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DEVELOPMENT OF A SHIPBOARD HIGH FREQUENCY SURFACE WAVE RADAR FOR ANTI-SHIP MISSILE DETECTION

SEPTEMBER 1998

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ABSTRACT

A shipboard high frequency surface wave radar (HFSWR), operating between 15 and 25 MHz, can detect low-flying anti-ship missiles by virtue of diffraction beyond the horizon in a surface-attached wave. Following several successful shore-side demonstrations, the Navy initiated a program in FY95 to demonstrate a shipboard HFSWR system. A system is currently under fabrication that will be tested in 1999 on the LSD-52 (*Pearl Harbor*) and on the US Navy's Self-Defense Test Ship. This paper describes the system and testing performed to date, as well as system trade studies and shipboard noise measurements.

1. INTRODUCTION

Timely detection and tracking of anti-ship missiles (ASMs) and aircraft flying as low as a few meters above the ocean's surface at speeds exceeding M2.0 present a severe challenge to the sensor suite on a Navy combatant ship. Typical microwave radars have detection and firm-track ranges limited by propagation and geometry to a distance of about 20 kilometers.

A high frequency surface wave radar (HFSWR) operates at frequencies within the 3 to 30 MHz HF band and detects targets at over-the-horizon (OTH) ranges by virtue of penumbra and shadow region illumination by a vertically-polarized surface-attached wave. Although the surface wave is attenuated rapidly over land, the attenuation rate over the relatively conductive ocean is sufficiently low to permit detection of ASM targets at ranges approaching 40 km and low flying aircraft to 80 km.

In FY95 the Navy began an Advanced Technology Demonstration (ATD) project to develop a shipboard HFSWR system. The primary targets of interest are ASMs, but aircraft, ships, and theater ballistic missiles (TBMs) are also in the target mix. This paper presents the results to date of the ATD program. The program was originally intended to end in FY97 with testing on a surface ship. However, in October 1996 the program was canceled as an ATD because of budget cuts in the Navy's ATD funding. The program continued at a much reduced funding level through FY97 using other funding; in February

1998, FY98 ATD funding was restored to continue the program through FY98, and shipboard testing will take place in January to March, 1999.

OTH detection and tracking of ASMs from shore-based HFSWR systems has been demonstrated by two systems[1]. The ATD was undertaken to address the risks associated with a shipboard installation:

- Control of potential interference generated by the HFSWR in shipboard communication systems;
- Achievement of the desired performance (firm track range, azimuth accuracy, etc) in the presence of high power same-ship HF communication transmissions;
- Reduction of azimuth tracking errors caused by the complex topside scattering environment.

This paper describes HFSWR development progress to date: a performance analysis (Section 2); the system specification issued in the request for proposals (Section 3); a description of the system under development by Sanders (Section 4); and supporting measurements and analysis in the areas of transmitter-generated electric fields (Section 5) and shipboard HF noise (Section 6). We finish with a summary.

2. PERFORMANCE EXPECTATIONS

2.1 FIRM TRACK RANGE

This section derives the bounds on performance that can be expected for a shipboard HFSWR system. The radar range equation is given by

$$SNR = \frac{P_t G_t D_r T_i \lambda^2 L_{sys}}{(4\pi)^3 k_B T_o N_{ext} R^4 L_{sw}} \tag{1}$$

where SNR is the signal-to-noise ratio, P_t = transmitter average power, G_t = transmit antenna gain, D_r = receive antenna directivity, σ = target radar cross section (RCS), T_i = coherent integration time (CIT), λ = wavelength, L_{sys} = system losses (a number less than unity), k = Boltzmann's constant, T_0 = reference temperature, N_{ext} = external noise figure, R = target range, and L_{sw} = excess surface wave loss (a number greater than unity).

By using the receive antenna directivity (instead of gain) and the external noise level, we have implicitly assumed that the noise figure of the receiving system is dominated by the external noise level. This condition can be met by reasonably small shipboard receiving antennas (volume of about 2 m^3). Equation (1) also assumes that the installed gains of the antennas--i.e., the antenna gains as measured on the ship over the sea water conducting ground plane--are used. The quantities G_t, D_r, σ, N_{ext}, and L_{sw} are all a function of wavelength and hence influence the choice of frequency of operation. For an ASM target, a frequency of 18 MHz is near optimum, and we set λ = 16.7 m.

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[1] R. L. Powers, M. Lewandowski, and R. J. Dinger, "High Frequency Surface Wave Radar," *Sea Technology*, Vol 37, pp. 32-40, June 1997.

