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HF Radar Signal Processing Algorithms for Air and Surface Target Detection

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***Abstract*—The well-known conventional microwave radars presently in use are efficient in target detection and tracking of targets at a few hundred kilometers range. The basic limitation of conventional radar systems operating at microwave frequencies is that the range coverage is restricted to regions where a line-of-sight (LOS) path exists between radar and target. The curvature of the Earth limits the microwave radar to distances that do not extend beyond the geometrical horizon. This distance may further be shortened due to topographical features such as mountains. Hence to overcome this limitation of microwave radars, we can use High Frequency (HF) radars which use the ionosphere for reflection of signals and detection of targets at distances beyond the line-of-sight or the geometrical horizon. In this paper we give an insight to the concept of HF radars, their working principle, and how they can replace the microwave radars in various fields.**

Keywords*— Range, Doppler, Resolution, Clutter, Dwell Time, LOS (line-of-sight), DFT (Discrete Fourier Transform), high frequency;

I. INTRODUCTION

The fundamental limitation of conventional radar systems operating at microwave frequencies is that the range coverage is nominally restricted to regions where line-of-sight (LOS) path exist between radar and target. Coverage may be restricted to much shorter ranges when topographical features such as mountains, shadow targets from radar illumination. Sometimes, microwave radars are prone to meteorological effects, like rain or hail, which has the potential to reduce target visibility due to weather clutter and increase signal attenuation, leading to poor performance.The HF radar overcomes the aforementioned limitations of conventionalmicrowave radar. The HF radar operates in the high frequency range (3-30MHz). An important property of HF band is the unique ability of HF signals to propagate over very long distances and illuminate the earth's surface well beyond the horizon. HF radar systems find application in early-warning wide-area surveillance and remote sensing. The targets maybe airborne (such as ballistic missiles, helicopters, military aircrafts, private aircraft and large commercial airlines) or could be surface targets (like patrol boats, cruisers, destroyers and aircraft carriers). Microwave radars also find application in similar areas such as surveillance functions, target detection, localization and tracking, and track-while-scan. Microwave radars differ from HF radars in providing early-warning at better resolution and accuracy.

II. HF RADAR

A. *Signal Environment*

A HF radar receives a mixture of different signals. The Signal Environment for HF radar is classified as shown in figure. Radar echoes are the signals received by radar due to echoes of the transmitted radar waveforms. Interference and noise come from other sources independent of the radar. Radar echoes are further subdivided into target echoes and clutter returns. Target echoes are commonly referred to as useful signals or desired signals. Unwanted echoes from other objects are referred to as clutter. In HF radar, clutter mainly arises due to backscatter from large areas of earth's surface (terrain or sea). External interference and noise may originate from natural or man-made sources.

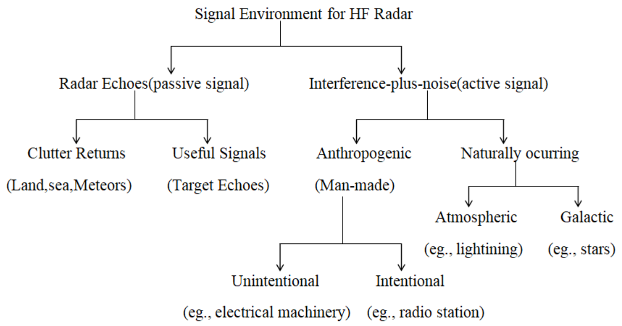

Fig 1.1 Signal Environment flow diagram for HF radar

In HF band, the main sources of natural noise include lightning and discharges, and galactic noise from sun and other stars. Man-made signals may be further subdivided as either originating from intentional and unintentional radiators. Intentional radiation includes short-wave radio broadcasts, point-to-point communication links, potentially jamming. Unintentional radiation may arise from industrial machinery and other electrical equipment. The sum of clutter, interference, and noise represents the composite disturbances that the radar echoes must compete with.

