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A Canadian Perspective on High-Frequency Over-the-Horizon Radar

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Defence R&D Canada – Ottawa
TECHNICAL MEMORANDUM
DRDC Ottawa TM 2006-285
December 2006

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Abstract

High-Frequency (HF) radar technology has been pursued by the Canadian Department of National Defence (DND) for military applications since 1984. Effort has been directed at developing High-Frequency Surface-Wave Radar (HFSWR) technology for ocean surveillance of ships and aircraft. However, the surface-wave technology cannot be readily applied to the problem of long-range surveillance of aircraft over land due to very high surface-wave attenuation over ground terrain. Thus, this memorandum briefly examines a related long-range HF radar technology referred to as HF sky-wave radar, or more commonly, Over-The-Horizon Radar (OTHR).

A basic description of OTHR technology and performance is provided, including coverage area and target localization capability. Mention is made of problems facing OTHR deployment in Canada, the most serious of which is spread-Doppler radar clutter caused by ionospheric irregularities undergoing convection in the earth's auroral zone. Previous OTHR efforts in other countries are examined, and are used to provide the basis for the way ahead in exploring OTHR applications in Canada.

Résumé

La technologie du radar haute fréquence (HF) pour des applications militaires est étudiée par le ministère de la Défense nationale (MDN) du Canada depuis 1984. Les efforts se sont concentrés sur le développement de la technologie du radar haute fréquence à onde de surface (HFSWR) pour la surveillance de navires et d'aéronefs au-dessus de l'océan. Cependant, la technologie de l'onde de surface ne peut être appliquée facilement au problème de la surveillance à grande distance d'aéronefs au-dessus du sol à cause de l'affaiblissement très prononcé de l'onde de surface passant par-dessus la terre ferme. Par conséquent, le présent mémoire examine brièvement une technologie de radar HF connexe appelée radar HF à onde ionosphérique ou, plus couramment, radar transhorizon (OTHR).

Une description de base de la technologie et des performances de l'OTHR est donnée, y compris la zone de couverture et la capacité de localisation des cibles. Sont mentionnés les problèmes auxquels se heurte le déploiement de l'OTHR au Canada et dont le plus grave est le clutter radar d'étalement Doppler causé par les irrégularités ionosphériques soumises à la convection dans la zone aurorale de la Terre. Des efforts antérieurs visant l'OTHR déployés par d'autres pays sont examinés et sont utilisés pour jeter la base pour les prochaines étapes de l'exploration des applications OTHR au Canada.

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Executive summary

A Canadian Perspective on High-Frequency Over-the-Horizon Radar

R. J. Riddolls; DRDC Ottawa TM 2006-285; Defence R&D Canada – Ottawa; December 2006.

High-Frequency (HF) radar technology has been pursued by the Canadian Department of National Defence (DND) for military applications since 1984. Effort has been directed at developing High-Frequency Surface-Wave Radar (HFSWR) technology for ocean surveillance of ships and aircraft. This effort has led to two operational HFSWR installations at Cape Race and Cape Bonavista, Newfoundland. However, the surface-wave technology cannot be readily applied to the problem of long-range surveillance of aircraft over land due to very high surface-wave attenuation over ground terrain. Thus, this memorandum briefly examines a related long-range HF radar technology referred to as HF sky-wave radar, or more commonly, Over-The-Horizon Radar (OTHR).

OTHR uses the earth's ionosphere to reflect radar signals and illuminate targets beyond the line-of-sight horizon. The density of plasma in the F region of the ionosphere (above 160 km in altitude) imposes limits on the frequency range that can be used by the radar, and the variation in the plasma density over time means that the radar must be capable of adapting its carrier frequency in real time. Radars can generally be designed to have sufficient flexibility to obtain coverage over a range of 500–2000 nautical miles (nmi) in good conditions, and 500–1200 nmi in conditions of strong low-lying plasma layers in the ionosphere E region (90–160 km). Large aircraft, such as commercial jets, can generally be observed 24 hours per day and located to within about 30 km of their actual position. Smaller airplanes and cruise missiles cannot be easily detected at night. In addition, the radar suffers vulnerability to outages due to disturbances in the ionosphere caused by adverse solar (or "space weather") events. Furthermore, in Canada, backscatter from fast-moving ionospheric irregularities in the region of auroral plasma convection can cause spread-Doppler clutter that can prevent target detection.

OTHR technology has been pursued by other countries for approximately 50 years with varying degrees of success. The successful approaches have generally involved a carefully staged succession of development. These experiences suggest a staged way ahead in Canada that considers one-way and two-way HF propagation experiments to quantify OTHR performance prior to proceeding with any radar acquisitions. Planning for acquisitions will also have to consider infrastructure requirements, including land preparation for the large antenna arrays, communications to support the co-ordination of separate transmit and receive sites, spectrum monitoring to determine

the background electromagnetic environment, and HF sounding to estimate the ionospheric propagation paths.

Sommaire

A Canadian Perspective on High-Frequency Over-the-Horizon Radar

R. J. Riddolls; DRDC Ottawa TM 2006-285; R & D pour la défense Canada – Ottawa; décembre 2006.

La technologie du radar haute fréquence (HF) pour des applications militaires est étudiée par le ministère de la Défense nationale (MDN) du Canada depuis 1984. Les efforts se sont concentrés sur le développement de la technologie du radar haute fréquence à onde de surface (HFSWR) pour la surveillance de navires et d'aéronefs au-dessus de l'océan. Ces efforts ont donné lieu à deux installations HFSWR opérationnelles au cap Race et au cap Cape Bonavista, à Terre-Neuve. Cependant, la technologie de l'onde de surface ne peut être appliquée facilement au problème de la surveillance à grande distance d'aéronefs au-dessus du sol à cause de l'affaiblissement très prononcé de l'onde de surface passant par-dessus la terre ferme. Par conséquent, le présent mémoire examine brièvement une technologie de radar HF connexe appelée radar HF à onde ionosphérique ou, plus couramment, radar transhorizon (OTHR).

L'OTHR fait appel à l'ionosphère de la Terre pour réfléchir les signaux radar et illuminer des cibles transhorizon. La densité du plasma dans la région F de l'ionosphère (altitude au-dessus de 160 km) impose des limites à la gamme de fréquences qui peut être utilisée par le radar, et la variation de la densité du plasma dans le temps veut dire que le radar doit être capable d'adapter sa fréquence porteuse en temps réel. Les radars peuvent généralement être conçus avec une souplesse suffisante pour assurer la couverture sur une portée de 500–2 000 milles marins (NM) en conditions favorables, et de 500–1 200 NM en conditions de couches de plasma de grande densité dans la partie inférieure de la région E (90–160 km) de l'ionosphère. Les gros aéronefs, tels que les avions à réaction commerciaux, peuvent généralement être observés 24 heures par jour et être localisés avec une précision d'environ 30 km. Les avions plus petits et les missiles de croisière ne sont pas faciles à détecter la nuit. De plus, le radar est sujet à des interruptions dues aux perturbations de l'ionosphère causées par des événements solaires défavorables. Au Canada, la réflexion troposphérique causée par des irrégularités ionosphériques rapides dans la région de la convection aurorale du plasma risque de causer du clutter d'étalement Doppler qui peut empêcher la détection des cibles.

Depuis environ 50 ans, d'autres pays étudient la technologie OTHR avec des degrés de succès variables. Les approches couronnées de succès se caractérisent généralement par un développement par étapes soigneusement planifiées. Ces expériences suggèrent que les recherches futures au Canada doivent se faire par étapes et envisager des

expériences de propagation HF unidirectionnelle et bidirectionnelle pour quantifier les performances de l'OTHR avant de procéder à toute acquisition de radars. La planification des acquisitions doit également tenir compte des exigences d'infrastructure, y compris la préparation du terrain pour de grands réseaux d'antennes, un réseau de communications pour appuyer la coordination de sites d'émission et de réception distincts, la surveillance du spectre pour déterminer l'environnement électromagnétique et des sondages HF pour estimer les trajets de propagation ionosphériques.

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Acknowledgements

The author would like to acknowledge the sources of several figures in this memorandum. Figure 1 is derived from an image provided by the US National Oceanic and Atmospheric Administration (NOAA). Figures 4 and 5 are derived from aerial photographs provided by the US Geological Survey (USGS). Figure 7 was provided by the Super Dual Auroral Radar Network (SuperDARN) program.

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1 Introduction

High-Frequency (HF) radar technology has been pursued by the Canadian Department of National Defence (DND) for military applications since 1984. Effort has been directed at developing High-Frequency Surface-Wave Radar (HFSWR) technology for ocean surveillance of ships and aircraft. The output of this effort has been the establishment of two operational HFSWR installations at Cape Race and Cape Bonavista, Newfoundland. However, the surface-wave technology cannot be readily applied to the problem of long-range surveillance of aircraft over land due to very high surface-wave attenuation over ground terrain. Thus, this memorandum briefly examines a related long-range HF radar technology referred to as HF sky-wave radar, or more commonly, Over-the-Horizon Radar (OTHR).

OTHR is an HF radar configuration that uses the electrically conducting bottom side of the earth's ionosphere to reflect HF radio waves and illuminate the earth's surface beyond the line-of-sight horizon [1, 2, 3, 4]. This configuration provides a high-altitude vantage point that permits radar surveillance to a range of approximately 2000 nautical miles (nmi). A conceptual view of an OTHR is shown in Figure 1. This figure shows an OTHR in Maine, United States, providing surveillance of the North Atlantic Ocean. The transmit antenna radiates a beam of HF radio waves toward the

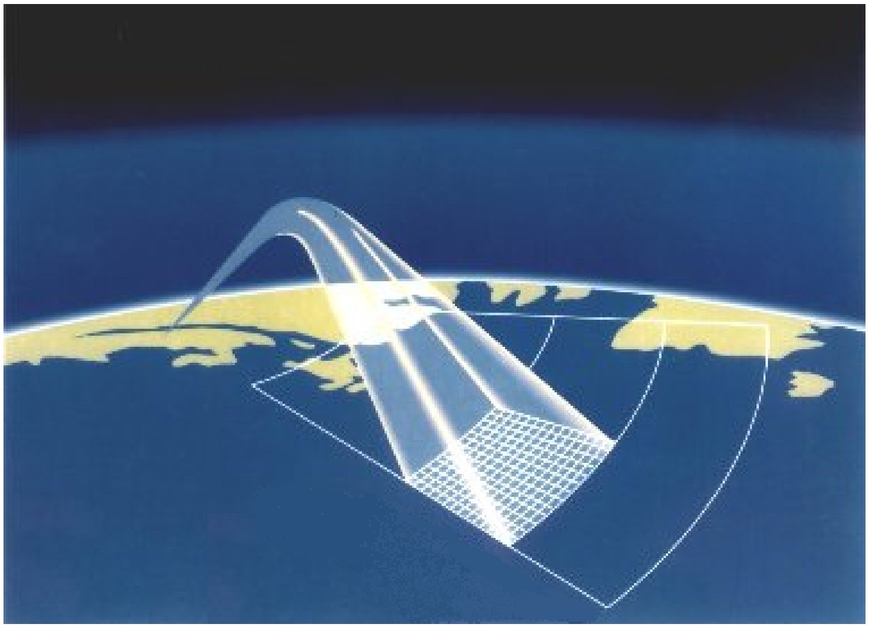

Figure 1: *Conceptual view of OTHR.*

ionosphere at a low elevation angle. The waves reflect and then illuminate a sector of the ocean. Illuminated targets in the transmit beam scatter the radio waves back to the radar via a similar propagation path, where they are detected by a receive antenna array. The receive array is of broad aperture, allowing the scattered signals to be resolved into fine azimuth cells. In addition, by timing the received signal, one can resolve the signal into range cells. The resulting range-azimuth resolution cell pattern is then treated as a search plane for targets, which would manifest themselves as local maxima of received signal power in a cell relative to the surrounding cells. The local maxima are declared as detections. Tracking the location of these detections over time provides target trajectories (or "tracks"), which can be correlated with other sources of information to confirm the identity of the tracked targets.