In designing the system, the radar engineer has control of the following parameters in equation (1): the peak transmitter power, the duty factor, the transmit antenna gain, the receive antenna directivity, the CIT, and system losses. It is convenient to combine these parameters as the *power-aperture-integration time product* $\rho = P_t G_t D_r T_i L_{sys}$. Hence,

$$SNR = \frac{\lambda^2 \sigma}{(4\pi)^3 k_B T_o N_{ext} R^4 L_{sw}} \rho \tag{2}$$

To examine the SNR as a function of range, with ρ as a parameter, we first need to arrive at values of σ and N_{ext}, and be able to calculate L_{sw}. The RCS for a generic ASM target modeled as a 30-cm-dia cylinder with 30-cm fins and a length of 4.5 m has been calculated using the Numerical Electromagnetics Code (NEC). The RCS for nose-on incidence is calculated to be σ = -23 dBsm at a frequency of 18 MHz.

The value of N_{ext} depends on season, geographical location, time of day, and the nature of nearby (on- and off-ship) man-made noise sources. Shipboard HF noise measurements were taken as part of the HFSWR ATD program and are described below in Section 6; based on those measurements, we set N_{ext} = 30 dB.

The calculation of L_{sw} was first developed by Berry and Chrisman[2] and improvements were made by Barrick[3]. We use Barrick's analysis for L_{sw} with a sea state of three in the following development.

We assume that SNR = 12 dB is required for target detection. This value is justified below (Section 4) in terms of the required false alarm rate and detection logic. In Figure 1 we use Equation (2) to plot the target detection range (the range at which SNR is 12 dB) as a function of ρ. The value of ρ varies between 61 dBJ (dBJ = dB relative to 1 joule) for detection at 15 nmi to 77 dBJ for detection at 25 nmi. In this interval each one-dB increase in ρ increases detection range by approximately 0.6 nmi.

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[2] L. A. Berry and M.E. Chrisman, "A FORTRAN Program for Calculation of Ground Wave Propagation Over Homogeneous Spherical Earth for Dipole Antennas," Report 9178, National Bureau of Standards, Boulder, CO, 1966.

[3] D. E. Barrick, "Theory of HF and VHF Propagation Across the Rough Sea, 1, Application to HF and VHF Propagation Above the Sea," *Radio Science*, Vol. 6, No. 5, pp 527-533, 1971.

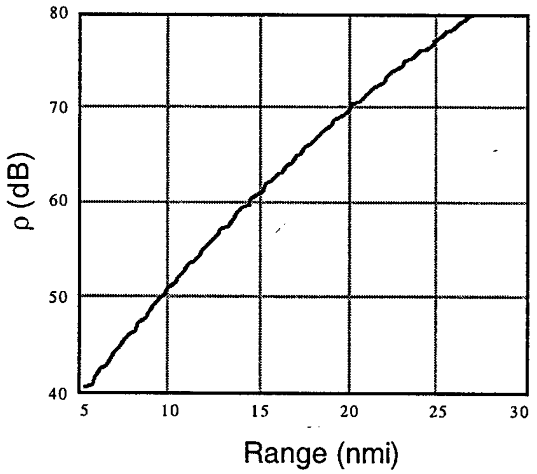

Figure 1. Target Detection Range Versus ρ.

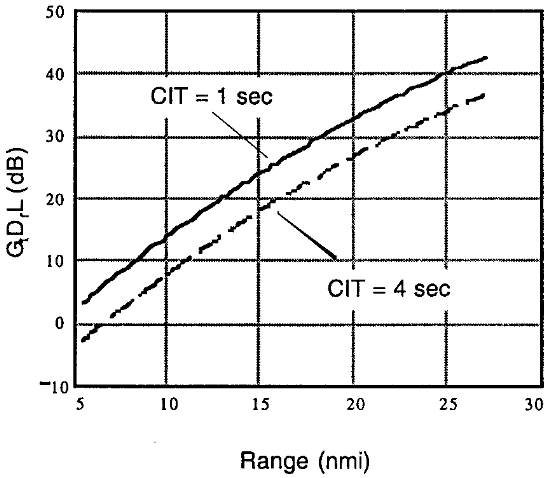

Figure 2. $G_tD_rL_{sys}$ Versus Range.

We now consider possible values for the five quantities whose product comprises ρ. The flexibility in choosing T_i and P_t is limited, and we consider them first. Most of the design flexibility is in the choice of G_t and D_r and in measures taken to keep L_{sys} as small as possible.

- *Coherent Integration Time* T_i. Based on considerations for a maneuvering target and ship's own motion, integration times between 1.0 and 4.0 s span the feasible limits.

- *Transmitter Power* P_t. The transmitter power limit is established by the permissible interference level that can be generated by the HFSWR transmitter in HF communication systems on the ship. For the HFSWR ATD system this limit has been set at 5 kW average and 10 kW peak, and is based on past shipboard experience. In fact, operation at lower power levels would be preferable. We set P_t = 5 kW (37 dBW) for the remainder of the analysis.

