequencies which have been scattered from the same area of the sea surface at the same time. We compare the scattered signal when a target is in the beam to that from an empty region of ocean surface. Thus we form the ratio of average signal plus clutter to average clutter for the two-frequency system:

$$\left(\frac{S}{C}\right)_2 = \frac{\left|\overline{(E_1 E_2^*)_T}\right|}{\left|\overline{(E_1 E_2^*)_C}\right|} = \frac{\left| r_T \sqrt{\overline{|E_1|_T^2}\ \overline{|E_2|_T^2}} \right|}{\left| r_C \sqrt{\overline{|E_1|_C^2}\ \overline{|E_2|_C^2}} \right|}. \tag{1}$$

*Work performed while the author was in the Aerospace System Branch, Space Systems Division. Manuscript submitted September 19, 1975.

Here we have used the definition of the correlation coefficient between two random variables:

$$r = \frac{\overline{E_1 E_2^*}}{\sqrt{\overline{|E_1|^2}\ \overline{|E_2|^2}}} . \tag{2}$$

Now let us consider very small frequency differences between E_1 and E_2, of about 0.1%. Then, to a very good approximation, $|E_1|^2 = |E_2|^2$, and Eq. (1) becomes

$$\left(\frac{S}{C}\right)_2 = \frac{\overline{|E_1|_T^2}\,|r_T|}{\overline{|E_1|_C^2}\,|r_C|} = \left(\frac{S}{C}\right)_1 \frac{|r_T|}{|r_C|}, \tag{3}$$

where $(S/C)_1$ is the ratio of powers of a single-frequency return. Equation (3) shows that the signal-to-clutter ratio obtained with two frequencies should be greater than that obtained by a single-frequency system by the ratio of the magnitudes of the correlation coefficients with and without a target in the beam.

Since we must expect the target return to be somewhat decorrelated, improvement can only occur if $|r_C|$ is very small. We may see that such small values of $|r_C|$ are reasonable by applying the sea-clutter model of Wright [7, 8] to the dual-frequency system. By this model the backscattered sea return can be written to first order as

$$E \sim e^{i2kR_0 \cos\theta} \int_{-\infty}^{\infty} f(x)\gamma(x, t) e^{i2k \cos\theta\, x}\, dx. \tag{4}$$

Here $f(x)$ is the illumination pattern on the water surface, $\gamma(x, t)$ is the capillary-wave amplitude, k is the microwave number, and R_0 is the distance to the center of the footprint. The amplitude of the capillaries may be modulated by any gravity waves which are present but for present purposes may be considered homogeneous over the illumination pattern. Then

$$\overline{(E_1 E_2^*)}_C \sim e^{i2\Delta k R_0 \cos\theta} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x) f^*(x+u)\overline{\gamma(x, t)\gamma^*(x+u, t)}$$

$$\times\ e^{i2\Delta k \cos\theta\, x}\, e^{-i2k_2 \cos\theta\, u}\, du\,dx, \tag{5}$$

where $\Delta k = k_1 - k_2$. But $\overline{\gamma(x, t)\gamma^*(x+u, t)}$ goes rapidly to zero as u increases. Thus $f(x) \approx f(x+u)$, and

$$\overline{(E_1 E_2^*)}_C \sim \left[\psi(2k_2 \cos\theta) \int_{-\infty}^{\infty} |f(x)|^2\, e^{i2\Delta k \cos\theta\, x}\, dx\right] e^{i2\Delta k R_0 \cos\theta} . \tag{6}$$

In this equation, $\psi(2k_2 \cos\theta)$ is the power spectrum of the sea evaluated at $2k_2 \cos\theta$. Equation (6) therefore shows that $\overline{(E_1 E_2^*)}_C = 0$ if $|f(x)|^2$ does not have spectral components at $2\Delta k \cos\theta$. This will certainly be true for broad illumination patterns and Δk's greater than about 0.2 m^{-1}, as were used in these experiments. Thus it is reasonable to expect that $|r_T| > |r_c|$ and that signal-to-clutter improvement will occur. Note that if $\Delta k = 0$ in Eq. (6), that is, if $E_1 = E_2$, the value of $(E_1 E_1^*)_c$ will never be zero, due to the integral over the illumination pattern. This indicates that clutter suppression is expected using this type of processing with dual-frequency returns.

