Development of Over-the-Horizon Radar in the United States

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***Abstract*—This paper provides a chronology of the development of high-frequency, over-the-horizon radar in the United States.**

I. INTRODUCTION

Use of the High Frequency (HF) Band (3 to 30 MHz) permits extending radar ranges beyond the horizon, 500 - 2000 nmi using sky wave propagation where the ionosphere can be thought of as providing a virtual mirror. In addition, modest extensions of line-of-sight range can be obtained in this frequency band by using surface wave propagation over the sea. In the Naval Research Laboratory's (NRL) initial development program of HF over-the-horizon (OTH) radar, essentially all of the elemental feasibilities were discovered and demonstrated [1]. This work was followed by the United States fielding three production radars, designated AN/FPS-95, AN/FPS-118, and AN/TPS-71. The successful realization of HF OTH radar is one of the more significant radar developments since World War II. While use of the HF Band makes possible very long ranges and some other new radar capabilities, the wavelength dimensions (10 to 100 m), require very large antennas and provide relatively coarse spatial resolution of targets. Practical data on OTH radar design is given in the *Radar Handbook* [2]. Later, Headrick and Thomason writing in Radio Science in 1998 [3] provided an overview of the principles of operation and summary of later development work on OTHR.

II. MADRE

In 1956 the Naval Research Laboratory concluded a definitive set of experiments that showed that the ionosphere is generally sufficiently stable for a HF sky wave radar to succeed for over-the-horizon aircraft detection [4]. Matched Doppler filtering was the essential contribution to HF radar success and was central to NRL designs. In 1961 NRL began operation of their MADRE OTH radar at a field site on the Chesapeake Bay. In the fall of 1961 MADRE began tracking aircraft on the North Atlantic air traffic route and beyond the conventional radar horizon. MADRE was a single site OTH radar that used the same horizontally polarized antennas for both transmitting and receiving. There were two primary antennas. The higher gain antenna was a large fixed array, which was steered by changing the length of the feed lines, and the other primary antenna was steered by rotating it. In addition there were other antennas, which were used for short times for special tests. For example, there was a vertically polarized, folded triangular monopole with a back screen that was used for detecting and tracking a variety of targets via the surface attached wave also sometime called the ground wave. The large fixed array was first used to detect and track aircraft over-the-horizon and later was used to track surface vessels. The smaller rotary antenna was routinely used to monitor US ballistic missile launches. Figure 1 shows the MADRE site with the two primary antennas. Typically the MADRE used a 100 microsecond, simple pulse with 25 kW of average power. Reference [1] provides a more detailed description of MADRE.

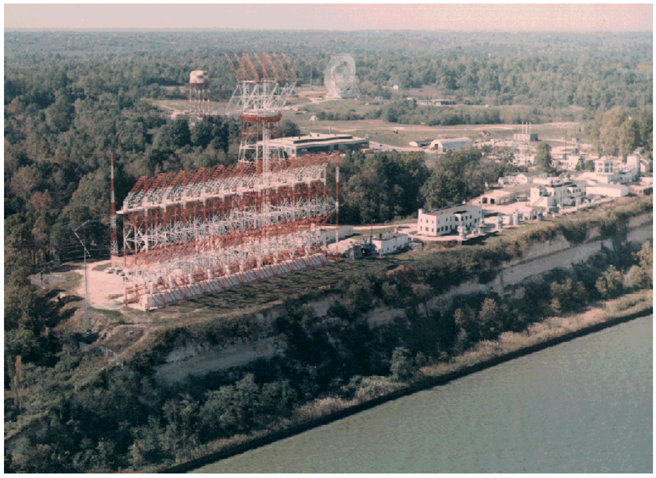

Fig 1. MADRE Over-the Horizon Radar

III. WARF

In the early 1960's Stanford University designed and built the Wide Aperture Research Facility (WARF) which was later operated by SRI International (then the Stanford Research Institute). The WARF is a high-resolution, two site OTH radar. The transmitter site is located near Lost Hills, California and the receiver site is near Los Banos, California. Separating the transmitter and receiver allowed use of a frequency modulated, nearly continuous waveform (FMCW). This waveform is more compatible with the other users of the high-frequency band than the pulse waveform used by MADRE. The operations center is co-located with the receiver. Later OTH radar designs separated the operations center from the receiver for logistical reasons. Both the transmit and receive antennas used by WARF were quite different from those used with the MADRE. Where

MADRE used horizontally polarized antenna arrays, the WARF uses vertically polarized array antennas. Where MADRE used antenna elements in front of a corner reflector for both transmit and receive, the WARF used two arrays of log-periodic arrays for transmit and an array of mono-pole pairs called TWERPs [5] for receive. From a performance viewpoint the most important difference between MADRE and WARF is the large receive aperture of WARF. This improvement in azimuthal resolution gave WARF much better performance against small, slow targets. Barnum provides a detailed description of the WARF in references [6 and 7].