B. *Principle of Operation of a HF Radar*

HF Radars operate in the 3-30 MHz range of frequency. They use the ionosphere for the reflection of signals, which allows them to map ranges between 1000 to 3000 kms. Askywave HF Radar operates as follows:

The transmitter antenna radiates the HF signal, which can be steered to different sectors of the radar coverage. These emitted signal rays travel in a straight line in the lower layers of the atmosphere, until they meet the ionosphere, at oblique angles. In the ionosphere the transmitted signals come across a free electron density that increases with height. At one or more heights beyond 100km and below 600km, electron density is sufficiently high to cause total internal reflection of the signal. The transmitted HF signals are thus reflected back to the earth, due to change in free electron density (i.e. also change in radio refractive index) with altitude. The reflected rays, exit the ionosphere, and illuminate the portion of the earth's surface and the space above it beyond the horizon. A fraction of the scattered power propagates back towards the highly sensitive HF radar receiver, through a similar path, along with interference in the form of galactic noise, clutter from terrain or sea surfaces, ionospheric irregularities.

HF radars in general are permitted to use broad bands of the HF spectrum on a secondary basis. In exchange, such systems employ a policy of non-interference by selecting unoccupied frequency channels that are clear of other users in accordance with national standards and ITU regulations.

The composite signal received contains clutter, interference and noise. It is the residual level and distribution of unwanted signal energy over the target search space at the signal processing output that determines detection performance as opposed to the power of the various disturbance signals at the receiver input. Effective mitigation of disturbance signals requires judicious signal processing algorithms which are explained in the following sections.

III. SIGNAL PROCESSING FLOW

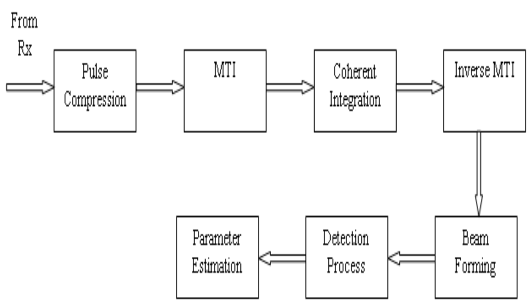

Fig 1.2 Block Diagram of Radar Signal Processing

IV. SIGNAL PROCESSING ALGORITHMS

The received signal not only contains the target echoes but also contains several other unwanted signals like clutter, noise, etc,. Hence to separate the required target echoes from the unwanted interference, signal processing algorithms are used. These algorithms aim to enhance the SDR (signal to disturbance ratio) and resolve the echoes in range dimension (pulse compression), velocity (Doppler processing), direction of arrival (beam forming) for target detection.Some of these algorithms are explained further.

A. Pulse Compression

A short pulse is required for achieving good resolution, whereas a long pulse is required to obtain a good detection performance. Pulse compressionoffers a solution by decoupling energy and resolution. The first objective of pulse compression is to increase the SNR of the echoes received with a round-trip time delay that matches each of the group range resolution cells processed. Second objective is to resolve the received echoes on the basis of their differences in round-trip time delay, such that contributions from independent scatterers received over different virtual path lengths can be effectively separated into different group range resolution cells.

Pulse compression (range processing) operates on samples of data acquired by the receiver to produce a number of range resolution cells for each transmitted pulse. It uses the concept of matched filtering. The impulse response of the matched filter is obtained by time-reversing and conjugating the complex waveform. The impulse response h(t) is given by

$$h(t) = \alpha x^*(T_M - t)$$

and output of pulse compression is given by the convolution of the received signal and impulse response of filter.

$$y(t) = \int_{-\infty}^{\infty} x'(s)h(t-s)ds$$

Where, x'(t) is the received signal consisting of target and noise component. T_M is the specific time at which SNR is maximized.