EXPERIMENTAL EQUIPMENT

Figure 1 is a sketch of the experimental site at the Chesapeake Bay showing parameters of the system for a typical mode of operation. Approximately 0.4 *W* of power is transmitted by one antenna, and the backscattered return is received by the second antenna. The electronics for the system are housed in the small building shown in the figure. In a typical experiment the antennas are aimed so that their footprints overlap by adjusting the azimuthal positions until the sea clutter is a maximum. In the target-detection experiments to be described, the antennas were positioned in this manner, and sea clutter was recorded. A target was then placed in the beam, and the return from it and the water was recorded. Care was taken not to change the antenna positions during the course of the experiment.

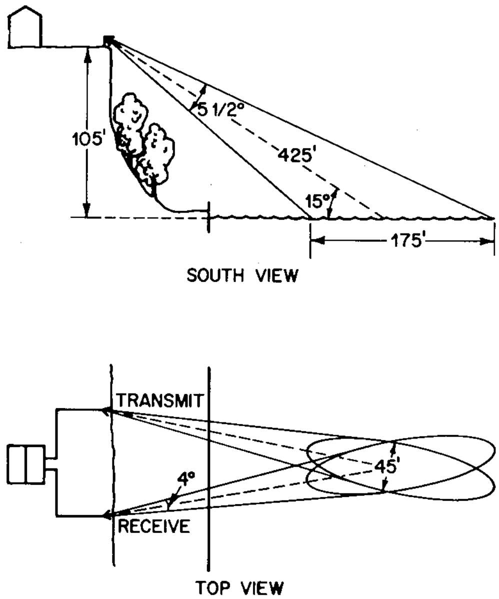

Fig. 1 — Delta *K* radar installation

Figure 2 is a block diagram of the system. A stable microwave signal is generated and then modulated at a frequency in the range of 3.5 to 75 MHz. The modulation is accomplished by driving crystals located in two arms of a magic *T*; by properly terminating these arms, carrier suppression can be achieved. Thus the transmitted waveform consists primarily of the two sidebands centered on the original microwave frequency. The frequency separation Δf between the sidebands is adjustable from 7 to 150 MHz.

A portion of the unmodulated signal is coupled into the receiver after being shifted by 400 Hz. This reference signal is beat with the received signal in a single-sideband generator. The outputs of the single-sideband generator go to a phase-matching circuit which separates the returns from the two sidebands and beats them down to 400 Hz. These two signals are then recorded on an analog tape recorder for later processing.

The basic limitation of the system is its inability to completely separate the returns at the two frequencies. We have been able to suppress the undesired signal in each channel by at least 20 dB across the range of Δf. However, it is believed that this residual suppressed signal is the principal cause of what little correlation is observed between the sea-clutter returns on the two channels.

RESULTS OF THE EXPERIMENTS

Data were recorded simultaneously from both channels of the Delta K system. The return from the higher sideband, E_1, was stored on one channel of the analog tape recorder, E_2 was stored on the second channel, and a trigger pulse was recorded on the third channel. The frequency separation between E_1 and E_2 was swept from 10 to 150 MHz in 1.35 seconds. The trigger pulse occured at the start of each sweep and was subsequently used to trigger a digital tape recorder to store a record. The output of the system was blanked during the return sweep, which took approximately 0.15 seconds.

To facilitate data reduction, the signals recorded on the analog tape recorder were digitized, and the analysis was performed on the computer. Programs were written to obtain the cross-correlation function between the channels and to form signal-to-clutter ratios for single- and dual-frequency systems. The two analog data channels were either multiplied together or squared and then written on digital tape. The procedure was to multiply E_1 and E_2 together and write the product on digital tape. The analog tape was then rewound, and E_1^2 for the same section of record was placed on the digital tape. Finally E_2^2 was recorded in the same manner. Each digital record, therefore, was 1.35 seconds long, with the separation between the two output frequencies of the Delta K system varying linearly from the beginning to the end of a record.

The program which performed the cross correlations read in a predetermined number of E_1E_2 records and averaged them point by point along the record. That is, each sample point of a record was averaged over several records. The same thing was then done for E_1^2 and E_2^2. The program then formed the correlation function $\overline{E_1E_2}/(\overline{E_1^2}\ \overline{E_2^2})^{1/2}$ at each point, that is, at successive frequency separations. The squared magnitude of this correlation function was then obtained by squaring its value at each point and averaging over a small range of Δf, usually about 2 MHz. To remove any small dc level induced in the correlation function by the residual suppressed signal, its average squared over the small range was then subtracted. Note, however, that this does not completely eliminate the effect of the residual suppressed signal since it will also affect E_1^2 and E_2^2. The