Figure 2 is a plot of the required $G_tD_rL_{sys}$ as a function of desired detection range. We now consider the feasible values for the three contributors to this product.

- *Transmit Antenna Gain* G_t. High antenna efficiency is important for the transmitting antenna, requiring physically large antennas. The difficulty of switching 5-kW power levels among multiple antennas precludes a multiple beam or scanning antenna on transmit. The only practical solution is a omni-directional transmit antenna. Measurements using 1/48th scale models (see Section 5) early in the HFSWR ATD program demonstrated that a gain of 10 to 12 dB could be achieved by a variety of transmit antenna designs. We take G_t as 10 dBi for this analysis; the actual system has achieved a peak of 14 dBi (based on scale model measurements), although the average over a double quadrant is closer to 10 dBi.

- *System Losses* L_{sys}. This term encompasses mostly processing losses such as windowing losses, beam scalloping losses, straddling losses, etc. We assume L_{sys} = 3 dB, although the Sanders design has achieved L_{sys} = 1.9 dB.

- *Receive Antenna Directivity D_r.* Most of the system design flexibility lies in the choice of the receiving element, their quantity, and their disposition around the ship. The receiving antenna can be much smaller than the transmit antenna since the efficiency can be much lower, as long as the system is externally-noise-limited. For a distributed array of receiving antennas installed along the deck of the ship, the topside superstructure will distort each element pattern, so that simple beamforming using standard amplitude and phase tapers with the assumption of an identical element pattern is not sufficient. Since the beamforming weights must be designed to compensate for the non-identical element patterns, the resulting gain and directivity will fall somewhat short of the values derived on the basis of ideal linear array theory. However, to a first approximation conventional linear array theory will give an adequate estimate of gain and directivity. For an array of N short vertically-oriented dipoles spaced by a distance d with an interelement phase shift α, the directivity is given by[4]

$$D_r = 4\left[\frac{2}{3N}+\frac{4}{N^2}\sum_{m=1}^{N-1}\left(\frac{N-m}{mkd}\right)\left(\frac{\sin mkd}{(mkd)^2}-\frac{\cos mkd}{mkd}\right)\cos m\alpha\right]^{-1} \qquad (3)$$

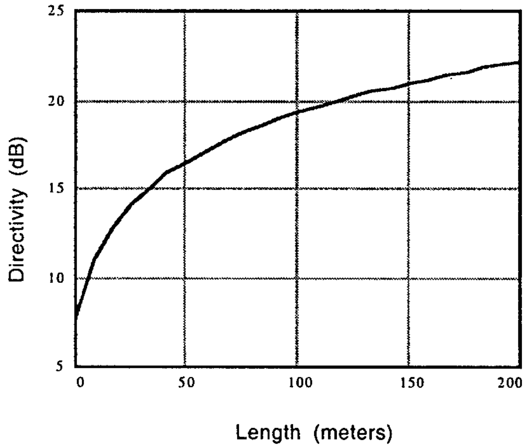

Figure 3. Array Directivity Versus Length.

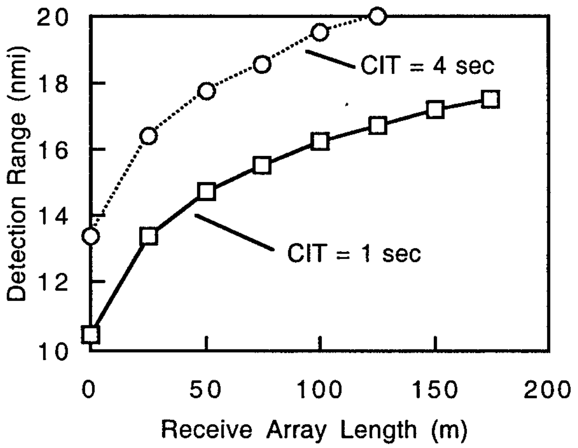

Figure 4. Detection Range Versus Array Length.

where $k = 2\pi/\lambda$. A factor of 4 is included to account for the presence of the conducting sea water. The beam scan angle θ_0, as measured from the array axis, is related to α by the equation $\alpha = -kd \cos \theta_0$. Figure 3 is a plot of D_r versus length for an element spacing of 0.5 λ for $f = 18$ MHz. The curve assumes an array scanned to broadside; for other scan angles, the directivity does not vary by more than a few dB. For the LSD-41 dimensions, D_r varies between 13 dB and 22 dB. In fact, these numbers are very close to the performance measured for the Sanders system (average of about 19 dB--see Section 4).

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[4] W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design*, John Wiley and Sons, New York, pp 144-145, 1981.

Finally, we can combine Equation (3) with Equation (2) to plot the detection range as a function of array length, with the other radar parameters as derived above (Figure 4). Detection ranges as large as 37 km (20 nmi) are possible.