The remainder of this memorandum is organized as follows. Section 2 provides a general description of OTHR technology, including the physics underlying the use of the ionosphere as a reflecting layer, the hardware, and the signal processing. Section 3 discusses detection performance, such as coverage range, target localization capability, target size, persistence, and effects of terrain. Section 4 briefly looks at vulnerabilities of the radars, including effects of electromagnetic and solar wind interference. Section 5 outlines previous experience by other countries and uses this information to outline a proposed way ahead for development of the technology in Canada. Section 6 presents ancillary issues, such as the requirement to characterize the ionospheric environment, and co-ordinate operations with other HF users. A conclusion is made in Section 7.

2 General description

In this section, we describe OTHR in general terms. The first subsection outlines the physical principles used by OTHR. In the second subsection, we look at the hardware used by OTHR systems. Signal processing is reviewed in the third subsection.

2.1 Physics

In this subsection we briefly review the physics underlying OTHR operation. The properties of the ionosphere are briefly reviewed, and the influence of the ionosphere on transmitter frequency and power is described.

2.1.1 The ionosphere

The proper functioning of an OTHR depends on an appreciation of the basic properties of the earth's ionosphere. The ionosphere is a broad layer of ionized gas, called a plasma, located in the region at 50–1000 km in altitude above the earth's surface. The ionosphere is classified into several subregions, including the D region ($<$90 km), the E region (90–160 km), and the F region ($>$160 km). The F region is the broadest and most strongly ionized layer, and is the most relevant for the OTHR application. In this layer, the ionized species are predominantly atomic oxygen and electrons. The peak plasma density is located at approximately 250 km, although there is a diurnal variation of about ±50 km.

The steady-state profile of plasma density arises from competing physical processes. With increasing altitude, the intensity of ionizing UV radiation increases, while the density of neutral gas available for ionization decreases. Models of the physics yield the expected steady-state profile. The earliest and most fundamental model of the processes yields the Chapman profile [5] of plasma density, shown in Figure 2. A simple three-dimensional model of the ionosphere comprises a plasma density N that is uniform in the horizontal plane and varies with altitude according to the Chapman profile. The peak density N_{max} varies widely with time of day, season, and number of sunspots, and can be predicted to some degree by standard empirical ionosphere models [6].

2.1.2 Refractive properties of the ionosphere

In the simplest isotropic model [7], the ionosphere has an index of refraction n given by $n = (1 - 81N/f^2)^{1/2}$. Here, N is plasma density in free electrons per cubic metre, and f is the radio wave frequency in Hertz. At ground level, where N is zero, the refractive index is 1. The refractive index decreases with altitude until it is zero, at

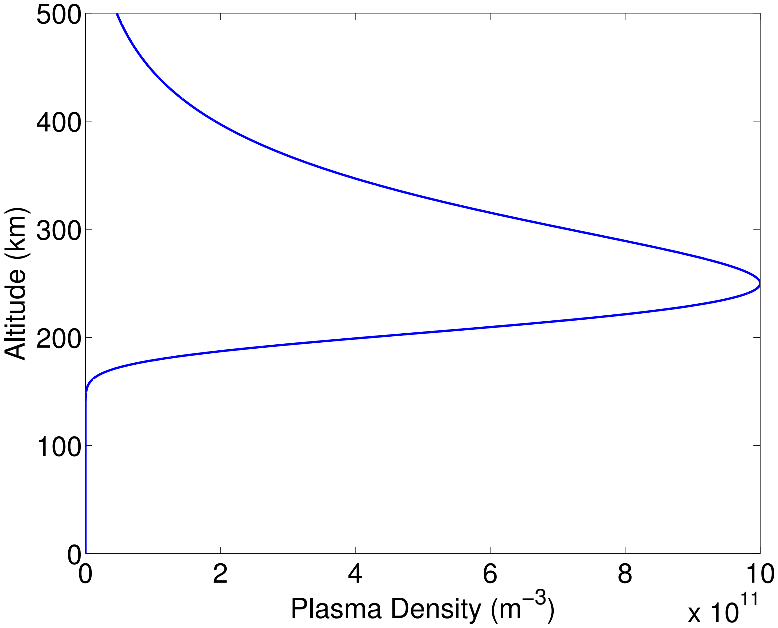

Figure 2: *Chapman profile of the ionosphere* ($N_{max} = 10^{12}\ m^{-3}$).

which point the local plasma density is $N = f^2/81$, and a vertically incident radio wave would undergo reflection. If the ionosphere is tenuous enough that the refractive index never reaches zero, then a vertically incident radio wave will escape into space. For example, if the peak plasma density in the ionosphere is $N_{max} = 10^{12}$ m^{-3}, then waves at frequencies above 9 MHz will escape at vertical incidence. In the case of an obliquely incident wave at an elevation angle θ with respect to the horizon, Snell's law predicts [5] that reflection will occur when the plasma density is $N = f^2 \sin^2\theta/81$. Since $\sin^2\theta < 1$ when $\theta < 90$ degrees, reflection at oblique incidence will occur at lower altitude than at vertical incidence. Similarly, for a given value of peak plasma density N_{max}, it is possible to reflect higher radio wave frequencies at oblique incidence than at vertical incidence. For example, if $\theta = 20$ degrees, and $N_{max} = 10^{12}$ m^{-3}, then reflection occurs for wave frequencies up to 26 MHz. Furthermore, for a given elevation angle in the range 20 to 90 degrees, reflection will occur for wave frequencies up to a corresponding value in the range 9 to 26 MHz.

2.1.3 Coverage range

The physical constraint on maximum coverage range is about 2000 nmi (3800 km) due to blockage by the curved surface of the Earth, as shown in Figure 3. The constraint on minimum range depends on the refractive properties described above.

Since a given frequency reflects only up to a maximum elevation angle, it follows that coverage starts at a certain minimum range, also shown in Figure 3. At higher elevation angles, the radar signals escape into space, and no target illumination is possible. The region of no target illumination between the radar and the minimum range is called the skip zone. Radar design considerations that impact the size of the skip zone are further discussed in Section 3.1.2, although we note here that current OTHR system designs generally have minimum ranges of about 500 nmi.

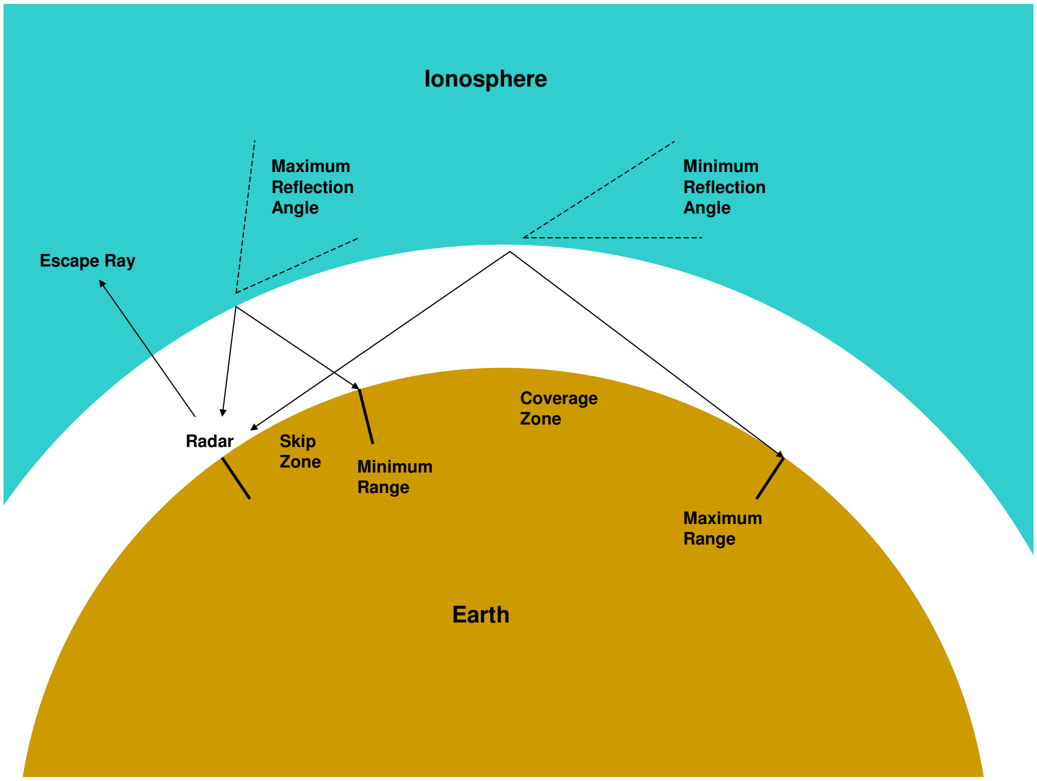

Figure 3: *The geometry of coverage and minimum/maximum wave elevation angles.*

In practice, one often finds that a single radar carrier frequency cannot effectively illuminate the entire coverage zone as shown in Figure 3. For example, if one picks a frequency low in the HF band to obtain a short minimum range, say 500 nmi, one will often find that this frequency propagates well in the vicinity of the minimum range, but suffers considerable attenuation at the further ranges (or equivalently, lower elevation angles). The bulk of the wave attenuation occurs in the ionospheric D region (50–90 km in altitude), where the attenuation rate varies with the inverse square of the radar frequency [3, 8]. Low elevation rays involve long transit paths through the D region and therefore suffer large attenuation. Thus, to get sufficient radar target illumination over the entire coverage zone shown in Figure 3 one often has to sequence the radar through two or three carrier frequencies.

2.1.4 Constraint on transmit power

Considerable Effective Radiated Power (ERP) is required to obtain adequate target illumination. Most OTHR systems run in the vicinity of 100 MW ERP. This ERP level is achieved using about 1 MW of transmitter power and about 20 dB of antenna gain. Even larger ERPs, on the order of 1 GW, have been obtained for the purpose of so-called HF ionospheric heating experiments [9], by increasing the transmit antenna gain to 30 dB. However, significant absorption of HF energy occurs in this case, as the higher power waves tend to excite a feedback loop in the ionospheric D region: higher wave power leads to plasma heating, which leads to increased wave attenuation, which leads to further heating, and so on. The consequence is that waves become absorbed as a result of their own action on the D-region plasma. Thus 100-MW ERP is a rough upper bound on transmitted power to avoid significant self-absorption through ionospheric modification.

2.2 Hardware

This section describes the hardware in typical OTHR systems. In the order of the signal propagation through a radar system, this hardware consists of transmitters, transmit antennas, receive antennas, and receivers.

2.2.1 Transmitters

To maximize average transmitted power, most current OTHR systems use a 100% duty cycle Frequency Modulated Continuous Wave (FMCW) waveform at a power between a few hundred kilowatts and a few megawatts. The RF amplifiers can comprise a significant cost of an OTHR facility. For example, a 1-MW frequency agile, 3–30 MHz CW solid-state amplifier system may cost a few tens of millions of dollars. The amplifiers themselves are generally class AB, with a power efficiency of around 50%. Given the low voltage tolerance of solid-state semiconductor devices, the amplifiers comprise the combined output of perhaps a few tens of thousands of individual transistors. Therefore, the degradation of performance with transistor failure is graceful rather than catastrophic. The amplifiers are usually broken into sets, each feeding a different transmit antenna, so that transmit array phasing can be accomplished by phasing the low-power inputs to the amplifiers. Harmonic filters can be used at the outputs of the transmitters to attenuate harmonics of the carrier frequency. If the amplifiers are to run over a large frequency range, then a bank of filters may be necessary.

2.2.2 Transmit antennas

The transmit antenna array is usually a conventional linear phased array of wideband elements such as canted dipoles or log-periodic antennas. The choice of vertical polarization over horizontal polarization allows the antennas to be smaller in the vertical extent, but in return requires the use of a ground screen. In particular, to realize adequate gain at low elevation angles, a fairly large ground screen, on the order of a few hundred metres in extent, is required in front of the transmit antenna.