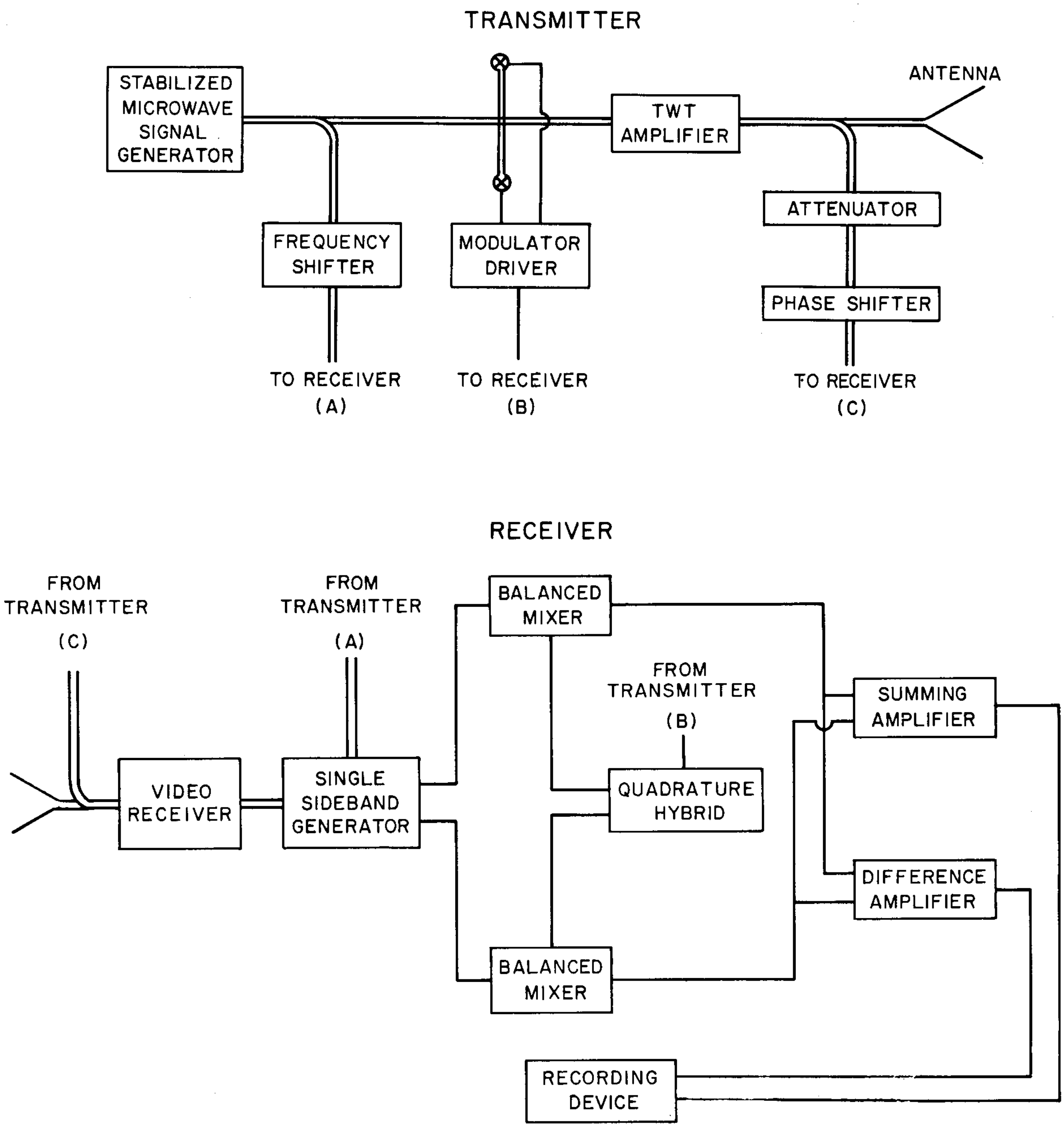

Fig. 2 — Simplified block diagram of the Delta K system

difference function is then the output of the system; it is the covariance of the cross-correlation function over a small range of Δf. If there were no residual suppressed signal, this function would just be the square of the magnitude of the cross-correlation function of E_1 and E_2.

Figure 3 shows a typical plot of this function for sea clutter. Note that even at the smallest available Δf values, the correlation function of E_1 and E_2 is less than 0.1. It is probable that this value would be even lower if more complete separation of the returns by the receiver could be achieved. Ninety records have been averaged to obtain the curve in Fig. 3.

