Progress in HFSWR research at Harbin Institute of Technology

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***Abstract*—The Experimental HF Surface Over-The-Horizon Radar set up in the late of 80's has been updated by installation of multi-channel receivers with digitization at the second IF stage, new designed transmitting and receiving antennas, wideband solid-state power amplifiers, frequency synthesizer with low phase noise and flexible signal generator, a new radar controller added to allow the automatic and manual control of the radar, a new designed signal and data processor built mainly with 16bits A/D converters and several multiprocessor boards with Sharc chip processors added in, and a electromagnetic spectrum monitor equipped in the updated radar system to be able to automatically survey HF spectrum occupancy for providing so called clear frequency channel suitable for radar operation. The purpose of the setting up of the updated radar system is to demonstrate some of new functions of the radar system, and to prove some new techniques to be possibly used in a near future. In the paper, some latest developments of countering measures with radio frequency interferences are presented, too.**

I. PREFACE

With the leading role in the setting up of an Experimental HF Surface Over-The-Horizon Radar (EHFR for short) in the late of 80's in China by HIT, the trials of detection and tracking of the beyond line of sight ships and low altitude airplanes were conducted in the same time slot by EHFR operation on the coast line of Northern China Sea and the results achieved were encouraging. It was reported elsewhere[1].

In order to gain a fully understanding of HF radar operation, to conduct more trials and accumulate more experimental data was widely recognized in our community, in view of it there was a huge demand of updating work in EHFR and it was approved and funded by related Chinese organization.

It was run smoothly and the first phase was ended recently.

On the newly setup EHFR site some experiments were conducted, and since then the Data base file has been building up with the daily operation activity

Here an outline of the updated work in EHFR and some experimental results will be reported.

II. MAJOR UPDATED WORK IN EHFR

A. System Configuration

A simplified schematic diagram of the EHFR is given in Fig.1. The radar system consists of two vertical polarized log-periodical transmitting antenna arrays, an eight-element vertically polarized receiving antenna array, two mutual-orthogonal horizontal polarized antennas for countering interferences by means of polarized information, two high power amplitude amplifiers used as the transmitters, 24 receivers, a frequency synthesizer, a signal and data processor, and a radar controller.

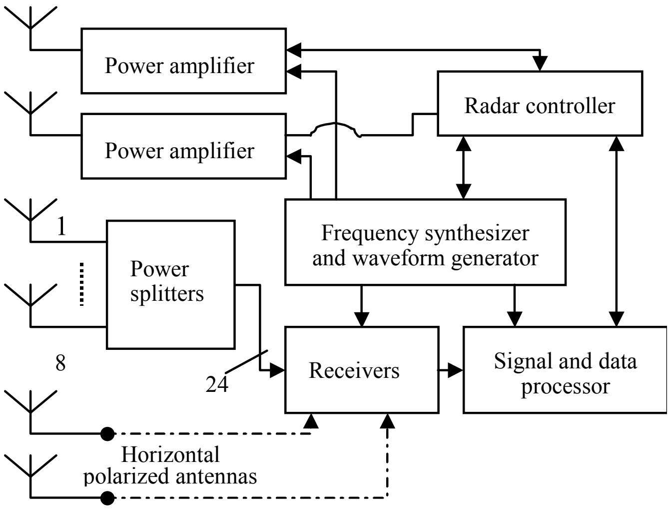


Fig. 1 A simplified schematic diagram of the EHFR

B. Antenna

The vertical polarized monopole log-periodical antenna array was introduced into the EHFR system as the transmitting antenna to expand the available HF spectrum usage. It consists mainly of the radiating elements, an impedance transformer, a ground screen and coaxial feed lines. Each of elements is a squirrel-cage made of copper wires. To reduce the ground loss and the effect of the local weather, and to ensure that the surface radio wave is effectively excited, the use of a ground screen around the transmitting antenna is indispensable. The length of the transmitting antenna array is less than 100m. The directivity of the transmitting antenna array is about 8dB. And the standing-wave ratio is better than 2 decibels with the operation frequency changing from 2 MHz to 20 MHz. Fig. 2 shows a picture of a vertical polarized monopole log-periodical antenna array. There are two transmitting antenna arrays fed by two