B. Moving Target Indication (MTI)

The stronger power of clutter signals compared to target echoes implies the need for Doppler filtering. In the first type called MTI, slow time filtering is done, to attenuate clutter in a given range-azimuth cell. In HF radars, clutter is often concentrated around zero Doppler frequency; a filter is required to suppress the clutter without attenuating target echoes at higher Doppler frequencies. While phase of the moving target varies due to changing range, the clutter component of the echo signal from each pulse would be identical. By subtracting echoes from successive pairs of pulses would cancel the clutter component.

The simple MTI filter produces an output $z_k(n)$ given by

$$z_k(n) = y_k(n) - y_k(n-1)$$

The MTI output is a slow-time signal containing noise, residual clutter, and one or multiple target information. Although MTI has computational advantages, it does not give an estimate of Doppler shift, and no information about the number of targets. It also provides a low SNR (signal to noise ratio). Hence, a second type of Doppler filtering called coherent integration method is used in HF radars.

C. Coherent Integration (CI)

In MTI processing, the fast time/slow time data matrix is high-pass filtered, yielding a new data sequence in which the clutter components have been attenuated. Pulse Doppler processing (coherent integration) differs from MTI in that filtering is replaced by explicit spectral analysis of the data for each range bin. Thus the result of coherent integration is a data matrix in which the dimensions are fast time and Doppler frequency. Coherent integration is performed by computing the discrete Fourier transform (DFT) of each row of the data as shown in fig 1.3.

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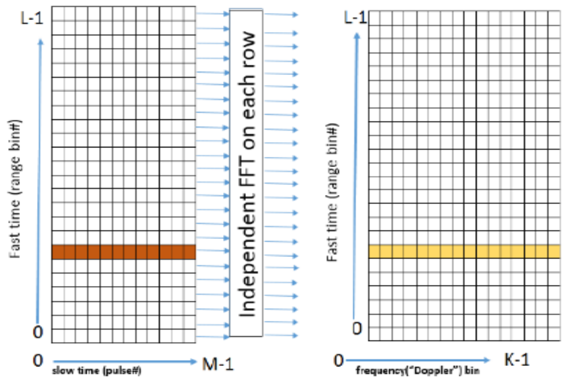

Fig 1.3: Conversion of fast-time/slow-time data matrix to a range/Doppler matrix.

Each Doppler spectrum sample is individually compared to a threshold to determine whether the signal at that range bin and Doppler frequency appears to be noise only, or noise plus a target. If the sample crosses the threshold, it not only indicates the presence of a target in that range bin, but also its approximate velocity, since the Doppler frequency bin is known.

The advantages of pulse Doppler processing (coherent integration) are that it provides at least a coarse estimate of the radial velocity component of a moving target, including whether the target is approaching or receding, and that it provides a way to detect multiple targets, provided they are separated enough in Doppler to be resolved. The chief disadvantages are greater computational complexity of pulse Doppler processing as compared to MTI filtering and longer required dwell times due to the use of more pulses for the Doppler measurements.

CONCLUSIONS

The limitations of microwave radar in early warning, long range detection, and remote sensing, pave the way for HF radars. HF radars effectively detect targets beyond line-of-sight. But, the implementation of radar systems in HF frequency range is quite different compared to conventional systems in microwave range, due to various challenges like bandwidth limitations, requirement of physically huge antennas, powerful clutter and external noises. Thus, requiring sophisticated signal processing. In this paper, a signal environment for HF was generated and processing algorithms were applied to study the radar applications in HF band.The simulation results demonstrate the detection of targets at different ranges, well beyond the horizon. These simulations can be extended to further include noise from galactic and lightning sources, and various other processing algorithms.