2.2 BEARING ACCURACY

For a linear array of length L scanned to broadside, the rms uncertainty in target bearing (in radians) is given by

$$\theta_{rms} = \frac{0.56\lambda}{L\sqrt{2(SNR)}} \tag{4}$$

This equation is for an ideal array with identical antenna element patterns. Figure 5 is a plot of Equation (4). A bearing uncertainty of 1.0 deg rms requires an array length of at least 100 m, and uncertainties of over 10 deg result if very short arrays are used. For bow and stern coverage, a broadside-scanned array of 25-m aperture (the LSD-41 width) produces a bearing uncertainty of approximately 4 deg at low SNR. However, somewhat lower uncertainties could be expected if the endfire contributions from the entire length of the array could be exploited. A system on an LSD-41-size ship should be able to achieve bearing uncertainties of less than 1.0 deg.

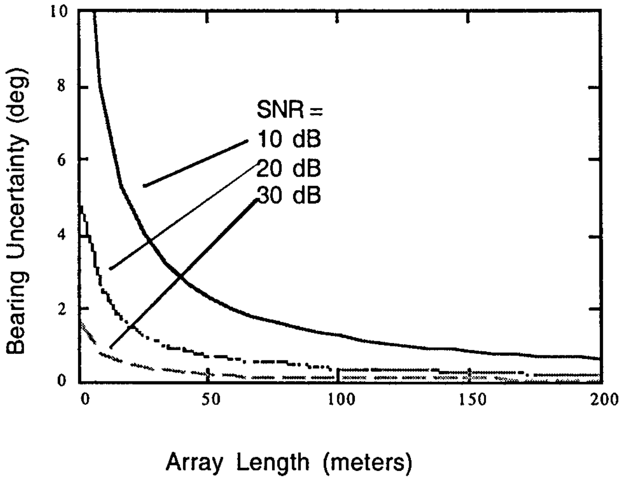

Figure 5. Azimuth Uncertainty vs Array Length

2.3 ALERTMENT TIME

It is of interest to compute the alertment time that the HFSWR system can provide. Assume an attacking ASM inbound at a velocity v_m and an engagement weapon system with an interceptor velocity of v_i and a desired engagement range of R_i. It is easy to show that

$$T_a = \frac{R_d - R_i\left(\frac{v_m}{v_i} + 1\right)}{v_m} \tag{5}$$

where T_a is the alertment time in advance of interceptor launch and R_d is the HFSWR detection range. For an interceptor with an average velocity of 550 m/sec and a desired intercept range of 5.5 km, Table 1 shows that a detection range of 35 km (19 nmi) permits a warning time of 88 sec and 35 sec, respectively, against a M0.9 and M2.2 ASM.

Table 1. Predicted ASM Alertment Time Provided by an HFSWR System. $v_i = 550$ m/sec; $R_i = 5.5$ km.

HFSWR detection range (km)	*Alertment Time (sec)*	
	$v_m = 300$ m/sec	$v_m = 750$ m/sec
25	55	16
30	72	23
35	88	29
40	105	36

3. THE SYSTEM SPECIFICATION

Based on the tradeoff study outlined in the previous section, a system specification was developed and an RFP issued. Table 2 summarizes the principal specifications contained in the RFP that was issued on 7 Dec 94. Quasi-Minimum Noise (QMN) is discussed in Section 6.

Table 2. Principal HFSWR System Specifications.

Subsystem	*Quantity*	*Value*
Transmitter	Peak power	40 dBW max
	Average power	37 dBW max
Receiver	Noise Figure	at least 10 dB less than QMN
	Assumed external noise	QMN+5 dBW/Hz
Waveform and Processing	Operational freq range	at least 1.0 MHz
	Instantaneous bandwidth	not to exceed 100 kHz
	First range ambiguity	greater than 200 km
Doppler	Resolution	better than 10 m/sec
	Unambiguous interval	greater than 850 m/sec
Detection	Firm track range	at least 37 km for ASM
	Range accuracy	400 m(at initial detection)
		200 m (at hand-over range)
	Range resolution	2000 m
	False Alarm Rate	less than one per 24 hrs
Angular performance	Azimuth uncertainty	<2.0 deg rms (initial detection)
		<1.0 deg rms (hand-over range)
	Coverage	-25 deg to +135 deg relative to bow