Fig. 2. A view of one transmitting antenna.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
14 APR 2005	**N/A**	**-**

4. TITLE AND SUBTITLE	
Progress in HFSWR research at Harbin Institute of Technology	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Research Institute of Electronics Engineering, Harbin Institute of Technology (HIT), Harbin, P.R. China**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001798, Proceedings of the International Conference on Radar (RADAR 2003) Held in Adelaide, Australia on 3-5 September 2003., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

transmitters respectively in the transmitting site. The distance between the two antenna arrays must be kept about several tens of meters for avoiding the mutual coupling.


Fig. 3. A view of a part of receiving antenna array.

The receiving antenna array consists of 8 element sub-arrays spaced evenly along a 120-meter strip of beach. Wideband matching networks and a grid ground screen are used. Each of sub-arrays is formed as an end fire array with four 6-meter height monopole squirrel-cage antenna. A power combiner and four phase shifting cables are used to improve the fore-and-aft ratio of the whole receiving antenna array. The directivities of the receiving antenna array would change from 11 to 16 decibels with the carrier frequencies being used by the radar. Fig. 3 shows a picture of receiving antenna array.

C. *Transmitter*

It is well known that the HF surface over-the-horizon radar works in a congested short-wave band. For avoiding the interferences, the radar has to frequently change its operation frequencies, and the setting time of the carrier frequency change should be short enough. Therefore, a wideband solid-state power amplifier is a best selection. In the EHFR, two 800w identical wideband solid-state power amplifiers are used to deliver high HF power to two transmitting antennas respectively. The amplifiers exhibit good linearity, which are driven by two waveform generators respectively. One waveform generator is called “ship” signal generator, another is called “airplane” signal generator. Fig. 4 is a picture of transmitters.


Fig. 4. Transmitter equipment.

D. *Receiver and Frequency Synthesizer*

An important step in updating the radar has recently been taken by installation of multi-channel receiver equipment. The 24 receivers are divided into three receiving groups, each of which consists of eight receivers. They are respectively used as receiving ship target signal echo, airplane target signal echo and signals from electromagnetic environment. The dynamic range of the updated design receiver is sufficiently increased to 90 dB to allow extraction of very weak targets in the presence of high level interference signals from other HF users and strong background. In addition, some measures of improving the performance of the receiver have been introduced, such as: anti-lightning devices added; dual gates (a hardware gate followed by a soft gate) for reducing switching effect; digital AGC; digitization at the second intermediate frequency stage for improving the passband response and I/Q orthogonality; real time calibration for correcting the differences in amplitude and phase among receivers. The rms residual errors are less than 0.1 decibel in amplitude, 1 degree in phase.


Fig. 5 A picture of the receiver and frequency synthesizer equipment.

A high performance frequency synthesizer offers some specified required frequencies for the receivers and common timing and waveform generators are set up. The generator generates transmitting and demodulating signals, and ensures correct synchronization of power amplifiers, receivers, signal and data processor, etc. Fig. 5 gives a picture of the receiver and frequency synthesizer equipment.

E. *Radar Controller*

The radar controller is built with high performance single board computers (SBC). There are two control modes, which are called automatic control mode and manual mode respectively. In the automatic mode, the operation parameters of the system are changed automatically based on the results of electromagnetic spectrum monitor. In the manual mode, operation parameters can be changed from the keyboard according to the operator. For both modes, the controller needs to check the operation status of all sub-systems in each time slot between adjacent coherent integration time periods of the system, and to display the status information, operational parameters of the system, the environment electromagnetic spectrum, the processed echo spectrum, the plots of the detected and tracked targets. Fig. 6 is picture of the radar controller.