The array is steered by phasing the elements, which produces a beam in a particular direction. During operation, the beam would be steered over the azimuthal range of coverage. However, since the azimuthal beamwidth is inversely proportional to the transmit antenna aperture, the maximum useful aperture (or minimum useful beamwidth) is set by the target dwell and revisit requirements. For example, if a dwell is 10 seconds, and the required target revisit time is 2 minutes, then the transmit array could operate with at most 12 azimuthal beams in scanning mode. However, if it is necessary to step through multiple carrier frequencies to illuminate the entire coverage range of the radar, as mentioned in Section 2.1.3, the revisit time would also be impacted.

The azimuthal extent of scanning for a linear array is typically limited to a sector of about 60 to 90 degrees. To achieve coverage over a larger azimuthal angle, say 180 degrees, one typically deploys multiple linear arrays. An example of such a deployment is shown in Figure 4. This picture shows a bird's eye view of the US

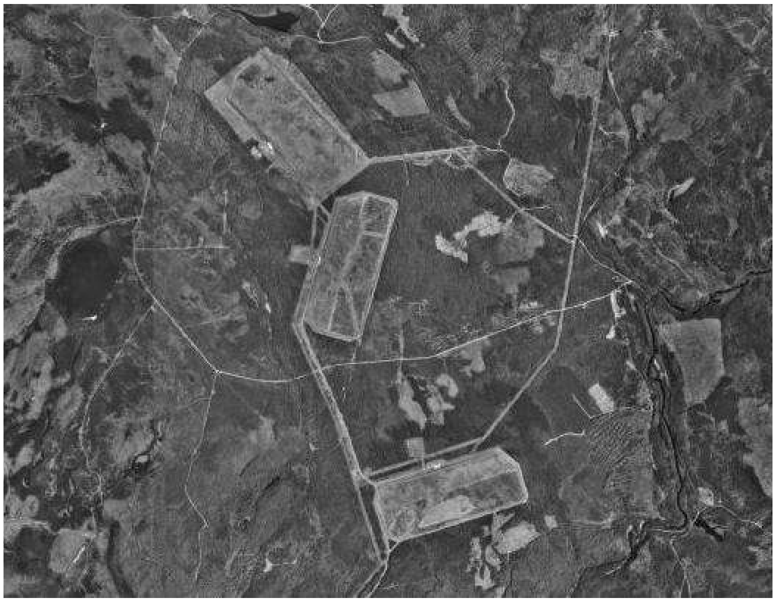

Figure 4: *OTH-B transmit arrays, 45°09' N 69°51' W.*

OTH-B East Coast transmit site in Maine. Here, three separate linear arrays, each 1 km in length, are combined to provide 180 degrees of coverage. In addition, since operation over the entire HF band cannot be efficiently achieved with a fixed set of element spacings, OTHR designs often use a variety of element spacing. In the arrays of Figure 4, each of the three linear arrays is composed of six subarrays. The subarrays consist of 12 canted dipoles in front of a vertical ground screen, each spaced between about 28 meters (for the lowest carrier frequencies) and about 5 meters (for the highest carrier frequencies). In the case of canted dipoles, the element lengths have to be scaled to be approximately the size of half a wavelength, and therefore the elements in the lower frequency subarrays are considerably larger than the elements in the higher frequency subarrays.

The use of a linear array does not allow for beam steering in the elevation direction. Therefore, the vertical extent of the transmit beam needs to be broad enough to provide target illumination at all possible elevation angles. This requirement demands rather non-directional transmit array elements such as canted dipoles or log-periodic antennas. Other types of arrays, such as planar, can provide elevation control, but at the expense of increased array complexity and cost.

2.2.3 Receive antennas

The receive array is usually a long linear array of monopoles, although planar arrays are sometimes used. The antenna elements can be individually sampled, or clustered into subarrays. Generally, a greater number of subarrays provides more degrees of freedom to adaptively null out interference from particular directions (see Section 4.2). In terms of physical antenna aperture, there is no inherent engineering limitation to the size so long as sufficient receive channels are available to form the required simultaneous beams. Some discussion is provided later in Section 3 to examine physical, rather than engineering, limitations on radar target-locating precision and thus limitations on useful antenna aperture. Existing radars exploit large apertures, typically a couple kilometres in length, consisting of hundreds of elements that are spaced one-half wavelength apart at the highest carrier frequency (a spacing of about 5 m).

The Signal-to-Noise Ratio (SNR) of signals received by the antennas is generally limited by external atmospheric noise, and therefore the antennas can be electrically short compared to a wavelength, and all the receiving elements can be the same size. If the elements are all set at the same distance apart, with a spacing suitable for operation at the highest carrier frequency, then sufficient spatial sampling of the apperture at lower carrier frequencies can be achieved by selecting every second element, or third element, and so on. As in the case of the transmit array, the linear receive array can generally be steered over an azimuthal sector of about 60 to 90 degrees in extent, depending on the details of the radar design (see Section

3.1.3). Larger azimuthal sectors can be covered using multiple arrays. An example of a three-array configuration is shown in Figure 5. Here, three 1.5-km linear arrays are combined to provide 180-degree coverage. Another popular configuration for 180-degree coverage uses two linear arrays arranged in an L-shaped configuration. Even larger azimuthal coverage, such as 360 degrees, can be achieved by rotationally symmetric O- or Y-shaped planar arrays.

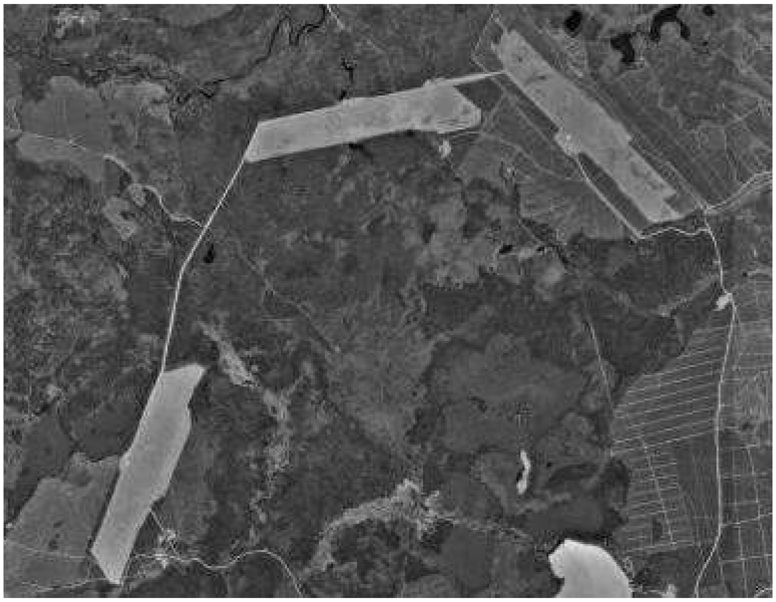

Figure 5: *OTH-B receive arrays, 44°47' N 67°48' W.*

As with the transmit arrays, linear arrays do not provide control over the elevation of the receive beams. Thus array elements must have broad elevation responses in the forward direction. The choice of monopoles provides such a broad pattern. However, it is usually necessary to be able to distinguish signals arriving at the front of the array versus signals arriving from the rear. This can be done either by erecting a vertical ground screen behind the receive array, or deploying two lines of monopoles and combining the front and rear monopole signals in such a manner that signals from behind the array can be identified and/or cancelled. Alternatively, as in the transmit array case, the receive arrays can designed as a planar array, which would provide complete control over the elevation and azimuth direction of the receive beams.

The use of an FMCW waveform implies the need for separate transmit and receive sites, so that the direct-path signal from the transmitter does not overwhelm the receivers. This requirement means that the OTHR receive site is typically a minimum of 100 to 200 km away from the transmit site. It is therefore generally impossible to find a contiguous tract of land on which to place the complete OTH radar.

2.2.4 Receivers

Since the external atmospheric noise, rather than internal device noise, tends to limit the detection of targets by OTHR, the radar receivers do not need to be particularly sensitive. However, good amplifier linearity is required to permit subclutter visibility of aircraft targets through Doppler processing, to be discussed in the next subsection. Specifically, the amplifiers need two-tone linearity sufficient to ensure that strong low-Doppler ground and sea clutter does not interact with high-Doppler aircraft target signals, which can be up to 80 dB weaker. Channel bandwidths are typically 10 kHz, which requires only modest digital sampling rates. However, the large number of receive array elements means that individually sampling each antenna can become quite expensive. Therefore, a subarray scheme is sometimes invoked to keep the system cost under control. Following signal sampling, the functions of pulse compression and beamforming are carried out by digital signal processing techniques. To control data size, only receive beams lying within the azimuthal extent of the transmit beam need be maintained. The retained beams are then forwarded to a computer for Doppler processing, detection, and tracking.

2.3 Signal processing

This subsection provides an overview of the signal processing particular to OTHR. Two OTHR problems, co-ordinate registration and transmit beam scheduling, are also outlined.

2.3.1 Waveforms

Most modern OTH radars use a 100% duty cycle FMCW-type waveform. Various economic arguments exist for how to achieve the most average transmitted power for a given cost. For example, one may argue that a 100% duty cycle 1-MW waveform is cheaper to produce than a 10% duty cycle 10-MW waveform, as the latter imposes peak voltage (arcing) issues even though it has the same average power level. However, there are other reasons to prefer CW-type waveforms. One is the problem of ionospheric modification in the D region, mentioned earlier, where it is advantageous to keep transmitted ERP well below 1 GW. Another is the problem of spectrum management; it is widely recognized that spectral leakage into adjacent frequency channels often occurs during the turn-on/off transients in pulsed waveforms.

Choice of parameters for the FMCW waveform should be made to avoid ambiguities in range and Doppler processing. To provide unambiguous range information over the interval of 500 to 2000 nmi, the waveform repetition rate cannot exceed about 50 Hz. This repetition rate is sufficient to resolve Doppler frequencies between -25 and +25 Hz, which corresponds to maximum line-of-sight aircraft speeds of 2400 kt at 3 MHz, but only 240 kt at 30 MHz. Thus, it is expected that high velocity air targets may alias in Doppler in the high part of the HF band. The solution is to observe the progress of targets across range cells to resolve possible Doppler ambiguities. However, as discussed in Section 2.1.3, it is often not possible to achieve coverage over the entire 500–2000 nmi range at a single carrier frequency, and so the transmitter will need to be stepped in carrier frequency. In these cases, the unambiguous range can be shortened, allowing higher waveform repetition rates.

2.3.2 Matched filtering

Following signal reception, matched-filter processing is performed on the recorded data to extract target content as a function of range. In formal terms, this filtering involves computing the temporal cross correlation of the transmitted radar waveform and the received radar echo. The output of the cross correlation is a signal whose amplitude as a function of correlator lag is proportional to radar target echo amplitude as a function of range. In practice, if the waveform is a linear FM sweep, the correlator is implemented by multiplying the received data by an FM sweep signal, and then performing a Fourier transform. A tapering function is usually applied to the data prior to Fourier transforming to control range sidelobes. The operation is then executed for all radar beams to produce a range-azimuth matrix of data.

The FM waveform is repeated a few hundred times, and a similar number of range-azimuth matrices are generated over a dwell period of, say, 10 seconds. Over this period of time, the signal echoes will be coherent, such that high-speed aircraft targets will exhibit a non-zero Doppler frequency, which can be used to separate them from near zero-Doppler ground clutter. This separation of signals in Doppler is important for the successful operation of OTHR, since the ground clutter signal can be as much as 80 dB stronger than the target signal. However, very long periods of coherent integration (say, minutes) tend to result in the ionospheric channel decorrelating, which will spread the low-Doppler clutter to higher Doppler cells. Once the dwell is completed and recorded, a Fourier transform is applied across sweep repeats to extract the Doppler content of the signals. This results in a three-dimensional data cube that may have a couple hundred points in range, a few tens of points of azimuth (spanning the transmit beam), and a few hundred points in Doppler. The transmit beam is then moved to the next azimuth, and a new data cube is generated for the new transmit beam location. On the order of 10 data cubes may be generated during the transmit azimuth scan. The cubes are searched for isolated local maxima that may correspond to targets and a list of all of the detected peaks is put into a detection file. The detection file is read by a multitarget tracker, which deduces target trajectories by a recursive nearest-neighbour association between the measured detection events and the target trajectories from the previous coherent integration dwell.