4. FEATURES OF THE SYSTEM UNDER DEVELOPMENT

This section summarizes the HFSWR system presently under development by Sanders (A Lockheed Martin Company), the prime contractor. Figure 6 summarizes the features of the system. The transmit and receive antennas are versions of a meanderline antenna (MLA) that is tuned by switched transmission line sections. The transmit antenna (Figure 7) is a two-element vertical MLA array, installed on the side of the LSD-41, with each MLA driven to produce a current maximum on the longest leg. The 24 receive MLA's (Figure 8) are electrically small antennas driven to produce a current maximum on the shortest legs, and have a vertical- monopole-like pattern. The antennas are positioned near the edge of the deck; each receive pattern is unique, as determined by interactions with the surrounding topside structure. The 24 elements provide the coverage over the 160-deg azimuth interval required for the ATD (an operational system would require 360-deg coverage). The transmit pattern measured on the scale model is reasonably broad (Figure 9), and the digitally formed receive beams (shown in Figure 10 as calculated using the receive antenna patterns measured on the scale model) have an approximate 6-deg beamwidth. The beamforming coefficients are determined by minimizing the error between a desired beam shape and the beamformer output. The average receive beam gain is 19 dB. A Watkins-Johnson Model 9119 receiver combined with a Hewlett-Packard E1430A A-to-D converter provides a spur-free dynamic range of at least 96 dB.

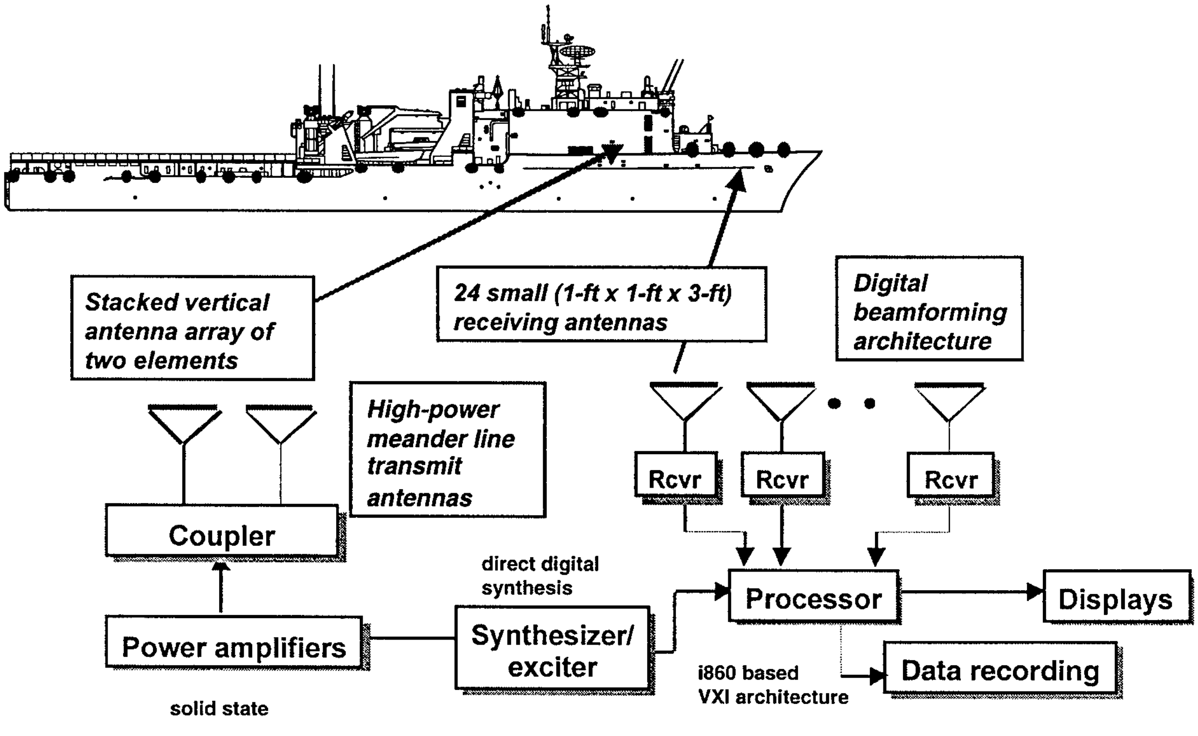

Figure 6. HFSWR System Features.

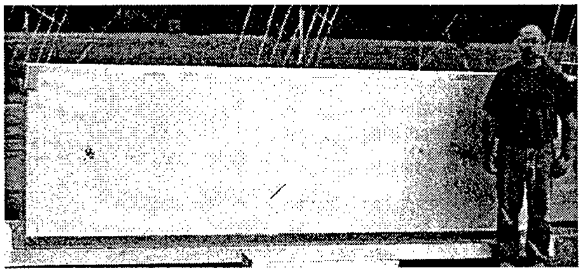

Figure 7. Transmit Antenna. Width = 12 ft and height = 4.0 ft.