Fig. 6. A view of the radar controller.

F. *Signal and Data Processor*

Since the digitization is carried out at the second IF stage of receivers, and a large amount of data must be stored and calculated in real time, it is necessary to integrate a proper signal and data processor. Therefore,

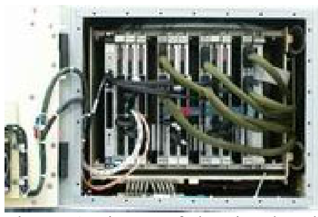


Fig. 7. A picture of the signal and data processor.

the signal and data processor of the EHFR is built with 24 16bits A/D converters, 1 host computer (single board computer) as a control unit to carry control and synchronization in the processor, several multiprocessor boards with Sharc chip processors built in, and the specific topological lattice offer a sufficient calculating ability. Fig. 7 is a picture of the signal and data processor. Essential functions realized in the signal and data processor include digitization at second IF stage, preprocessing (I/Q transform and filtering, etc.), various compensations, range processing, lightning filtering, adaptive beamforming (ADBF), Doppler processing, target detection, estimation of the detected target position, track initiation, track association and filtering of the detected targets, and data processing of the electromagnetic spectrum monitor. Nearly all the signal processing function is programmable. In addition, a data acquisition unit is attached to the processor. The data collected in the unit is processed off line afterwards, The main purpose is to adjust or verify hardware units, to debug application software, to demonstrate some of functions of the radar system, and to prove some new techniques possible to be used in a near future.

G. *Electromagnetic Spectrum Monitor (ESM)*

It is well known that radio interferences are dominant in HF band. A dedicated sub-system called “Electromagnetic Spectrum Monitor” (ESM for short) to survey HF spectrum occupancy has been equipped in the radar system for providing so called clear frequency channel suitable for radar operation. The signals from eight receivers are digitized at the second IF. The collection of data should be synchronized with the radar system operation. The normal spectral analysis and digital beamforming are performed after some necessary preprocessing (including orthogonal transforming, filtering, calibrating etc.) in the digital receiver. The measurements of spectrum across the entire band to be possibly used are carried out in step 30kHz with a resolution of about 1kHz at a short time interval. The resulting spectra averaged in time are used for data processing of the ESM.

Before the end of each radar operation, the ESM will recommend two clear frequency channels to be used in next radar operation period for ship and airplane target detections respectively. The channels should match up to the signal and receiver IF bandwidths. In the determination

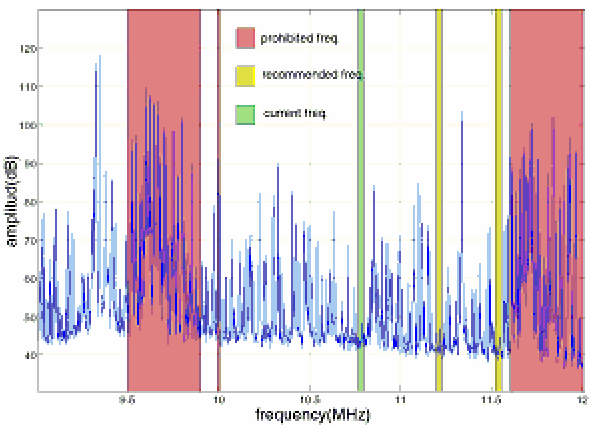


Fig. 8. An example of a portion of the measured spectrum

of clear frequency channels, a proper criterion has been set up, in which the performance of radar at current operating frequency, the temporal non-stationary properties of external noise and interferences, the number of interferences in a channel, noise background, propagation loss, the directivities and efficiencies of radar antennas have been considered together to ensure the radar system to as close as possible approach its potential performance in actual interference and noise background.

Fig.8 illustrates a portion of the measured spectrum. Generally, HF radar cannot be allowed to work at a frequency channel in the so-called prohibited frequency band, in which there are many broadcasting and civil communication users. In the Fig. 8, the green ribbon means the current operation frequency channel of the radar, and yellow ones are the recommended frequency channels for next operation period.