2.3.3 The problem of co-ordinate registration

One processing problem specific to OTHR concerns the conversion of signal group delays (or slant ranges) observed by the radar into physical ground ranges. The difficulty lies in the fact that the typical linear receive arrays cannot easily resolve the elevation angle of the rays comprising the target echoes. The solution to this problem is to either install a two-dimensional antenna array that can resolve elevation angle, or to deploy ionospheric sounding downrange of the radar to estimate the height at which the reflections are occurring. The latter ionospheric sounding (or "ionosonde") approach is used to various degrees in most OTHR systems, where in the most extreme cases there can be 10 or more ionosondes positioned downrange from the radar to determine the ionosphere profile at the reflection point. In the case where an OTHR looks over an ocean, sounding is not possible at the reflection point, thus sounding at the radar site is used as a proxy. A significant assumption is made that the ionosphere profiles do not change over a distance of up to 2000 km in the horizontal direction. Recent research has aimed at an iterative approach, where vertical-incidence ionosonde profiles at the radar sites are progressively refined to match the properties of ground clutter observed downrange by the OTHR [10].

2.3.4 The problem of transmit beam scheduling

An operational problem encountered in OTHR is the need for continuous coverage of a large azimuthal fan by a rather narrow transmit beam. Two solutions have been considered. The first is to do away with the transmit beam gain, and install a "floodlight" transmitter that radiates over a large azimuthal sector. All regions are illuminated simultaneously, albeit with reduced transmit gain. An alternative method that maintains transmit gain is to transmit orthogonal waveforms from each of, say, M transmit array elements and extract the signal from each transmit antenna on the receive side by using M different orthogonal matched filters on each receive channel. This is referred to as a Multiple-Input, Multiple-Output (MIMO) scheme. One can effectively perform transmit beamforming by taking linear combinations of the data from various receive-channel and matched-filter combinations. While this method allows simultaneous transmit beams, it does impose increased demands on the information capacity of the frequency channel. For example, if one forms orthogonal channels from disjoint frequency channels, the radar will require M times the bandwidth to operate with the same level of range resolution. Alternatively, if one forms orthogonal channels from disjoint Doppler channels, the radars will require M times the waveform repetition frequency, which would cause targets to become aliased in range. Thus, when the range-Doppler plane is fully occupied by targets and the frequency channel is constrained, it can be difficult to find the necessary degrees of freedom to implement an OTHR MIMO scheme.

3 Detection performance

In this section we review the typical performance characteristics of an OTHR, including extent of coverage, target-locating ability, observable target sizes, coverage persistence, and influence of terrain.

3.1 Coverage

This subsection examines the basic OTHR performance characteristics. The extent of coverage range and azimuth is described, and the resolution, accuracy, and precision of target detections is discussed.

3.1.1 Maximum range

In the previous section, the physical basis of the maximum and minimum ranges for an OTHR were discussed. The maximum range is constrained by the curvature of the earth, as shown in Figure 3. The exact range will depend on the height of the reflecting F-region plasma and details of the ray trajectory near the reflection point. For simplicity, these rays have been shown as making a sharp-angle turn at the reflection point. However, a more detailed analysis will show that the ray will make a gradual turn within the plasma. In practice, the maximum ranges achievable are on the order of about 2000 nmi. Occasionally the ionosphere experiences conditions with strong E-region plasma density, which is centered in the region near 100–110 km in altitude. If the E-region plasma density becomes stronger than the F-region density, then the OTHR can no longer access the F-region plasma as a reflecting layer, and the E-region plasma becomes the only reflecting layer usable by the OTHR. In this case, the 100-km altitude of the reflecting layer constrains the maximum range of the OTHR to approximately 1200 nmi. Occurrence patterns of E-region plasma layers will be discussed in Section 3.3.1.

3.1.2 Minimum range

The minimum range of the OTHR is determined by the choice of carrier frequency. As we saw in Figure 3, choosing a carrier frequency fixes the maximum elevation angle for which rays will reflect from a given ionosphere profile. Rays at higher elevation angles will go through the ionospheric plasma and into space. It is desirable for the maximum elevation angle to be less than 90 degrees, otherwise zenith rays reflect from directly over the OTHR, and cause clutter. Since both the ground and the ionosphere are reflective, often the zenith rays bounce several times, which leads to clutter that spreads over all radar range bins and interferes with the detection of downrange targets. The obvious question is what should be the maximum elevation angle. Practical limits are established by a number of factors. First, higher elevation angles require lower carrier frequencies, which are more easily absorbed in the D-region plasma since the D-region attenuation rate varies with the inverse square of frequency. Second, the gains of the antenna arrays degrade at lower frequencies due to reduced physical aperture relative to a wavelength. Third, target radar cross section tends to reduce rapidly when the radar wavelength becomes large compared to the target. Fourth, atmospheric radio noise levels are higher in the lower frequency range. In short, there are a number of factors which incur large performance penalties at the lower end of the HF band, and after some point it becomes uneconomical to compensate for the penalties through scaling the radar design. Most existing OTHR systems have minimum ranges of about 500 nmi, which corresponds to a maximum elevation angle of about 30 degrees. However, there appears to be no good physical (as opposed to economical) reason why OTHR could not be designed to work at somewhat higher elevation angles, such as 60 degrees. Of course, at very high elevation angles, like 85 degrees, the component of an air target's velocity along the radar beam becomes comparable to that of low-velocity ground and sea clutter, and the target would become buried in the clutter. Furthermore, errors in estimating the maximum plasma density in the overhead ionosphere could lead to unanticipated direct reflections from zenith.

3.1.3 Azimuth coverage

With regards to azimuthal coverage, the constraint is provided by the design of the antenna array. The central consideration is the size of the antenna aperture from each look direction. Long apertures permit performance to be maintained over larger steering angles. For example, a 3-km linear array has a 3-km aperture at boresight, but only a 2-km aperture when viewed from a 45-degree steered angle. Steered to an angle of 90 degrees, the aperture is zero. Thus linear arrays cover a finite azimuthal sector, typically 60 to 90 degrees in extent in most radar designs. Broader azimuth coverage can be obtained by using multiple linear arrays, or by implementing L-, Y-, or O-shaped receive arrays, with correspondingly greater complexity and cost, as noted previously.

3.1.4 Target resolution

The range resolution is determined by the bandwidth of the radar transmission. This choice of bandwidth is in turn determined by the bandwidth of available HF channels. Most operational systems use bandwidths of at most 10 kHz, which imposes a range resolution of about 15 km. However, converting echoes of an FMCW waveform into range information requires a Fourier transform across the range extent. To reduce range sidelobes, a windowing function, such as a raised cosine, is applied to the data. This window has the side effect of degrading the range resolution in the transformed data by a factor of two. Thus a range resolution of 30 km may be the best achievable in practice.

The azimuthal resolution is determined by the aperture of the radar. A weighting function, such as a raised cosine, is usually applied to the receive channels to reduce azimuthal sidelobes, at the expense of doubling the size of beam. A tapered aperture of 3 km would lead to a beamwidth of 4 degrees at 3 MHz, and 0.4 degrees at 30 MHz, which corresponds to linear ground resolutions of 200 km and 20 km, respectively, at 3000-km range. Thus, in the higher part of the HF band, the azimuthal ground resolution can be made comparable to the range resolution with realistic apertures of a few kilometers. Larger apertures (a few tens of km) are unrealistic due to the difficulty in finding sufficient land.

The Doppler resolution of the radar is related directly to the coherent integration time of the radar. Typically the ionosphere is stable enough for coherent integrations lasting perhaps 30 seconds. This provides a basic Doppler resolution of 0.03 Hz. Again, a windowing function is applied to reduce Doppler sidelobes. Since the clutter signal can be as much as 80 dB larger than the target signal in Doppler, a low-sidelobe (say, Blackman) window should be used. This has the side effect of degrading Doppler resolution by a factor of three, which results in a resolution of 0.1 Hz. This figure corresponds to a velocity resolution of 10 kt at 3 MHz, and 1 kt at 30 MHz. This is ample resolution for air targets, and so dwell times are often shortened to allow for improvement in scan rate, and thus track update time. Usually dwells on the order of 10 seconds are used, which corresponds to a velocity resolution of 30 kt at 3 MHz, and 3 kt at 30 MHz.

3.1.5 Positional accuracy

Range accuracy (absolute positional accuracy) is limited by the quality of the co-ordinate registration process. Even with good ionospheric characterization, the accuracies are generally no better than the resolution capability of the radar (around 30 km) and thus co-ordinate registration continues to be an active area of research. One recent research result [11] has been to use identifiable ground terrain features as reference points, which can provide up to a factor of 5 improvement in absolute positional accuracy, reducing errors to about 6 km. If the land under surveillance is in friendly territory, then ground-based transponders can be used to provide a similar sort of range calibration.

Azimuthal accuracy is constrained by bearing errors introduced by the ionospheric plasma. Lateral deviation of a ray path can be predicted by accounting for anisotropic plasma effects in the calculation of the ray path, but there will always be variations due to unknown ionospheric plasma structure in the horizontal dimension. Again, terrain-based features and/or transponders can be used to provide a calibration to within a fraction of a degree, allowing for linear azimuthal ground accuracies similar to the range accuracies.

Doppler accuracy can be affected by plasma drifts at the location of the ionospheric reflection point. Horizontal drifts tend not to impose Doppler shifts on the OTHR signals because the rays traverse the medium twice in the OTHR configuration, and Doppler shifts incurred during the first transit are cancelled by those incurred during the second transit. Vertical drifts, however, can impart Doppler errors of a few tens of knots. These offset errors can generally be calibrated out by using Doppler information acquired during ionospheric sounding of the reflection point plasma.

3.1.6 Positional precision

Precision errors relate to the spreading of signals in the range, azimuth, and Doppler extents. These spreadings have two sources. The first is the inherent signal spread due to the resolving capability of the radar. The precision in this case is a fairly basic radar result—it is roughly equal to the radar resolution divided by the squareroot of the signal to noise ratio. Assuming a 10-dB SNR is required for signal detection, then the precision in range, azimuth, and Doppler should be better than the resolution figures by at least a factor of 3, and by larger amounts at higher SNRs.

The second source of spreading is due to irregularities in the ionospheric plasma [12]. At least two mechanisms can be identified. The first mechanism is that the irregularities tend to randomize the ray path of the radar signal during the ionospheric reflection, resulting in a random component in the signal ground range, group delay (slant range), Direction-Of-Arrival (DOA), and Doppler. Thus, say, in the case of DOA spread, the signal incident on the target actually originates from a broad region in the ionosphere due to a randomization of the signal propagation path. The second mechanism is that irregularities impose spatially or temporally inhomogeneous phase delays (scintillations) on the propagating radar signal. Therefore, any antenna configuration that estimates DOA by coherent phase from one antenna channel to the next, and Doppler by coherent phase from one waveform repetition to the next, will interpret phase scintillations as actual DOA or Doppler randomization. If this randomization exceeds the resolution of the radar, then the SNR advantages of a large receive aperture, or a long coherent dwell, cannot be realized. As a consequence, it is important to perform one-way propagation measurements at the intended radar location in realistic conditions prior to designing the OTHR system to put practical upper bounds on the receive array size and coherent integration dwell time.