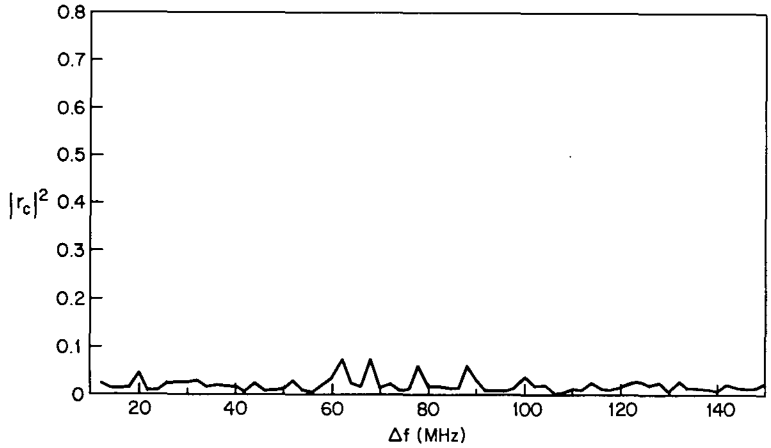

Fig. 3 — Correlation function of sea clutter

The program which forms signal-to-clutter ratios first reads in either E_1E_2 or E_1^2 for the case when a target is in the beam. These values at each point of the record are then averaged across the records, as before. Both the average and standard deviation of this averaged function are then formed over a small range of Δf. This same procedure is then performed on either E_1E_2 or E_1^2 for the case of an empty sea. Ratios of averages and standard deviations are then formed as measures of the signal-to-clutter ratios.

Now, as indicated in the second section, the signal-to-clutter ratios which we want to compare are ratios of magnitudes, either $\overline{E_1^2}$ or $\overline{E_1E_2}$. Clearly the average magnitude of $\overline{E_1^2}$ is obtained when the average over the small Δf ranges is taken. Thus

$$\left(\frac{S}{C}\right)_1 = \frac{\left\langle \overline{E_1^2} \right\rangle_T}{\left\langle \overline{E_1^2} \right\rangle_C} , \tag{7}$$

where $\langle\ \rangle$ indicates an average over Δf values. For $E_1 E_2$, however, as Eq. (6) shows, the phase factor $2\Delta k R_0 \cos\theta$ will cause $\langle \overline{E_1 E_2} \rangle$ to be 0. Thus to obtain $|\overline{E_1 E_2}|$, we must square $E_1 E_2$, average over a small frequency range, and take the square root. Thus

$$\left(\frac{S}{C}\right)_2 = \frac{\sqrt{\left\langle (\overline{E_1 E_2})_T^2 \right\rangle - \left\langle \overline{E_1 E_2} \right\rangle_T^2}}{\sqrt{\left\langle (\overline{E_1 E_2})_C^2 \right\rangle - \left\langle \overline{E_1 E_2} \right\rangle_C^2}} \tag{8}$$

since $\langle \overline{E_1 E_2} \rangle = 0$ for both the target and clutter case if the residual suppressed signal is absent. The signal-to-clutter ratio for the case of two frequencies is therefore the ratio of the standard deviation of $\overline{E_1 E_2}$ over a small range of Δf.

Figures 4 through 6 show the results of these experiments. In all three figures the upper graph indicates the degree of correlation induced in the returns on the two channels when a target is in the beam. The lower graphs then compare $(S/C)_1$ and $(S/C)_2$ as determined above. Note that $(S/C)_1$ should be independent of Δf; all three figures show this to be the case within experimental error. The ordinates on all these figures are linear.

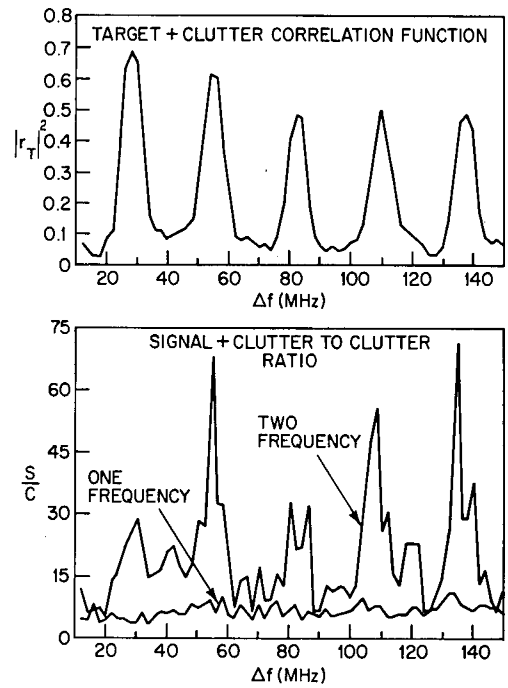

Fig. 4 — Correlation function and signal-to-clutter ratios for a series of corner reflectors spaced 18 ft apart

Figure 4 shows the results obtained for a series of small corner reflectors strung out in the water. The reflectors were 18 ft apart and, as would be expected for such a system, have a periodic correlation coefficient. The lower graph shows that $(S/C)_2 > (S/C)_1$ whenever $|r_T|^2$ is large. This is as expected from the considerations of the second section, since the correlation coefficient of the clutter is uniformly low.