IV. AN/FPS-95

The AN/FPS-95 also known as Cobra Mist was developed jointly by the US Air Force and the Royal Air Force. The radar was located at Orfordness in England and used a simple pulse waveform similar to that used by MADRE but with about 10 dB higher average power. The same antenna was used for transmit and receive. The Cobra Mist antenna consisted of 18 log-periodic arrays. Each log-periodic array was 2,200 ft in length and carried both horizontal and vertical radiating dipoles. To form a beam six adjacent log-periodic arrays were connected. However the Cobra Mist had poor resolution in range and azimuth and did not perform as well as expected. After about two years of testing, it was removed from service. Details of the radar and the subsequent testing are available on the web at http://users.ev1.net/~vmitchel/Orfordhis.htm. This web site provides a declassified report [8] by several engineers from MITRE, one of the groups who were called in to determine why the AN/FPS-95 did not meet expectations.

V. AN/FPS-112

The AN/FPS-112 was developed by the US Navy with the assistance of the ITT Electro-Physics Laboratory (EPL) and was installed in mid-1970s at a site near Williamsburg, Virginia. In this radar EPL used a phase-coded pulse waveform which provided good range resolution with a high duty factor and allowed the transmitter and receiver to be collocated. The AN/FPS-112 was also capable of frequency hopping between unoccupied channels. This frequency-hopping feature has advantages and has been adopted in later radars. The AN/FPS-112 was dismantled to make room for one of the AN/TPS-71 transmitter sites.

VI. AN/FPS-118

The US Air Force developed the AN/FPS-118 in the late 1970s with the assistance of General Electric. The first phase was a two site experimental radar located in Maine to demonstrate technical feasibility. In the second phase a separate operations center was added. Later another radar was added on the west coast. These radars used the FMCW waveform pioneered on the WARF by SRI International but with much higher power. In 1988 David Hughes [9] described a series of tests that verified the radar's ability to detect cruise missiles. In 1991 in response to a reduced perceived air threat the US Air Force put the system in warm storage.

VII. AN/TPS-71

The US Navy developed the AN/TPS-71 with the assistance of Raytheon. The AN/TPS-71 can provide surveillance over an area of more than a million square nautical miles at ranges that extend to 2000 nmi from the radar. The threat that drove the AN/TPS-71 design and procurement is that of long and medium range bombers and missile carriers to the Battle Group at sea. To counter this threat a surveillance system is required that can detect targets over the entire theater of operations, together with the means to give timely information to tactical response resources. To address the threat given, the U. S. Navy developed the relocatable OTH radar, also known as the ROTHR. The concept is that the radar would be packaged so that it could be air transported to a previously prepared site, assembled and put in operation rapidly. In April of 1984 the Space and Naval Warfare Command under the sponsorship of the Chief of Naval Operations awarded a contract to the Raytheon Corporation for the full scale, development phase for the AN/TPS-71. A prototype was constructed, installed in Virginia, tested, relocated to the Aleutians, and again tested and evaluated. The radar was found useful and three production units have been built. The first production unit is installed in Virginia, the second in Texas, and the third in Puerto Rico. These sites were chosen since the open ocean threat had diminished and drug traffic routes were of concern. In 1996 in the Naval Engineers Journal, Headrick and Thomason [10] provided a good description of the U. S. Navy's OTHR.

VIII. New Capabilities

In 1997 Papazoglou and Krolik [11] devised a technique for using matched field processing to measure the altitude of aircraft targets being tracked by an OTHR using a single coherent dwell of radar data. Later in 1999, Papazoglou and Krolik [12] extended the technique to allow using multiple short dwells of radar data and in 2002 Anderson et al [13] used a state-space fading model of the multipath propagation to make the target altitude estimate more robust to random changes in the ionosphere.

All operational HF sky wave radars designs rely heavily on 1970's thinking and technology. They scan serially in azimuth and range (frequency) to cover an area where scan rates are governed by coherent dwell and revisit requirements. This mode of operation means multitasking for different class targets must be serial. Although the radar may have a capability for aircraft, ships, missiles, and sea state, its use will generally restricted to only one type target at a time. Using currently available technology HF radars could be developed to employ a parallel target tasking philosophy, which would both increase performance capability against a particular target class, and enable multitasking.

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