III. Radio Interference Suppression Based on Polarization Filtering Antenna Measurements

A. *Introduction*

As High Frequency Surface Wave Radar (HFSWR) works in the lower part of short wave band (2-18MHz), the radio signals reflected by ionosphere constitute the dominant interference source. At present, frequency agility technique and adaptive beam forming technique are taken as two main approaches to suppress the radio interference in HFSWR. Both techniques have their intrinsic limitations: frequency agility can’t suppress co-channel interference and beam-forming technique can’t cope with co-direction interference. Polarization technique has been paid more attention in recent years since it can overcome these two limitations.

Here some fundamental definitions are briefly recalled to describe the polarization signals proposed in the following sections.

In a right-handed Cartesian xyz co-ordinate system, if the polarization state is invariant, the EM field vector of a plane wave propagating along the z-axis can be represented by a complex vector given by

$$\vec{E}_i = \begin{bmatrix} E_H \\ E_V \end{bmatrix} = \left|\vec{E}_i\right| \begin{bmatrix} \cos\varepsilon_i \\ \sin\varepsilon_i \exp(j\delta_i) \end{bmatrix} \qquad (1)$$

Where the subscripts H and V denote the horizontal and vertical electric field components, while $0 \le \varepsilon_i \le \pi/2$ and $-\pi \le \delta_i \le \pi$, represent the amplitude relationship and the phase difference between the two orthogonal polarized components [2].

B. *The Latest Development of Polarization Filtering for Suppressing Radio Interference*

1) *Polarization Features of Target and Clutter*

Although the target signal is too small to be observed in a echo of HF radar, we can analysis the mixture echoes that consists of clutter, targets and interference, etc. Fig. 9 gives the echoes of both vertical and horizontal channels, which shows the vertical signal is stronger than horizontal one. After processing on range and velocity domains, the amplitude and phase polarization characteristics of the target can be calculated as shown in table 1.

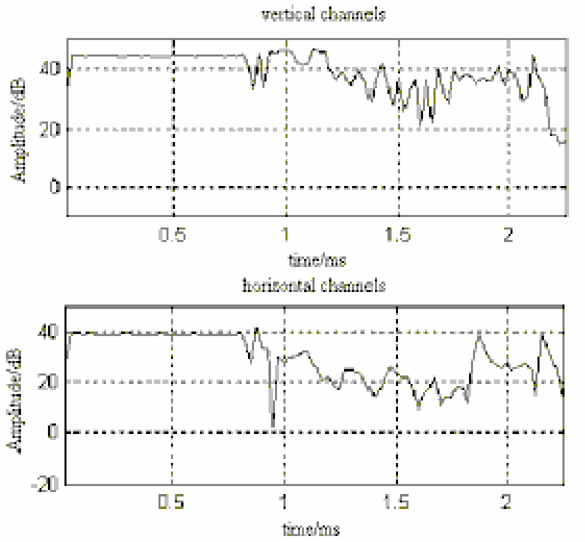


Fig. 9 Amplitude of vertical and horizontal channel echoes

TABLE 1 POLARIZATION CHARACTERISTICS OF TARGET SIGNAL

Sample NO.	1	2	3	4	5	6
ε_i (degree)	77.8	79.2	79.0	80.7	75.0	74.6
δ_i (degree)	-126.2	-142.5	-143.7	-142.8	-138.4	-130.2