The mechanisms of radar signal randomization have been the subject of recent research study [13], particularly with regard to Doppler spreading, as this represents the biggest threat against successful detection of aircraft in the presence of intense ground clutter. Recent results [14] have extended the technique to account for spreading of radar signals in ground range, group delay, DOA, and Doppler, including anisotropic plasma effects. The results of this work need to be verified by experiment, particularly for the case of auroral ionosphere propagation, where irregularities comprising structured ionization due to the precipitation of energetic particles tend to impose significant spreading of the aforementioned radar signal properties.

3.2 Target size

Target sizes for radar are measured in terms of a Radar Cross Section (RCS) in decibels relative to one square metre (dBsm). A perfectly conducting sphere of radius R has a radar cross section of πR^2. More complicated objects are assigned angle-dependent RCS values that correspond to the appropriate size of the sphere that would produce the observed scatter in a particular direction.

The dominant influence on target cross section is the size of the object relative to a wavelength. Targets that are larger than a wavelength tend to have RCS values that are similar to their physical size. Objects that are smaller than a wavelength have RCS values that vary with the fourth power of the radar frequency (the Rayleigh scattering limit). Thus, the major issue with target RCS is that small targets become invisible at the lower end of the HF band [15]. For example, a cruise missile is comparable to a wavelength at 30 MHz, and may have an RCS of 10 dBsm. However, at 3 MHz, the RCS may drop to about -30 dBsm. In comparison, a large aircraft with an RCS of 30 dBsm, such as a passenger airliner or a long-range bomber, is about ten times the linear size of a cruise missile, and remains greater than, or equal in size to, a wavelength throughout the HF band, and thus maintains fairly consistent RCS with frequency.

Most current OTHR designs are scaled to permit routine (>10 dB SNR) detection of 30-dBsm RCS targets throughout the entire coverage region, 24 hours a day. However, the requirement to detect small targets at night, when frequencies at the bottom of the HF band are being used, requires observation of targets perhaps 40 dB or more below the detection threshold of current OTHR designs. Small-target detection may be possible during the day, in good conditions, but 24-hour coverage is not realistic. To overcome the low RCS values that result from working at low HF frequencies at night, improvements to the power-aperture product would have to be made. Transmitter power and gain are somewhat constrained to around 100 MW ERP to avoid ionospheric modification, and coherent integration times are limited to a few tens of seconds due to the temporal coherence of the ionospheric layer. One possible area for improvement is in the receive array aperture. Within the constraints of a site that is a few kilometers on a side, a two-dimensional planar array can be used to significantly narrow the receive beams in the elevation direction.

3.3 Persistence

This section looks at two of the dominant influences on the persistence of OTHR coverage. The first is the presence of a low-altitude E-region plasma layer that prevents propagation of HF radar signals to distant ranges. The second is the presence of long-range high-Doppler auroral ionospheric clutter that confounds aircraft target detection.

3.3.1 The problem of the E region

As previously remarked, the occasional formation of strong plasma layers in the ionospheric E region can prevent the propagation of radar signals up to the F region of the ionosphere. This phenomenon of “blanketing” occurs when the peak plasma density of the E-region plasma exceeds the peak density in the F region. The result is that the coverage is reduced from about 500–2000 nmi to about 500–1200 nmi during periods of this blanketing effect. The occurrence patterns of this phenomenon have been studied at various latitudes [16]. For OTHR operation in the middle latitude and auroral regions, where the ionospheric reflection point is in the range of 45–75 degrees in latitude, the occurrence rate of the blanketing effect is in the 20–40% range, with a maximum occurrence in the summer time period and a minimum occurrence in the winter time period. There is no strong diurnal variation. The effect of intense E-region plasma layers could be mitigated by exploiting two-hop propagation modes; in other words, the radar signal would reflect from the ionosphere, reflect from the ground, reflect from the ionosphere again, and then illuminate the target. This two-hop propagation requires traversing the ionosphere D region 8 times as opposed to 4 in the normal one-hop propagation mode of the OTHR, and thus attenuation is increased. However, in daytime conditions, there is ample SNR, and the effects of blanketing should be possible to overcome using a two-hop propagation mode. Assuming no diurnal variation in the E-region plasma layer occurrence patterns, the radar coverage would therefore be reduced from 500–2000 nmi to about 500–1200 nmi between 10% (winter) and 20% (summer) of the time.

3.3.2 The problem of auroral ionospheric clutter

The persistence of OTHR detection capability in the auroral region can also be influenced by the convection of plasma irregularities. Shown in Figure 6 are two radar ray paths. The first is the trajectory of a radar signal that travels to and from a target. The second is the trajectory of a signal that scatters from ionospheric irregularities. Both the target and the irregularities are at the same slant range, and thus the target appears buried in clutter. The irregularities consist of small-scale plasma drift waves driven by the large-scale plasma density gradients resulting from the generalized Rayleigh-Taylor instability [17]. The phase speed of the drift waves

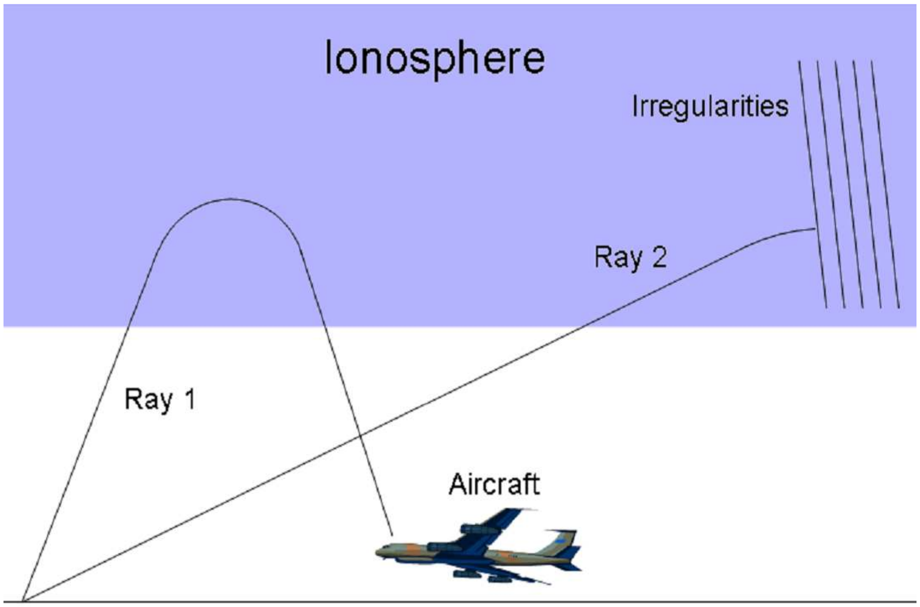

Figure 6: *Origin of ionospheric clutter.*

is on the order of the plasma diamagnetic drift velocity (<20 m/s) which means that the Doppler shift produced by these irregularities is small compared to typical aircraft speeds (>100 m/s). Thus, the aircraft appears free from clutter after Doppler processing; this is the case in the mid-latitude ionosphere. However, in the auroral ionosphere, the action of the solar wind on the earth's magnetosphere drives convection patterns within the auroral region [17]. Consider Figure 7. Shown is the typical auroral two-cell plasma convection pattern in the ionosphere. The plasma drifts along the black oval contours at speeds up to 2000 m/s. This convection transports the aforementioned plasma irregularities at aircraft-like speeds, and so the radar clutter becomes sufficiently spread in Doppler to obscure aircraft echoes. The coloured vectors in portions of the convection cells show actual HF radar Doppler measurements of the moving irregularities.

Along these lines, some experimental investigation of the HF radar angle-Doppler characteristics of this clutter would need to be made prior to installing an OTHR near the auroral zone. Thus, for example, if the moving irregularities are well-confined in Doppler along a certain look angle, then they would not interfere with the detection of aircraft targets in adjacent Doppler cells. However, if the clutter is spread in Doppler, even along a specific narrow receive beam, then large regions of the range-Doppler-azimuth search volume would be rendered unusable. One possible defence against this

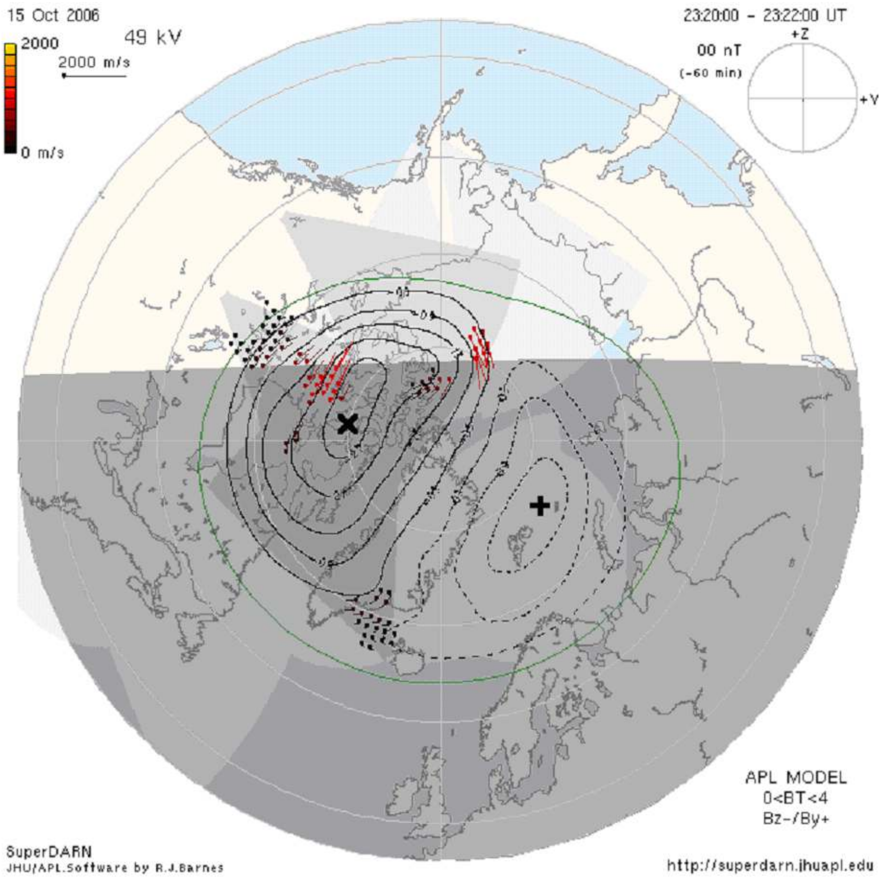

Figure 7: *Auroral convection diagram.*

type of clutter would be elevation angle control in the transmit and/or receive beams. Since for a given range bin, the clutter originates from elevation angles different than those producing target echoes, elevation control should be able to mitigate the clutter problem to some degree.

3.4 Terrain and environment

OTHR surveillance can be performed over either ocean or ground. In the former case, sea waves produce clutter returns that are strongly confined in Doppler to a set of narrow lines referred to as Bragg lines. These lines consist of echoes from ocean waves that have a wavelength equal to one half of the radar wavelength (the Bragg condition). Radar reflections from successive wave crests result in strong constructive interference when the Bragg condition is satisfied. An ocean wave dispersion relation connects the spatial and temporal variations of the ocean wave field, and thus waves satisfying the Bragg condition appear confined in Doppler. Fortunately, the frequency of the Bragg lines corresponds to target velocities in the range 5–20 kt in the HF band, and therefore most air targets will appear outside this sea clutter.

Operation over ground provides an even more benign clutter return. Here the clutter is confined to a single resolution cell at 0 Hz, assuming no Doppler spreading during the signal transit of the ionosphere. Aircraft signals will be well removed from the clutter as long as they are not moving nearly tangential to the radar beam. This near-tangential trajectory possibility can be mitigated by overlapping radar coverage in the important surveillance areas, which provides multiple look angles at the targets.

Terrestrial weather, such as rain, does not affect signal attenuation in the HF band. Although high winds can create higher sea state, aircraft will be removed from the sea clutter by virtue of their speed, and detection performance will be independent of sea state.

4 Vulnerabilities

OTHR is at the mercy of a number of external influences. In this section we account for some of these influences. The subsections are concerned with infrastructure disruption, intentional radiofrequency jamming, the space environment, and human factors.