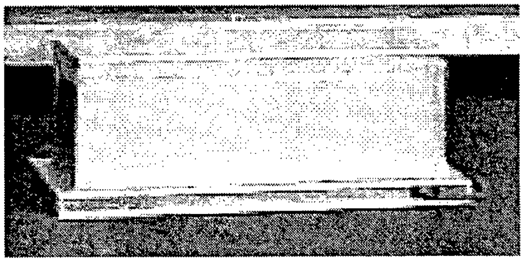

Figure 8. Receive Antenna. Width = 3.0 ft and height = 1.0 ft.

The primary ASM detection waveform is a 16-chip phase code with a 12.5-µs chip, 225-µs pulse width, 2 kHz prf, and 45 % duty cycle. The direct digital synthesizer exciter permits the generation of any arbitrary waveform, however, and a linear frequency modulation waveform is an alternate. The signal bandwidth is 80 kHz in the primary ASM detection mode. The center frequency can be positioned at any frequency within 15 to 25 MHz; the tuning time is less than 1.0 s within contiguous 3.0 MHz portions of this band, but requires manual switching (for the ATD system) for shifts greater than 3.0 MHz.

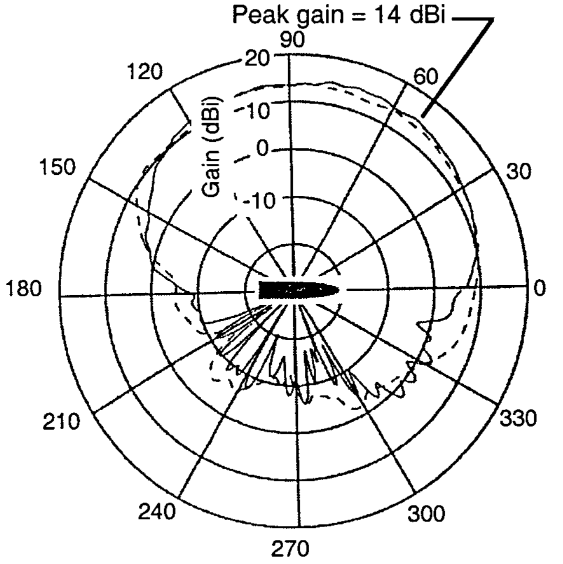

Figure 9. Transmit Antenna Patterns. Solid Line: 1/48-scale model measurements. Dashed line: NEC calculation.

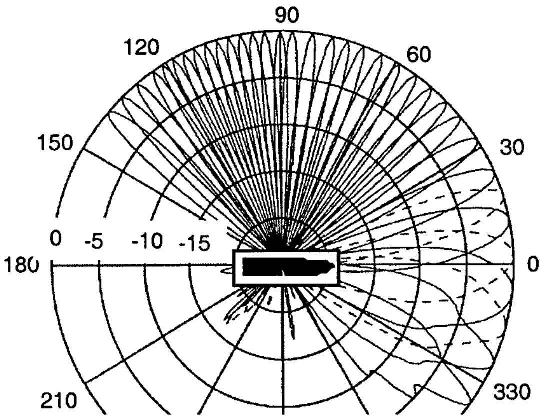

Figure 10. Digitally-Formed Receive Beams.

The signal processor uses 43 Mercury i860 DSP modules. The output of each receiver is range-compressed, Doppler-processed, and then combined with the other receiver outputs to form 48 simultaneous beams. Oversampling and overlapping in time (75 % overlap), range (50 % range cell overlap), Doppler (88 % dwell overlap), and azimuth (50 % beam overlap) achieve high detection sensitivity, resolution, and accuracy, and low latency. Beam interpolation determines the target azimuth to better than 0.5 deg at broadside and 2.0 deg in the bow quadrant.

A two-out-of-three CIT detection criteria and a one-per-24-hr false alarm rate result in an approximate SNR requirement of 12 dB for detection. Target tracking uses an alpha-beta tracker, designed under a sub-contract by Syracuse Research Corporation, with range-Doppler-angle association, nearest neighbor detection-track correlation, variable coefficient filtering, and maneuvering target handling.

The exciter, power amplifiers, receivers, processors, displays, and data recorders will be mounted, for the ATD, in a 20-ft ISO shelter. During testing the transmit and receive antennas will be cabled to the shelter by temporary cables lashed to the superstructure.

5. MEASUREMENTS OF ELECTRIC FIELDS GENERATED BY THE HFSWR TRANSMITTER

A critical issue for a shipboard HFSWR is the magnitude of the electric fields produced by the transmitter on the ship. The field levels must meet hazards of electromagnetic radiation to personnel (HERP) standards for Naval ships.

Measurements were made of the fields generated by the transmitting antenna on a 1/48th-scale brass scale model of the LSD-41 ship using a small electric field probe. Figure 11 is a plot of the measured electric field as a function of frequency for 9 locations of the probe on the ship model, as scaled in frequency and power level to the full-size ship . Also plotted is the HERP limit for long-term exposure. The measured electric field values are less than the HERP limit by at least 10 dB; the probe location of the highest field value is on the bridge immediately in front of the transmit antennas. We conclude that the transmit antenna design will meet Navy HERP limits.