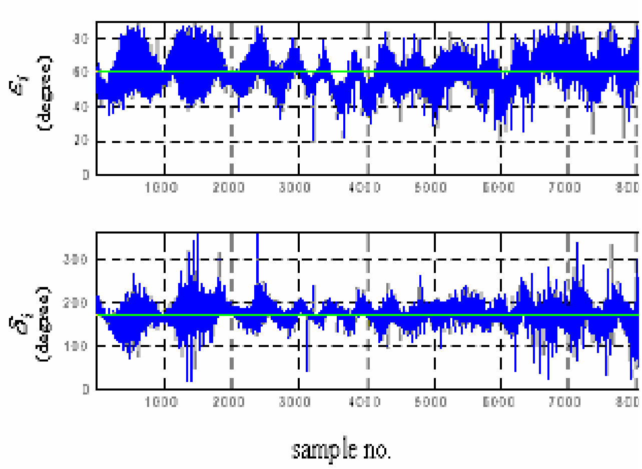


Fig. 10 Time-domain polarization spectrum of interference in one accumulation cycle

2) Polarization Features of Radio Interference

As shown in Fig. 10 [3]and Fig. 11, the polarization state of the radio interference changes greatly in one accumulation cycle while keeps stability in one pulse cycle.

3) Null Phase-Shift Polarization Filter

In application of a Single Notch Polarization (SNP) filter, a varied phase-shift of the target signal is observed after processing by the SNP filter and it is correlated with the position of the filter notch. On countering radio interference, in order to suppressing the radio interference signal reflected by the ionosphere, the positions of the filter's notches must be changed ,as the polarization states

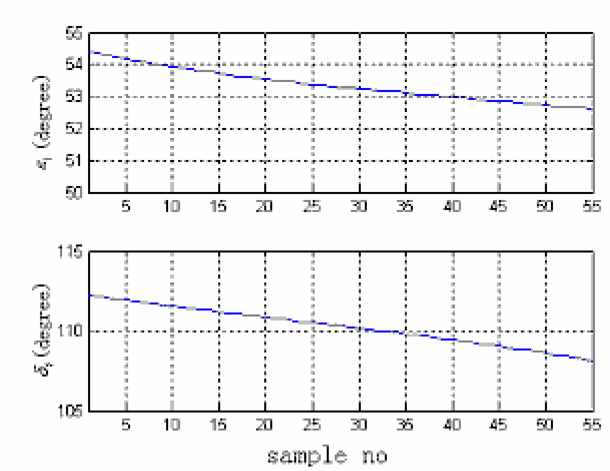


Fig. 11 Time-domain polarization spectrum of interference in one pulse cycle

of radio interferences are time-variant. The different phase-shifts of target signal are resulted during the course of such processing. As a result of the mentioned phase changes, the target signal can't be accumulated correctly even if the radio interference is suppressed a lot. That means the variant phase-shift(phase distortion) make it

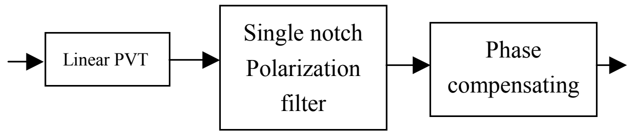
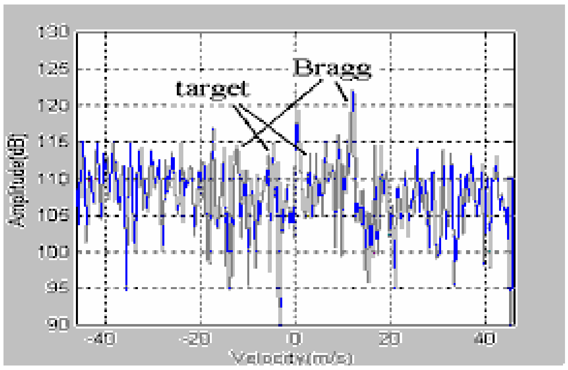
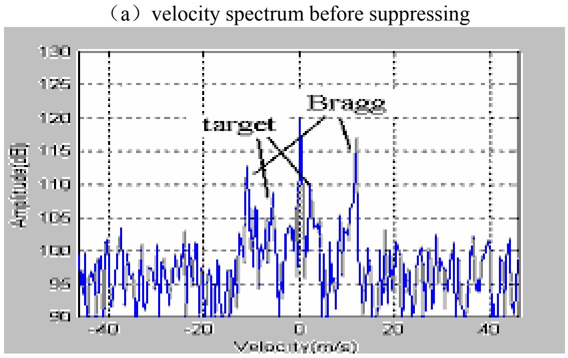