4.1 Disruption of utilities

Due to their extreme size, most OTHR systems are located in remote areas where access to large amounts of power from the electrical grid is inadequate. Therefore, diesel generators are routinely used. Conventional class AB amplifiers run at best around 50% efficient, and thus a 2-MW generator would be required for a 1-MW transmitter. Although using generators prevents disruptions due to grid problems, a 2-MW generator could consume about 15,000 litres of diesel fuel per day, which leads to a separate problem with continuous fuel supply. Disruptions in fuel supply (say, due to severe adverse winter weather events) could be mitigated by keeping a reserve of fuel for a few days. In addition, mechanical failures of the generators could be mitigated by having backup generators available.

As previously mentioned, the use of an FMCW waveform implies the need for separate transmit and receive sites, so that the direct-path signal from the transmitter does not overwhelm the receiver. Communication links would need to be maintained between the sites to co-ordinate operations. In the event of a communications link failure, the receive site would not be able to determine the correct current waveform parameters, such as operating frequency, waveform repetition rate, and waveform bandwidth. In this case, it would be useful to have a backup communications line available. In the event of both lines failing for a period of time, the transmitter could run autonomously, and the receive site could have a spectrum monitor system that would attempt to discern the correct parameters from the ground wave signals from the transmit site. It would be an interesting problem to determine how to automate such a system, as it may be worthwhile to eliminate the need for routine (as opposed to diagnostic) inter-site communications.

4.2 Jamming

OTHR depends on the detection of scattered radio waves. The systems can therefore be attacked by jammers. A couple defences are available against jamming. First, OTHR uses an active spectrum monitoring system, whereby the radar scans the background radio spectrum and chooses to operate in frequency channels where it does not detect another HF user. Thus, the OTHR will automatically respond to an in-channel jammer by changing carrier frequency. However, even in the absence of jammers, the radar will change carriers at periodic intervals to evade detection by jammers, and to minimize impact on other HF band users.

The second defence against jammers lies in the capability of a large receive array to detect environmental interference and digitally produce receive beam patterns that contain nulls in the directions of strong interference. However, this has the side effect of reducing the sensitivity of the radar to targets located in the nulled directions. Therefore it is desirable to have as narrow a receive beam as possible to minimize the effect of the nulls on target detection. It should be noted that directional nulling is effective against signal repeater jamming, whereby the transmit signal is intercepted by the jamming device, digitally spread in time (range) and Doppler, and then retransmitted back to the radar. This type of jamming basically attempts to flood the range-Doppler detection plane at a particular azimuth.

A successful jamming attack would have to specifically exploit the weaknesses in the defences described above. For example, one could imagine setting up a jamming transmitter in a foreign country that tracked the frequency and timing of the OTHR signal. The transmitter would be low enough in power to escape the attention of the OTHR spectrum monitor and the routine monitoring by international radio communication regulatory bodies, but high enough in power to prevent the OTHR detection of targets. An aircraft intruder could then fly in along the OTHR receive beam in which the interference was being received (and presumably being nulled by the radar). One way for the radar designer to counter this directional interference threat is to have overlapping radar coverage in the important zones, so that any aircraft in these zones would be viewed from at least two directions. In this case, ground-based jammers could be defeated and thus the aircraft itself would have to carry the jamming device. However, the azimuthal movement of the directional interference could eventually be recognized by the OTHR as an aircraft-based jammer.

4.3 Space weather

Since HF systems depend on the ionosphere for their operation, disruptions will occur during adverse space weather events. The US National Oceanic and Atmospheric Administration (NOAA) maintains a site (www.sec.noaa.gov) that provides notices to the public of adverse space weather events and their effects on various engineering systems.

The NOAA information is briefly summarized here. The space weather events are categorized into three broad areas. These three areas consist of (1) elevated geomagnetic activity, (2) elevated energetic particle flux, and (3) elevated X-ray flux.

The geomagnetic activity is gauged by the level of fluctuations on ground-based magnetometers. The fluctuation levels are measured on a so-called Kp scale, which is related roughly to the logarithm of the field fluctuation level in nanotesla (nT). The scale ranges from a Kp of 0, which is a fluctuation level of 0–5 nT, and a Kp of 9, which is a fluctuation level above 500 nT. Although the physics are not currently understood, there has been an observed correlation between magnetic field fluctuations and Joule heating in the neutral atmosphere. This heating forces upwellings of the neutral atmosphere into the ionosphere, which increases the recombination rate of atomic oxygen ions, leading to a decrease in plasma density by up to a factor of 2. This means that fixed-frequency HF sky-wave communication links that normally expect ionospheric reflection will instead propagate straight through the ionosphere. An OTHR, however, is able to respond to this situation by appropriate adjustment of the operating frequency, and so the effect can be mitigated.

Energetic particle flux is gauged by the flux levels of protons from the sun with energy exceeding 10 MeV. When these particles encounter the earth, they travel along the direction of the magnetic field of the earth, which is the direction of high conductivity in a fully ionized plasma. The precipitating particles penetrate to the ionosphere D region, where they encounter neutral nitrogen and oxygen and create ionization. The elevated levels of ionization in the D region increase the attenuation of HF radio waves as they propagate up to the F region of the ionosphere. This increased attenuation causes a loss of the OTHR signal. The radar can reduce the attenuation by moving to higher frequencies, as the attenuation decreases with frequency. However, higher frequencies also limit the OTHR to very low elevation angles, and the coverage range becomes impacted. Although the effect of energetic particles is confined to the auroral zone, there is little an auroral-based OTHR can do about it. Storms of S3-level intensity (sufficient to impact OTHR coverage) happen about once per year, and may last about two days.

Elevated X-ray flux from the sun is largely similar to energetic particles in terms of the impact, except that effects occur over a different region of the earth, and last for shorter periods of time. Instead of affecting auroral regions for a couple days, the flux affects sunlit regions of the earth for a couple hours. X-rays penetrate into the D region of the ionosphere, where they produce increased plasma density and greatly increased HF wave attenuation. The increased attenuation creates what is known as a radio blackout. The blackout can be overcome somewhat by moving to higher frequencies, but the coverage region of the OTHR becomes compromised. Thus, the OTHR cannot operate effectively during the couple hours of the X-ray event. Events leading to blackouts exceeding one hour (R3-level events) occur about 10–20 times per year, and blackouts exceeding ten minutes occur about 20–40 times per year. However, the radar will be on the sunlight side of the earth on average half of the time, so blackouts of >1 hour will affect radar operation 5–10 times per year, and blackouts of >10 minutes will affect operation 10–20 times per year.

4.4 Opposition by local population

Imposing HF installations are usually unpopular due to concerns about radiation hazards, escalation of hostility, and secret military agendas. To gain popular support for these systems, a two-pronged approach is necessary.

The first task is to publish material in the open literature about the systems and discuss the operations of these systems to the extent possible without revealing sensitive details about system performance. For unclassified aspects of the facilities, this effort can include public open houses for one day per year to allow interested people to tour parts of the facilities.

The second task is to employ local people in the maintenance and operations of the facilities. If classified aspects of the facilities can be suitably compartmentalized in separate (guarded) buildings, then local people can be employed for at least the unclassified aspects of the operation. Furthermore, local hotels, bed & breakfasts, and restaurants, can receive increased business by providing services to visitors to the sites. By engaging the local population in a constructive manner, the success of the project becomes consistent with the well-being of the community.

5 State of development

This section reviews some of the previous experiences of other countries in OTHR and looks at the prospects of starting new programs, in terms of costs, risks, trials, and siting requirements.

5.1 Review of previous experience

A number of experimental and operational OTHR systems have been deployed around the world. There is considerable information in the open literature about OTHR experience in the United States; at least two experimental systems and three operational systems have been documented, and are discussed below. There are also current OTHR efforts in Australia, France, and China. In particular, the Australian effort has resulted in the deployment of operational systems. OTHR programs have been previously pursued in various other countries, including the UK, Russia, and Canada.

5.1.1 US OTHR: experimental systems

Although it has been known since the 1930s that ground clutter could be observed by HF sounding using a reflection from the bottom side of the ionosphere, it was not until the early 1950s that sounding experiments were done to determine if the ionospheric layer was sufficiently stable to allow for use in over-the-horizon radar detection of airplane and ship targets. Specifically, the technique of coherent (or Doppler) processing was considered as the way ahead in separating the intense ground clutter return from small target returns. To demonstrate the feasibility of Doppler processing for OTHR applications, in the late 1950s the US Naval Research Laboratory (NRL) built the experimental MADRE radar in Chesapeake, Virginia [1, 18]. The radar used a horizontally polarized linear array with beam steering by mechanical transmission line extenders. The waveform was a 100-μs pulse at an average power of 25 kW. The data was recorded on a magnetic drum device (hence the radar name) and the recorded data was fed into a cross-correlation signal analyzer. By 1961, aircraft flying across the Atlantic Ocean were detected and tracked by this radar.

The second experimental OTHR built in the United States was the Wide Aperture Radar Facility (WARF) in central California, which pioneered the use of vertically polarized antennas, FMCW waveform, and a large receive aperture (2.5 km in length). The radar was originally installed by Stanford University in the early 1960s, and was later transferred to SRI International. One aim of WARF has been to extend the capability of OTHR to allow ship detection within the intense low-Doppler sea clutter. The wide aperture provides sufficient angular resolution to reduce the amount of sea clutter within a resolution cell to the point that ships can be resolved [19, 20]. There has also been much interest in developing ocean remote sensing techniques with the radar, as the radar echo carries information regarding ocean currents and directional ocean wave spectra. The WARF radar has been highly influential in the design of most modern OTHR systems.

5.1.2 US OTHR: operational systems

The first attempt at an operational OTHR radar was a joint project between the US Air Force (USAF) and the UK Royal Air Force under the name Cobra Mist [18, 21]. While the project was intended for deployment in Turkey to provide surveillance of the western Soviet Union, Turkey denied the US a site for the radar, and the USAF later accepted an offer from the UK to host the radar at Orfordness, UK. A contract was awarded in 1966 to RCA, and testing began in 1971. By 1972 it became clear that the radar receiver noise floor was approximately 20–30 dB higher than expected across all range and Doppler cells over land areas, and this caused a massive degradation in detection and tracking capability. An intensive effort was undertaken by the USAF and a team of industry experts to determine the source of the spread-Doppler noise. By May 1973, no conclusive evidence for a source of the problems in either the radar hardware or the environment could be found, and the following month the project was cancelled.

The second operational US OTHR was another USAF effort, this time to provide surveillance of the approaches to the United States by bomber aircraft from the Soviet Union [22]. The program, termed OTH-B, was ambitious, consisting of 180-degree azimuth coverage radars on the US east and west coasts, a 240-degree azimuth south-looking radar in the central US, and a 120-degree azimuth west-looking radar in Alaska. Combined with the North Warning System (NWS) in the Canadian North, OTH-B provided air coverage of all approaches to the continental US. A contract was awarded to General Electric in 1982 to develop the radars, and the east coast radar began limited operations in 1988. Meanwhile, the US Department of Defense became aware of the submarine-launched cruise missile threat to the United States in the early 1980s, and soon expressed a goal that the system be able to detect cruise missiles. However, the capability of this system against cruise missiles was eventually determined to be rather limited, particularly at night, and the goal was dropped in 1989. The subsequent collapse of the Soviet Union removed the primary bomber threat for which the radar was intended to address, and the project was suspended in 1991. Further attempts by NOAA to revive the radars as sea state monitors have largely failed.

The third operational US OTHR radar was a US Navy effort to develop a relocatable system to provide surveillance in support of battle groups deployed at sea. The program was termed ROTHR, for Relocatable Over-The-Horizon Radar [23]. Following the development of a prototype system, a contract was awarded in 1989 to Raytheon for the procurement of three operational systems, with an option for a fourth. Today, three ROTHR systems are currently deployed in Virginia, Texas, and Puerto Rico, respectively. Over the years, priorities have shifted such that the radars are currently aimed toward the south in an attempt to monitor the approach of small airplanes to the United States in support of the US counter-drug effort. In particular, the Puerto Rico radar points deep into South America. These radars provide a long-range complement to the current deployment of aerostat-based microwave surveillance radars along the southern US border. At this time, ROTHR is the only OTHR in use in the United States.