RESULTS AND DISCUSSIONS

The simulations performed are done using Matlab. The signal environment is generated for HF radar system. Signal processing algorithms are applied to the received signal in order to extract range and velocity information of the specified target(s). The target specifications are as in table 1.0

Table 1.0 HF Radar Target Information

Target	Range (km)	Velocity (m/s)
1 Air Target	1500	150
2 Air Target	2200	-200
3 Ship Target	2000	13
4 Land Clutter	800-1000	0
5 Sea Clutter	1700-2600	30
6 Sea Clutter	1700-2600	-30

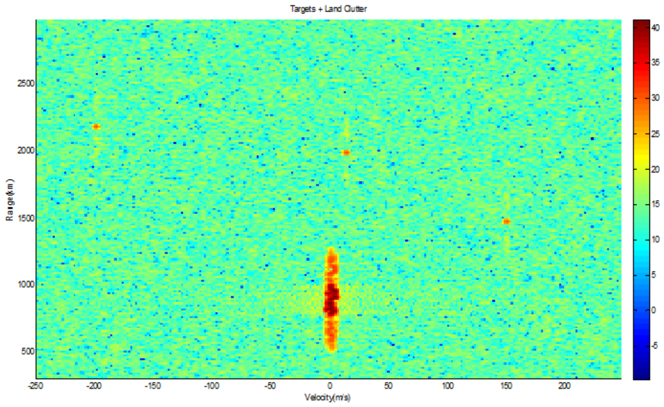

Fig 1.4 Range Doppler map of targets along with land clutter

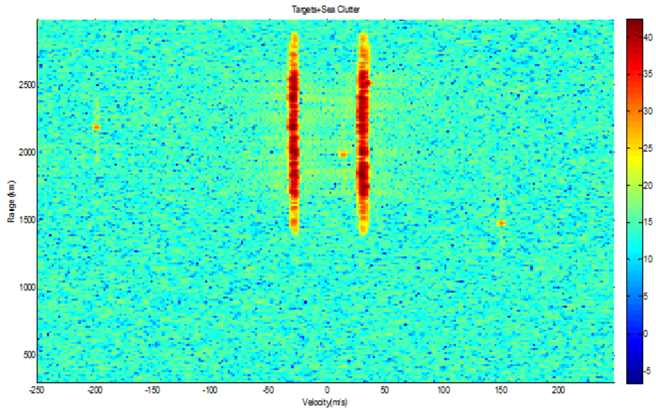

Fig 1.5 Range Doppler map of targets along with sea clutter

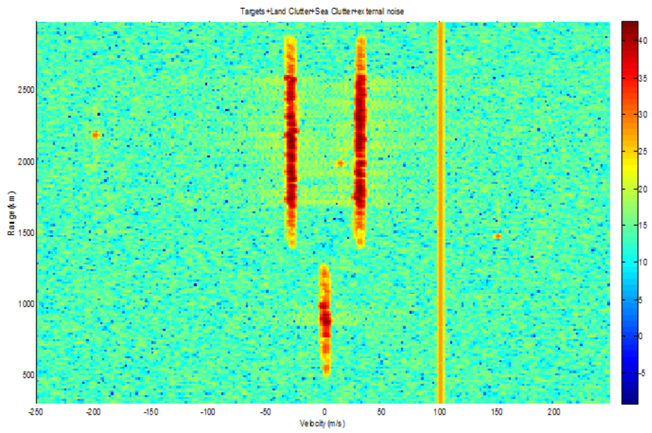

Fig 1.6 Range Doppler map showing targets along with land clutter, sea clutter, and external noise

Figure 1.4 shows the Range Doppler (RD) map obtained after performing coherent integration on the received signal. It shows the detection of air targets and ship targets with corresponding range and velocity, amidst land clutter.

Figure 1.5 is the RD map depicting targets with sea clutter. Sea clutter consists of echoes from two components, namely advancing and receding Bragg wave-trains. The effect of reflection from ionospheric layers, the movement of the waves and the state of the sea is seen as spread along Doppler for the sea clutter signals. The spread in range appears due to the look down geometry of the radar. Sea clutter spectrum does not occur at zero Doppler but appear on both sides of zero Doppler, slightly away from zero Doppler.

Figure 1.6 shows the detection of specified targets amidst the presence of land clutter, sea clutter as well as external noise. The single line at non-zero Doppler (at 100 m/s) signifies external noise which may be from other HF communication system operating in the same frequency range.

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