Fig. 12 Null phase-shift polarization filter

impossible for a Doppler radar such as OTHR to utilize a time-variant SNP filter or MLP filter. In order to overcome this problem, a Null Phase–Shift Polarization filter as Fig.12 is proposed. A Linear PVT is used to turn the target signal polarization state into a vertical one, then through a



（a）velocity spectrum before suppressing



（b）velocity spectrum after suppressing

Fig.13 Linear polarization cancellation of a typical "plane interference" phase compensation device to align the distorted target phases after processed by the SNP filter. Ideally, the output signal would have the same phase as the input target signal'.

Fig. 12 is named as Null Phase-shift SNP (NPSNP) filter. Replacing the normal SNP filter in Poelman's MLP filter with the NPSNP filter, a Null Phase-shift MLP (NPMLP) filter based on NPSNP filter can be developed to suppress multi-interference or apply in other more adverse environments.

C. Performance Evaluation with Experimentally Derived Data

Based on the argument mentioned above, many works have been done to evaluate the performance of the polarization signal processing methods with experimentally derived data. Some main results are figured below.

Fig. 13 gives the results in the velocity domain of a typical interference. It is shown that the signal to interference ratio (SIR) can be improved about 10dB processing by the polarization filter mentioned above.

IV. Some Other Counter Measures Against Interferences

A. Adaptive Interference Cancellation

HF radar has to extract targets from a strong combined background of sea echo, external noise, and interference. Moreover, the user congestion in the HF band significantly reduces the number of clear frequency channels available for the operation of the HF radar, it is important to counter HF radio frequency interferences to increase the channel availability. Otherwise, radio interferences within the same channel would notably degrade the system performance. In such situations, some of techniques may be utilized to adaptively cancel unwanted radio frequency interference.

1) A Cursory look at the temporal and spatial characteristics of high frequency interference

Most of HF interferences propagate by ionospheric paths or possible mixed paths, and they behave extreme nonstationary because of ionospheric disturbance and reflections from different ionospheric regions. The obvious embodiments of nonstationary signals are the amplitude fluctuation and the DOA swing.

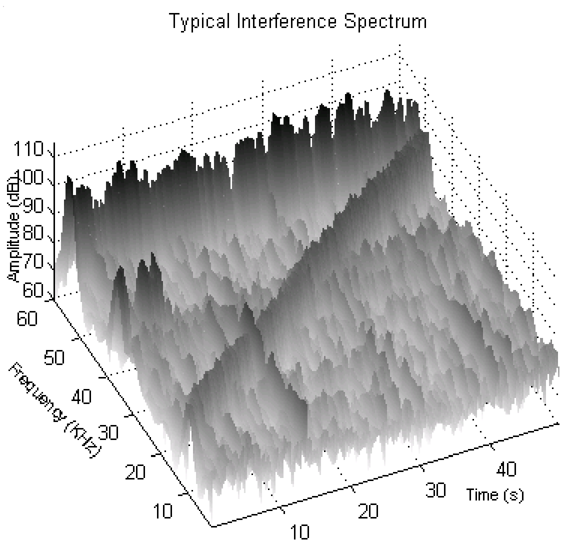


Figure 14. A typical base band spectrum

Figure 14 shows a typical temporal-frequency spectrum at baseband of HF interferences within 50 seconds. It contains a strong interference at 55 KHz and an FM interference and some other instantaneous interferences with narrow band or wide band. It not only shows a complex scene of interferences but also exhibits that even if an interference is strong, the fluctuation in amplitude is possible about 10 to 20 dB even up to 30 dB.