5.1.3 Australian OTHR

There is also a significant OTHR effort ongoing in Australia [24, 25]. The Australian effort is aimed at providing air and ship surveillance to the north of the country, with a 180-degree azimuth radar (featuring L-shaped transmit and receive arrays) located at Laverton, West Australia, and 90-degree azimuth linear-array radars installed at Alice Springs, Northern Territory, and Longreach, Queensland. The program began in 1970 with one-way propagation studies to establish that the ionosphere over Australia has sufficient temporal stability to support aircraft detection, followed by a limited capability experimental radar called Jindalee A, installed at Alice Springs, Northern Territory, in 1974. A larger-scale prototype radar called Jindalee B, followed in 1978. This radar was heavily influenced by the WARF system in California, and the Australians received considerable hardware and technical assistance from the US. By 1986, the Australian parliament was satisfied with the results of Jindalee B, and an operational system, called JORN (for Jindalee Operational Radar Network) was approved, consisting of new radars at Laverton and Longreach, and integration of the experimental Jindalee B radar at Alice Springs into the network. A contract was awarded to Telstra in 1991, for completion by 1997. In 1996, following a number of delays and cost overruns, the Australian National Audit Office wrote a report that was critical of the project management, and in response, the prime contractor Telstra was replaced by RLM, a joint venture between Tenix and Lockheed Martin. The system was eventually completed and delivered in 2004.

5.1.4 French OTHR

The French OTHR system is of a decidedly different configuration than the US and Australian radars. The system, called NOSTRADAMUS, is located about 80 km to the west of Paris [26]. The OTHR is a pulsed monostatic radar that uses an 800-m diameter Y-shaped planar array, which provides both azimuth and elevation beam control. The availability of elevation information alleviates the need for external ionosondes to complete the target co-ordinate registration. The planar configuration also permits 360-degree coverage in azimuth. The array is populated by 288 randomly positioned biconical antennas, with transmitters and receivers being housed in underground tunnels beneath the array. Tracking results have been shown for ships and airplanes in both the Atlantic Ocean and Mediterranean Sea.

5.1.5 Chinese OTHR

The Chinese OTHR program began with an experimental pulsed OTHR in the early 1980s [27]. The pulsed system had a transmitter power of 600 kW peak, 100 kW average, and used an 8-element dipole array for transmit and a 32-element log-periodic array for receive, all vertical polarization. The waveform was a linear FM sweep. By the mid-1980s, it was decided to change the waveform to FMCW to permit higher average radiated powers and provide better control of radiation leakage into adjacent frequency channels. Such a system was fielded by the late 1980s and for time synchronization it was designed to use long wave radio time signals to update rubidium clocks at both the transmit and receive sites.

5.2 Costs and NRE

Radar costs vary widely depending on the amount of hardware flexibility that is desired and the extent of site preparation required for installation. The hardware costs are driven largely by the amount of transmit power and the number of radar receivers that are required. A recent trend has been a move toward larger and more powerful receive arrays in concert with a reduction in transmit power. This trend is driven by the progressively decreasing cost of digital signal processing components, such that it is now feasible, although still expensive, to attach every antenna to its own receiver and analog-to-digital converter. However, sampling individual antennas also has the advantage that the receivers can be physically located at the antennas, which avoids transmission line attenuation. Furthermore, increasing the number of data channels improves the ability to exploit adaptive signal processing algorithms.

Site preparation can also drive costs. Transportation of goods and personnel to remote locations can increase project costs. If the site is on permafrost, precautions need to be taken to prevent melting, such as installing thermopiling to remove excess heat from the ground. Low-lying sites may need to be pumped and dams installed near river courses to prevent flooding during storms. The sites may need to be built up and/or leveled to provide an appropriate surface for the large receiving array, as an elevated ground screen may be impractical given the size of the array. If the radar is below the tree line, forests may need to be cleared. On areas of the Canadian Shield, large quantities of granite rock may need to be blasted away to provide a flat surface.

Due to the size of an OTHR installation, the radars tend to be one-time specialized efforts, and cost comparisons are difficult to make. Nevertheless, Non-Recurring Engineering (NRE), acquisition, and site preparation costs have been reported by various news sources for the OTH-B, ROTHR, and JORN radars. Of these three radars, ROTHR is the most modest in terms of cost and performance, and as a result is perhaps the easiest to quantify. Details of the ROTHR program were reported by the US General Accounting Office [28] in response to a request by the US Congress to clarify the Department of Defense's OTHR programs. The program described in that report was for a 12-radar acquisition at a cost of some \$1.8B. The NRE for the program was \$291M, acquisition costs were \$1,113M, and site preparation costs were \$379M. In executing the program, the NRE was essentially spent in construction of the first prototype radar in Virginia. Costs of additional radars can be drawn from the acquisition and site preparation costs. The per-radar system acquisition cost as provided in this report is therefore (\$1,113M+\$379M)/11=\$136M/radar. Note that all costs above are in 1990 US dollars.

In the case of an OTHR system being placed in Canada, some additional NRE cost would be required to assess the suitability of OTHR operating in the auroral environment. A staged approach would be necessary to mitigate technical risks associated with setting up a radar in this environment. Stage 1 could assume the scope of a Technical Demonstration Project (TDP) that would assess one-way propagation and two-way auroral clutter backscatter characteristics using low-power HF beacons and radars, respectively. The TDP results would define the required NRE for the next stage of development, Stage 2, which could consist of the deployment of a, say, quarter-scale OTHR, with suitable technical support, to develop and demonstrate algorithms that may be needed to cope with conditions encountered in the auroral environment. Stage 3 may be a full single radar acquisition, followed by a realistic operational evaluation. Stage 4 would involve procurement of additional systems to address the relevant surveillance requirements.

5.3 Risks

The advantage of the staged approach is that results can be assessed at the end of each stage and suitable off-ramps can be taken if it is clear that the future stages are not going to succeed. The disadvantage of this approach is that it takes a long time, as can be seen from the review of previous experience at the beginning of this section. However, given the abundance of challenges that have arisen in other countries' experiences in the OTHR technology, accelerating the process is likely to confound the early identification of problems. For example, the noise problems leading to the 1973 Cobra Mist program cancellation described earlier could perhaps have been identified before full radar construction was undertaken, in particular if suitable one-way propagation trials and reduced-scale radar tests had been conducted. Understandably, however, the threat from the Soviet Union was considered such a pressing matter that a staged strategy never materialized.

Specific to Canada, the auroral convection process has potential to spread clutter from irregularities throughout the Doppler extent of the radar and prevent aircraft detections over a large range of azimuthal angles. The characteristics of this clutter relevant to OTHR operation should be assessed by low-power HF backscatter measurements of the auroral zone. Irregularities can also spread OTHR signals in ground range, slant range, DOA, and Doppler, all of which can degrade the coherence of target echoes. These characteristics should be verified by one-way HF propagation measurements.

Given the technical risk of adverse radar performance in the auroral conditions, a cautious approach is necessary. Aside from the time that is expended, there exists little risk inherent in carrying out these experiments. Stage 1 can be carried out without significant commitment to acquiring expensive OTHR technology. The subsequent stages, described in the following subsection, similarly allow verification of performance predictions at each level of development, before proceeding to the next stage for a corresponding increase in financial commitment to the technology.

Mitigation of technical (and equivalently, cost) risks by the above staged approach imposes schedule risks, as time is required to conduct the necessary investigations at each step, and unexpected additional experiments may need to be carried out to determine the sources of problems.

5.4 Trials

The first trial for a proposed Stage 1 should involve placing HF transmitters at proposed radar locations, and receivers at the corresponding location of expected downrange targets. Some serious thought should be given to preferable look directions for the radars in terms of coverage area and their view of the auroral convection patterns. The problem is not simple in that radars at southern locations aimed north tend to observe magnetic field-aligned ionospheric irregularities at right angles, which produces the strongest ionospheric clutter return, whereas radars at northern locations aimed south would tend to be prohibitively expensive to install and maintain. A compromise may be possible with radar beams aimed east and west, although a variety of look angles in Stage 1 would be preferable to get a good assessment of the relevant tradeoffs. With the test locations established, the one-way HF channel characteristics would be analyzed for spread in group delay (slant range), DOA (azimuth), and Doppler. The impact on performance based on the radar equation would be assessed. Specifically, one would want to determine the effective size of the radar resolution cell given the measured spread of radar signals in the range, azimuth, and Doppler extents.

The second trial for Stage 1 would involve placing low-power HF radars at the proposed OTHR locations and configuring the radars with OTHR-like operating parameters (carrier frequency, waveform, waveform repetition frequency, and so on). The Doppler spread of the moving auroral ionospheric irregularities will be mapped out as a function of group range and azimuth, and some assessment can be made of the suitability of computer algorithms, such as Space-Time Adaptive Processing (STAP), and other techniques, such as two-dimensional planar arrays, to counter the spread-Doppler clutter.

A trial for a proposed Stage 2 could involve actual airplane tracking. Commercial airplanes follow great circle routes to Asia which take them over large portions of Canada. A scale model of the radar may not be sensitive enough to detect airplanes in all day/night conditions. However, a good assessment of daytime tracking performance in the presence of auroral ionospheric irregularities, over a limited azimuthal extent, would provide the required risk mitigation to proceed with Stage 3.

Stage 3 could provide a full operational evaluation of wide-area surveillance within the field of view of one radar. This will involve airplane tracking over a broad azimuth sector, and tracking persistence could be assessed against trajectories established by Secondary Surveillance Radar (SSR) detections and commercial aircraft flight plans. Controlled air targets could also be provided to test the detectability of targets undergoing maneuvers. Stage 4 would involve similar operations, but over wider ranges. Here, one would want to demonstrate track handoff between the various radars, and remote operation of a radar network from an operations centre. Considerable emphasis would be placed on developing a user interface that suits the requirements of the radar operators.

6 Support

This section briefly enumerates some of the ancillary issues related to OTHR operation. The first subsection discusses ionospheric sounding support and its role in determining correct radar carrier frequency. The often-overlooked topic of frequency management is presented in the second subsection. The third and fourth subsections discuss the more mundane issues of intersite communication requirements and obstacles to site approval, respectively.

6.1 Ionospheric sounding

Accurate characterization of the ionosphere is necessary for at least two OTHR functions: frequency selection and co-ordinate registration. Frequency selection is typically done by backscatter sounding [29]. In this technique, the radar emits a waveform over a swept frequency range, typically the whole HF band. Ground clutter is received across this frequency range, and the group delay of the clutter is plotted as a function of frequency. This two-dimensional plot can be used to empirically identify what frequencies will reflect from what parts of the ionosphere. Various propagation modes can be identified on this plot. For example, ground clutter resulting from reflection in the E region will appear as a lower group-delay trace compared with traces from the F region. In addition, the E region will generally have a lower maximum plasma density than the F region, and so F-region traces will extend out further in frequency than E-region traces. To obtain propagation to a far range in a single propagation mode (reflection from a single layer), one would need to choose a frequency beyond the end of the E-region trace. To detect targets at near ranges, however, one may have to be content with both E- and F-region propagation modes, and the radar would have to identify the multipath and merge the detections. In addition, in many daytime situations, the F region breaks into distinct layers referred to as the F1 and F2 layers, and backscatter sounding can be used to resolve over what frequency ranges propagation is supported by each layer.

The main problem with backscatter sounding described above is that it provides group delay (or slant range), but gives no indication of actual ground range. There are two ways to recover ground range. The first is to provide the radar with beam elevation control, and perform backscatter sounding in elevation as well as frequency. This will allow the signal elevation angles to be determined, and permit co-ordinate registration.