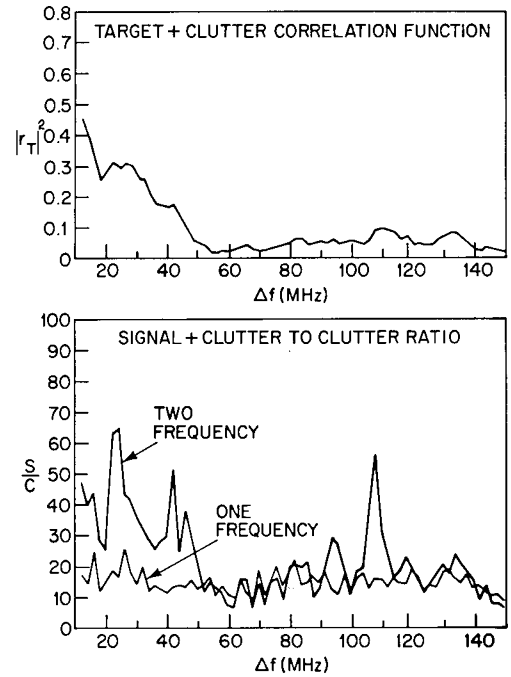

Fig. 5 — Correlation function and signal-to-clutter ratios for a boat 14 ft long

Figure 5 shows the correlation function and signal-to-clutter ratios for a small boat approximately 14 ft long. The correlation function is greater than that shown for sea clutter in Fig. 3 out to a Δf of about 50 MHz. Over this range of Δf, $(S/C)_2 > (S/C)_1$, as would be expected. Note also that there seems to be a bump in $|r_T|^2$ near 110 MHz which is reproduced in $(S/C)_2$.

Finally, Fig. 6 shows the results for an aluminum sphere which is 2 ft in diameter. The correlation function is now greater than the sea clutter to higher Δf values than was the case for the boat. This is not surprising since the sphere is considerably smaller than the boat. Once again $(S/C)_2 > (S/C)_1$ whenever the sphere return is more correlated than the clutter return. Note also that $(S/C)_1 \approx 2$. Since in reality this is the ratio of signal plus clutter to clutter, it indicates that the return from the sphere was about the same as that from the water. Since the ratio is larger by a factor of five or six for two frequencies, the possibility of subclutter visibility is indicated for the two-frequency system. That is, it should be possible to see targets whose backscattered power is less than that of sea clutter with a dual-frequency system if the two returns are partially correlated by the target.

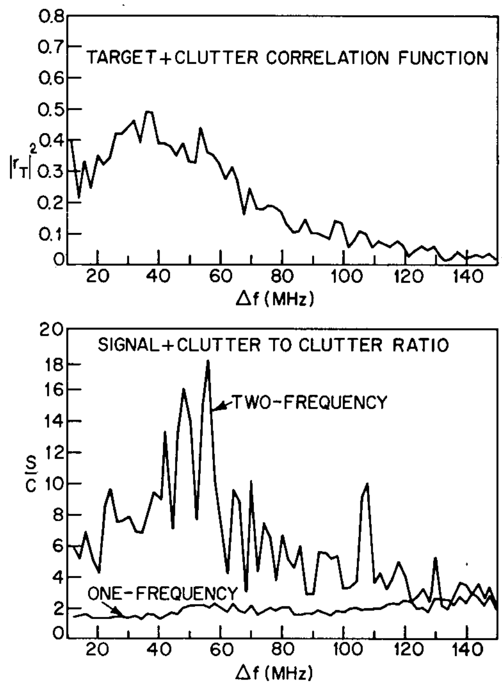

Fig. 6 — Correlation function and signal-to-clutter ratios for a sphere 2 ft in diameter

CONCLUSIONS

These experiments have shown that sea-clutter suppression can be achieved by multiplying the backscattered fields at two frequencies and averaging over times on the order of a few minutes. This effect can be used to improve the detection of stationary targets in a sea-clutter environment over that achievable with a similar single-frequency system, provided that the target return is not decorrelated to the same extent as the clutter. This has been found to be the case for three different targets up to the size of a small boat. It is felt that still more signal-to-clutter improvement could be achieved if the returns at the two frequencies could be separated more completely.

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