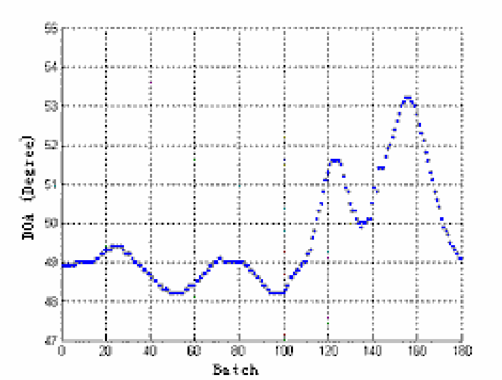


Figure 15 DOA curve within about 5s

In figure 15, it was observed that the spatial characteristic of an HF interference presents a notable variation with time. Total 180 times DOA estimations at a 28ms interval were made and each of DOA estimations utilized 14ms sample data. It is shown that the maximum range of DOA swing is up to 5 degree.

2) Short-time adaptive cancellation

In an HF surface wave radar system, coherent integration time (CIT) is usually required from at least several seconds for airplane target detection to several tens of seconds for ship target detection. However, radio interference cannot be looked as a spatial stationary signal at a time longer than 300ms[4]. In order to reject a nonstationary interference, relatively long CIT is partitioned into a number of short time processing intervals, in which it is considered as "almost" stationary. Then, the sample spatial covariance matrix R is estimated according to the sample data within the relative steady interval.

The traditional optimum weight is derived in accordance with the sample matrix inverse (SMI) technique[4], which can gain a minimum least-square output, but the main lobe and the side lobe of the beam is out of control, which is very important for the target azimuth estimation.

In order to maintain the required main lobe and sidelobe level, the selected eigenvector weighted projection algorithm is presented in the following.

One solution to the matrix inversion problem is offered by eigenmatrix projection[5].However, in a practical system, the eigenvalues are distributed more widely, increasing the span of the interference space that the interference power seems to creep into the noise space and a clear separation between both spaces disappears, especially for strong jammers. As a consequence the value of K, the assumed number of interference, would have to be increased, which leads the noise component to spoil the side lobe. To lessen this problem, eigenvectors are weighted according to the corresponding eigenvalues[5]. Then the adaptive weight is:

$$W = [I - DGD^H]W_0 \quad \text{with}\ G = diag\{\frac{\lambda_k}{\lambda_k + \alpha\sigma^2}\} \quad (2)$$

where λ_k is the bigger eigenvalues, D consists of corresponding eigenvectors, σ^2 is the noise variance, α is a proper coefficient, and W_0 is the model weight

When a interference comes from the main lobe of the wanted weight, the just described weighted projection cannot avoid its damage. Hence, a supplementary rule is defined to filter this kind of eigenvector components from the projection matrix, that is we have to select the appropriate eigenvectors.

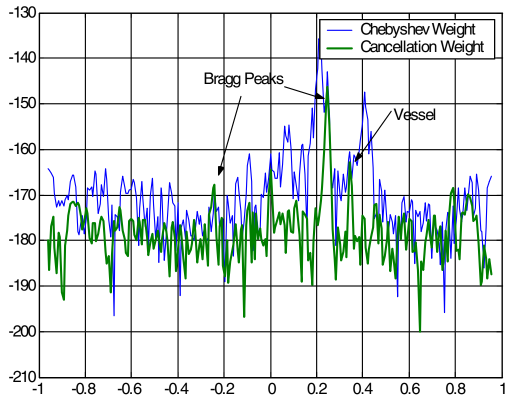


Figure 16 Suppression compare with Doppler spectrums containing a vessel at 0.33Hz(about 30Km/h)

Figure 16 gives an example of interference suppression. The received signals contain a ship target with a velocity of about 30Km/h, corresponding a Doppler frequency of about 0.33Hz, an interference from a broadcast station at a azimuth angle of about –20 degrees with respect to the normal line of sight of the radar and other background noise. The dashed line presents the result without interference suppression, and the solid line presents the result with adaptive cancellation. As a result, the amplitudes of the ship, Bragg peaks and fixed target are kept, and the interference is rejected to a level near background noise.