The other method is to run ionospheric sounders to measure the ionospheric plasma density profile and determine at what altitudes the reflection process is occurring. An ionospheric sounder (or “ionosonde”) is a low-power swept-frequency HF radar that emits pulses and measures the time delay between the pulse transmission and the receipt of an echo from the overhead ionosphere. As described in Section 2, the echo occurs at a point in the ionosphere where the plasma density N, in free electrons per cubic metre, is equal to $f^2/81$, where f is the sounder carrier frequency in Hertz. By sweeping f over a large range, say 1–20 MHz, and recording the group delay of the pulses, a profile of plasma density versus height can be generated. It should be noted that as the ionosonde pulse is propagating through the ionosphere to the reflection height, the group velocity is less than the speed of light, and so the time delay is longer than the time delay in free space. This effect needs to be accounted for in converting the measured group delays into plasma density versus physical height. The recovery of height can be made by a simple mathematical inversion of the group delay data.

Ideally, the ionospheric sounding would be done at the location of the reflection point of the radar beam, as this is where the plasma density is required to determine the OTHR carrier frequency. However, the reflection point is often over water, and therefore not accessible to a ground-based sounding device. One generally makes observations at the transmitter site or at the nearest land-based location to the reflection point, and then makes the assumption that the plasma density does not vary in the horizontal direction. This assumption is not always correct; in particular, there can be large horizontal density gradients at low magnetic latitudes ($\approx$ 20 degrees) in the location of the equatorial anomaly, and at high magnetic latitudes ($\approx$ 70 degrees) in the location of the auroral cusp. Thus, OTHR operation in the low and high latitudes greatly benefits from downrange sounder measurements to refine the propagation calculations.

6.2 Frequency management

One of the most overlooked problems in HF radar operations is spectrum management conditions connected to the authorization to operate. According to the Canadian table of radiofrequency spectrum allocations, radiolocation services (such as radar) are not allocated at any frequency in the HF band (3–30 MHz). What this means is that to operate a radar in the HF band, the operator must not cause harmful interference to allocated services (such as fixed/mobile communications, broadcast, and amateur), and it must accept all interference from allocated services. This condition is referred to as Non-Interference Basis, Non-Protected Basis (NIB/NPB) operation.

A popular method for attaining NIB/NPB operation is a combination of spectrum monitoring and automatic dynamic frequency selection [30]. The idea is that a broadband receiver attached to an isotropic antenna samples the HF spectrum from 3 to 30 MHz. Many channels within the HF band are normally occupied by various communications and broadcast signals. The spectrum monitor samples the spectrum and determines which channels do not contain any detectable signals. These are designated “clear channels” and the results are reported to the radar, which in turn makes a decision about which clear channel it will transmit on. The radar then retunes to this frequency and the transmission begins. If at any time during the transmission another user is detected by the radar, then the radar must stop transmitting until another clear channel can be located. If multiple clear channels can be continuously identified, then the radar is encouraged to hop among them from dwell to dwell in order to minimize the radar’s temporal occupation of any specific frequency channels.

Spectrum monitoring with automatic dynamic frequency selection does not realize perfect NIB/NPB. The fact that a channel appears to be clear does not mean that the channel is not being used. For example, the power level being employed by the user may be of such low power that the radar does not detect the user’s signal and then proceeds to transmit high-power radar waveforms on the channel, disrupting the low-power communications. Since frequency assignment tables provided by regulatory authorities do not reflect actual HF channel usage, there is little that the radar can do to anticipate low-power users, except to have some form of co-operative transmission scheme based on active (perhaps automated) co-ordination with these users, such as Automatic Link Establishment (ALE) technology.

A further consideration for practical NIB/NPB is that the radar transmission itself is so powerful that it can leak into adjacent frequency channels and produce interference to HF users outside the radar channel. This problem can be addressed by implementing waveforms with good spectral confinement. It is generally the case that pulse waveforms are more difficult to contain within a channel than FMCW waveforms, primarily because of the rapid transients that occur at the turn-on and turn-off times of the pulse waveforms. The exact shape of these transients cannot be controlled very easily, and thus there is considerable frequency content generated outside the radar band when these transients occur.

6.3 Networking

As previously mentioned, the use of the FMCW waveform requires separate transmit and receive sites for the radar. Thus, there is a requirement to communicate the operating carrier frequency, and possibly other parameters such as waveform repetition frequency and waveform bandwidth, between the transmit and receive sites. There is therefore the need for at least a low-bandwidth link (a few kB/sec) between the transmit and receive sites. A high-bandwidth link (for time synchronization, for example) is generally not necessary because the timing can be derived from local oscillators that are continuously adjusted to remain synchronized to Global Positioning System (GPS) Pulse-Per-Second (PPS) timing signals. The low-bandwidth link can be made via a microwave signal to the nearest fiber optic connection, which may be a few tens of kilometres away for most sites in southern Canada. Alternatively, one can use satellite communications, although the satellite links do not have guaranteed routine 100% availability due to the possibility of adverse space weather events.

Due to the electromagnetic radiation levels at the transmit site, the radar operators are typically either located at the receive site, or at a third site called the operations centre. In Canada, this site could be the Canadian North American Aerospace Defence (NORAD) Regional Sector Air Operations Centre (R/SAOC) in North Bay, Ontario. If the receive site is in a remote region, then it makes sense to build a separate operations centre near a populated area where there is good access to services. However, the drawback is that a high-bandwidth link (a few hundred kB/sec) is required between the receive site and the operations centre to communicate radar data. It is usually impractical to continuously retrieve raw radar data in real time from the receive site; typically the data will be reduced to a form such as detection files before transmitting to the operations centre. Occasional retrievals of radar data for, say, offline examination, could be accommodated with such a communications link.

6.4 Site approval

Typically, large experimental projects require some form of environmental assessment prior to commencement. The major issues to be addressed include modification of the terrain at the site, installation of infrastructure, radiation hazards, spill hazards from diesel fuel, and noise pollution from generator operation.

The modification of the site terrain includes grubbing to remove vegetation, landfill to remove swampy areas, and grading to remove elevation variations. The impact on terrain can be minimized by judicious site selection, i.e. selection of flat, dry areas for the installation of antennas. In instances where water bodies and courses cannot be avoided, drainage ditches and bridges need to be built, and the impact on local wildlife populations has to be accounted for. Another consideration is the impact of adverse weather events on routine radar operations. For example, if a site needs to be actively pumped to remain dry, such a pumping system may be overwhelmed during heavy rains, resulting in destruction of the installation. Sites that are protected from the elements by passive measures, such as high elevation, are to be preferred. In locations of permafrost, disturbing the terrain can also cause melt, leading to unstable ground. The risk can be mitigated by installing thermopiles that can passively vent excess ground heat into the environment.

Installation of infrastructure presents a hazard to local wildlife in cases of inadvertent entry into buildings, or being snagged by structures such as antenna guy wires. These hazards can usually be avoided by installing suitable fencing around the key structures. Steel fences, with a portion buried underground, will prevent entry of roaming and burrowing creatures. However, steel fences in close proximity to OTHR antennas can interfere with the radiation patterns of the antennas. Some installations use non-conducting wooden fences as an alternative, however, these tend to fall apart after several years in the open weather. A better solution is to use steel fences arranged in such a manner that the impact on antenna radiation is negligible, either by moving the fences sufficiently away from the antenna, placing insulating sections between sections of fences, or by incorporating an elevated ground screen above the fence.

Radiation hazards are usually dealt with by fencing off the area where electromagnetic exposure exceeds maximum levels published in standards such as Canada Safety Code 6 or IEEE/ANSI C95.1-1992. For large HF installations, radiation levels may exceed safe levels up to a kilometre in front of the array. However, an exclusion zone in front of the transmit antenna is already required in terms of the need for a ground screen in the transmit antenna design to ensure good low-elevation transmit beam response. Thus the need for an exclusion zone does not in itself usually impose additional site constraints.

Hazards associated with diesel power generation are routinely overcome. The magnitude of the problem is as follows. A 1-MW transmit facility may need 2 MW of generator capacity, and therefore consume approximately 15,000 litres of diesel fuel per day, which is approximately the capacity of a small tanker truck. Therefore the site requires fairly level, year-round road access for fuel delivery. The radar site should also have a few days of backup fuel available, perhaps 50,000 litres, to ensure continuity of operations in case of supply disruptions. This implies the need for an array of storage tanks, and the need for dams around the tanks in order to contain the fuel in case of a leak or spill during refueling. Finally, noise pollution from the generators can be mitigated by installing mufflers on the exhaust systems, and housing the generators in soundproof enclosures.

7 Conclusion

High-Frequency (HF) radar technology has been pursued by the Canadian Department of National Defence (DND) for military applications since 1984. Effort has been directed at developing High-Frequency Surface-Wave Radar (HFSWR) technology for ocean surveillance of ships and aircraft. This effort has led to two operational HFSWR installations at Cape Race and Cape Bonavista, Newfoundland. However, the surface-wave technology cannot be readily applied to the problem of long-range surveillance of aircraft over land due to very high surface-wave attenuation over ground terrain. Thus, this memorandum briefly examined a related long-range HF radar technology referred to as HF sky-wave radar, or more commonly, Over-The-Horizon Radar (OTHR).

OTHR uses the earth's ionosphere to reflect radar signals and illuminate targets beyond the line-of-sight horizon. The density of plasma in the F region of the ionosphere ($>$160 km in altitude) imposes limits on the frequency range that can be used by the radar, and the variation in the plasma density over time means that the radar must be capable of adapting its carrier frequency in real time. Radars can generally be designed that have sufficient flexibility to obtain coverage over 500–2000 nmi in good conditions, and 500–1200 nmi in conditions of strong low-lying plasma layers in the ionosphere E region (90–160 km). Large aircraft, such as commercial jets, can generally be observed 24 hours per day and located to within about 30 km of their actual position. Smaller airplanes and cruise missiles cannot be easily detected at night. In addition, the radar suffers vulnerability to outages due to disturbances in the ionosphere caused by adverse solar ("space weather") events. Furthermore, in Canada, backscatter from fast-moving ionospheric irregularities in the region of auroral plasma convection can cause spread-Doppler clutter that can prevent target detection.

OTHR technology has been pursued by other countries for approximately 50 years with varying degrees of success. The successful approaches have generally involved a carefully staged succession of development. These experiences suggest a staged way ahead in Canada that considers one-way and two-way HF propagation experiments to quantify OTHR performance prior to proceeding with any radar acquisitions. Planning for acquisitions will also have to consider infrastructure requirements, including land preparation for the large antenna arrays, communications to support the co-ordination of separate transmit and receive sites, spectrum monitoring to determine the background electromagnetic environment, and HF sounding to estimate the ionospheric propagation paths.

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3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C or U) in parentheses after the title.)

A Canadian Perspective on High-Frequency Over-the-Horizon Radar (U)

4. AUTHORS (Last name, first name, middle initial)

Riddolls, Ryan J.

5. DATE OF PUBLICATION (month and year of publication of document)

December 2006

6a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

53

6b. NO. OF REFS (total cited in document)

30

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

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(U) High-Frequency (HF) radar technology has been pursued by the Canadian Department of National Defence (DND) for military applications since 1984. Effort has been directed at developing High-Frequency Surface-Wave Radar (HFSWR) technology for ocean surveillance of ships and aircraft. However, the surface-wave technology cannot be readily applied to the problem of long-range surveillance of aircraft over land due to very high surface-wave attenuation over ground terrain. Thus, this memorandum briefly examines a related long-range HF radar technology referred to as HF sky-wave radar, or more commonly, Over-The-Horizon Radar (OTHR).

A basic description of OTHR technology and performance is provided, including coverage area and target localization capability. Mention is made of problems facing OTHR deployment in Canada, the most serious of which is spread-Doppler radar clutter caused by ionospheric irregularities undergoing convection in the earth's auroral zone. Previous OTHR efforts in other countries are examined, and are used to provide the basis for the way ahead in exploring OTHR applications in Canada.

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