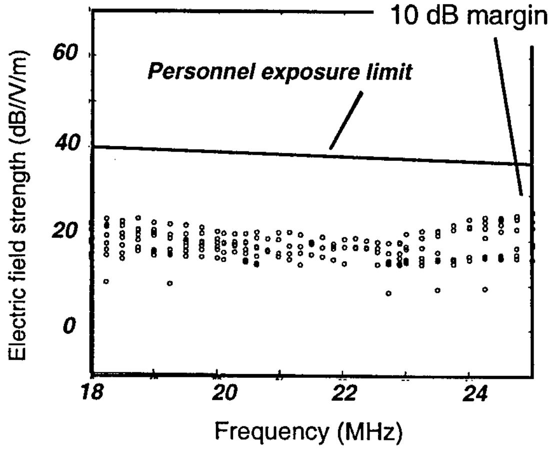

Figure 11. HERP Measurement Results. Electric field strengths measured at 9 points near the transmit antenna are shown.

6. MEASUREMENTS OF THE SHIPBOARD HF NOISE ENVIRONMENT

Because the HFSWR is an externally-noise-limited radar, a full knowledge of the shipboard HF noise environment is clearly important. Using a noise measurement system originally designed for the Navy's Relocatable Over-the-Horizon Radar (ROTHR), measurements of the HF noise aboard the *USS Ashland* (LSD-48) were made in April 1995 and aboard the Self-Defense Test Ship (SDTS) in August 1996. A complete description of the noise measurement system can be found in the literature;[5] the major components are a low-noise HF receiver, a computer-controlled local oscillator, a 16-bit digitizer, and a computer for control and data recording. On the LSD-48 the standard 17-ft dual whip antennas were used, and on the SDTS a 17-ft wire cage monopole was installed for the measurements. The system swept from 5 to 28 MHz, with a 3-kHz bandwidth resolution, every 22 seconds. Since the goal of the measurements is to characterize the ship's immediate HF noise environment, interference from other users of the HF band had to be identified and removed. Reference 5 describes the excision technique.

Figure 12 shows the average external noise levels measured aboard the SDTS. Three days of data have been averaged for this plot. The noise power level generally decreases with increasing frequency, and the variability throughout the day is less as the frequency increases. There appear to be two broadband noise sources near 22.5 and 25 MHz that are believed to be of shipboard origin. Also shown is the curve for QMN noise, which is an approximation to average shipboard HF noise measured in the 1970's that is the design standard for HF communication systems.[6] The HFSWR system noise specification (Table 2) is 5 dB above this level; the specification approximates very well the actual noise measurement of Figure 12 between 15 and 20 MHz. Noise measurements on the LSD-48 gave similar results. All shipboard noise measurements to date have validated QMN + 5 dB as a reasonable choice for system design. There are periods, however, when the external noise could be expected to exceed this value (for example, during periods of solar storms).

7. STATUS AND PLANS

The system described in Section 4 is currently nearing completion at Sanders' Nashua, NH facility. Table 3 is a schedule of the planned testing of the system.

Following factory acceptance testing, the HFSWR system will be installed on the SDTS at its Port Hueneme, California home port. In Figure 13 we show an artist's concept of the installation on the SDTS. The transmit antenna array will be amounted on the mast as shown, and the 24 receive elements will be mounted symmetrically around the ship to provide 360-deg receive beam coverage. The SDTS will be positioned on the Naval Air Warfare Center-Weapons Division's Pt. Mugu sea range, and a variety of targets flown to evaluate HFSWR performance. The primary target will be a BQM-74 drone, but detection and tracking of fighter aircraft and small surface targets will be also be evaluated.

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[5] S. A. Rodriguez, "High Frequency Noise and Spectrum Occupancy Measurements for Virginia and Texas," *Radio Science*, (in press).

[6] W. E. Gustafson and W. M. Chase, "Shipboard High Frequency Receiving Antenna System: Design Criteria," Technical Report 1712, Naval Electronics Laboratory Center, San Diego, CA (June 1970).