B. Signal Processing Techniques for Randomly Discontinuous Spectra Waveforms

A major problem with all OTH HF radars is a relatively poor range resolution available, since there are many interference sources in the HF band, and it is difficult to find broad clear continuous frequency bands, therefore many HF radars are restricted to operating within narrow frequency bands. To operate with wideband, i.e. > 10 KHz, based on the result of ESM, frequency bands used for

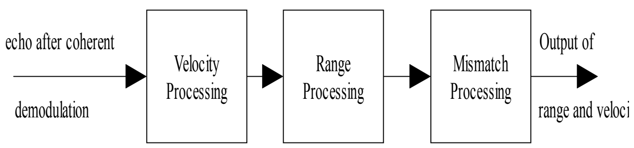


Figure 17 The processing scheme for RDS waveforms

transmission must be made discontinuous to avoid interferences. Waveforms with randomly discontinuous spectra (RDS) can evade the external interferences with their flexible energy distribution. However, it results in high range sidelobes when matching with the reflected echo, which will eventually cause severe ambiguities in targets detection. So it is indispensable to study the processing technique for RDS waveforms. There are some algorithms in the literature [6-9], however these algorithms are still far out of practical use. In this paper we introduce a new signal processing technique to lower the range sidelobes. The processing scheme is shown as figure 17. The simulation results using RDS waveforms are shown as figure 18,19, where the RDS waveform is simply a burst of pulses, whose number is of 30, and the carrier frequency for each pulse is randomly selected within the frequency band spanned about 400KHz, coherent integration time (CIT) is of 46.08s, two targets are located at range of 115.5Km, 116Km with velocity 21.6Km/h, and the third stationary target is located at range 116Km.

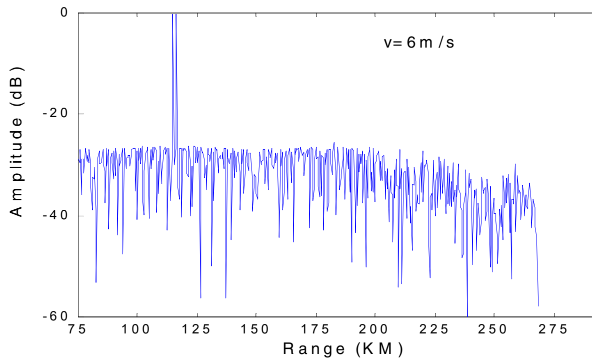


Figure 18 Simulation result for two targets with the same velocity located at near range bin

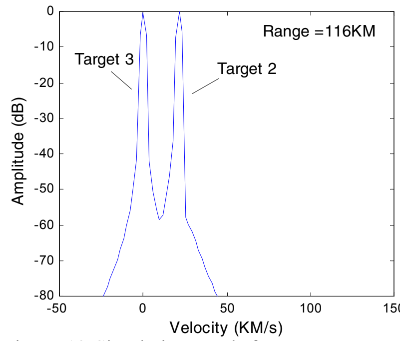


Figure 19 Simulation result for two targets with the different velocity located at the same range bin

It is clear from Figure 18 that two targets with the same velocity located at near range bin can be easily distinguished, while self-clutter is below -30 dB after mismatch processing .As well for the case of two targets with a different velocity locate at the same range bin. It is worth mentioning that the achievable system bandwidth in the simulation is about 400KHz.

The proposed technique is quite effective to deal with RDS waveforms, and the advantage of adoption of this waveform is not only wide bandwidth, but also the ability of anti-interference can be achieved.

V. SUMMARY

It is confirmed with a lot of trials that the updated experimental HF surface radar described in the paper can operate well in a strong interference background at day and night time within various weather conditions by means of the new designed or equipped subsystems and some counter measures against interferences. Furthermore, not only it could provide the capability of simultaneously detecting and tracking ship and airplane targets, but also the flexibilities for proving some new techniques to be possibly used in a near future.

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