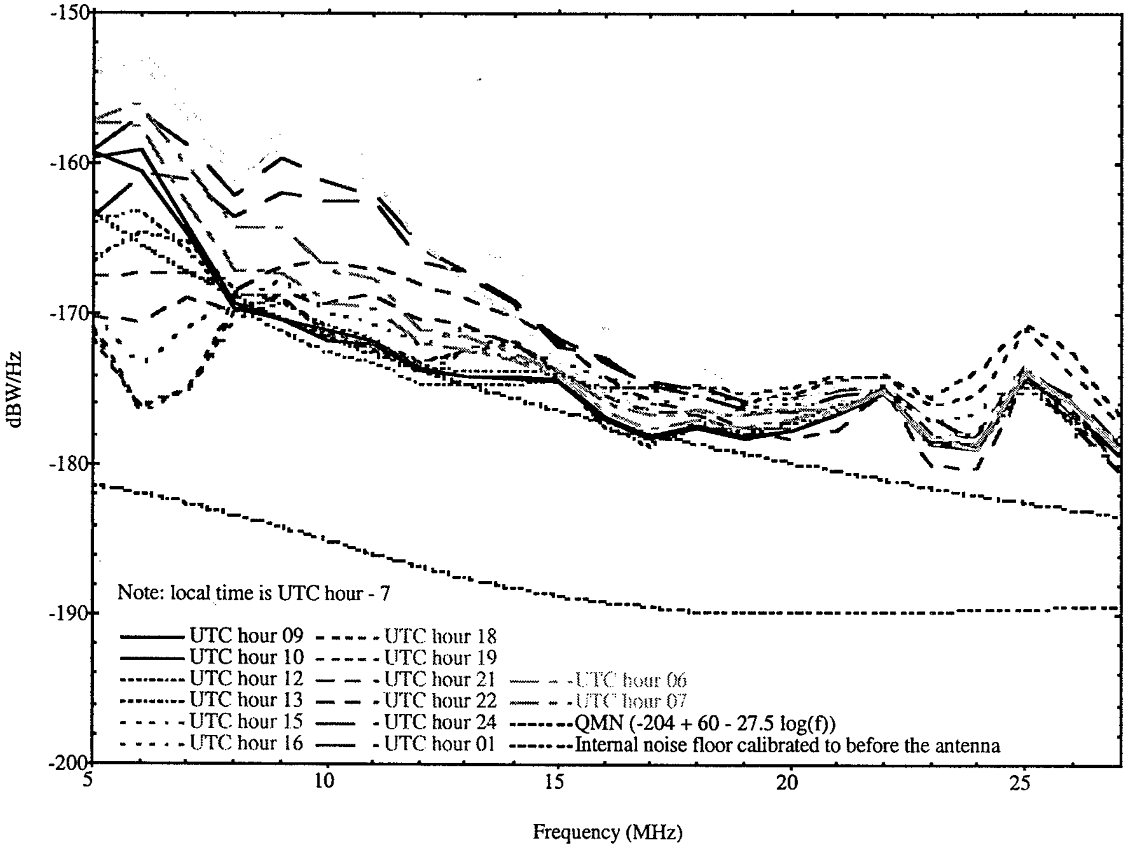

Figure 12. Noise Measurements Taken on the SDTS in August 1996.

Table 3. HFSWR Testing Schedule.

Event	*Planned Dates*
Factory Acceptance Testing	14 - 18 Dec 98
Installation on SDTS	11 - 22 Jan 99
Testing on SDTS	25 Jan – 12 Feb 99
Installation on LSD-52	1 – 5 Mar 99
Testing on LSD-52	8-12 Mar 99

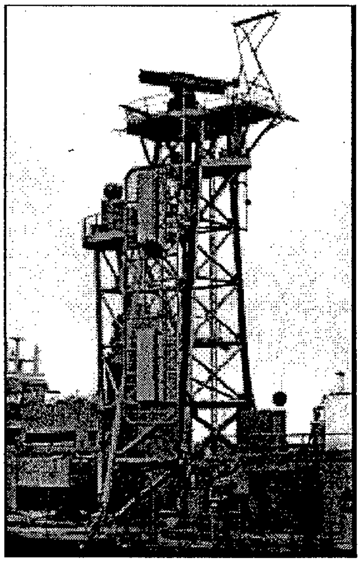

Figure 13. Artist's Concept of Transmit Antenna Array Mounting on SDTS Mast.

Determination of electromagnetic compatibility (EMC) with the existing HF communication system installed on fleet ships is a critical objective of the ATD. Since the SDTS is a retired fleet ship used for single-purpose testing, it does not carry the standard HF communication suite. Therefore, the HFSWR system will be installed on the LSD-52 (*Pearl Harbor*) to evaluate system EMC. This testing will be carried out near San Diego, California.

8. SUMMARY

The HFSWR ATD program has defined a feasible shipboard system for ASM detection and tracking. Funding uncertainties in FY97 delayed the program, but funding is currently on-track and the system is nearing completion. The radar design successfully minimizes the impact of the antennas and HF emissions on the other shipboard systems. System testing will be carried out in January to March 1999 on the NAWC/WD test range at Pt. Mugu, California and near San Diego, California.

9. ACKNOWLEDGEMENTS

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