Over-the-Horizon Radar in the HF Band

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Invited Paper

***Abstract*—Over-the-horizon (OTH) HF radar using sky-wave propagation via refraction by the ionosphere is capable of detecting targets at distances an order of magnitude greater than conventional microwave radar limited by the line of sight. Some of the characteristics, capabilities, and limitations of OTH radar based on the experience of the MADRE radar as developed by the Naval Research Laboratory are described. Also discussed is the application of OTH radar to air-traffic control and to the remote sensing of sea conditions.**

I. Introduction

Radar frequencies are generally synonymous with microwave frequencies. The standard radar bands (Fig. 1) established by the International Telecommunications Union (ITU) extend as low as VHF, but the lowest frequency band (137–144 MHz) is now used chiefly for experimental purposes. The next lowest band (216–225 MHz) has limited operational application, but the vast majority of radars in the United States operate at UHF or higher.

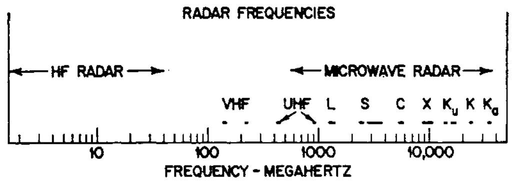

Fig. 1. Frequency spectrum showing the relationship between HF radar frequencies and conventional microwave radar bands (letter designations) as assigned by the ITU for Region II.

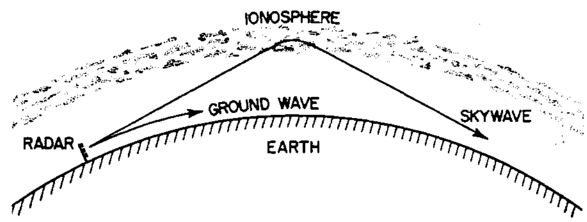

Fig. 2. Geometry of sky-wave and ground-wave propagation.

Radars at the lower frequencies suffer from a crowded spectrum, limited bandwidth, high ambient noise, and wide beamwidths. Nevertheless, there have been significant applications of radar in the HF band[1] in the past. The earliest "radars" were at HF and were used to measure the height of the ionosphere. In the middle 1920's Appelton employed FM-CW equipment, and Breit and Tuve used pulsed equipment to determine the ionospheric height by what would now be considered classical radar methods. The first operational military radar system was also at HF. This was the CH radar system installed by the British in 1938 for aircraft detection. These line-of-sight radars, which were crude by modern standards, were given credit for a major contribution in defending against German bombers during the Battle of Britain and conclusively demonstrated the worth of radar. They were built at HF because there was no other alternative available for a system that had to be installed in 1938. They did the job well, however. Just prior to World War II, radar frequencies reached up to about 200 MHz, and during the war the microwave region was exploited successfully.

UHF and microwave radars are used widely in both military and civilian applications, and it is unlikely that frequencies outside this relatively large portion of the electromagnetic (EM) spectrum will be competitive for the majority of current applications. However, there is a very important property of the HF region that has always been of interest to the radar designer, if it could be properly exploited. This property is the ability of HF radiation to propagate beyond the line of sight by either ground waves diffracted around the curvature of the earth or sky waves refracted by the ionosphere (Fig. 2). The range of a ground-wave HF radar typically might be of the order of 200–400 km, and the coverage of a sky-wave radar might extend from a minimum of 1000 to perhaps 4000 km or more. The HF over-the-horizon (OTH) radar can extend the 400-km range typical of a ground-based air-surveillance radar by an order of magnitude. The area covered increases by about two orders of magnitude.

The targets of interest to an HF OTH radar are the same as those of interest to microwave radar and include aircraft, missiles, and ships. The long wavelengths characteristic of HF radar also provide a means for gathering information about the sea and land, as well as aurora and meteors.

Experiments with OTH radar began at the Naval Research Laboratory early in the 1950's. It was realized that if targets of interest were to be seen, the extremely large undesired clutter echo returned from the ground must be suppressed relative to the target signal. For example, the echo from the ground might easily be 40–80 dB greater than an aircraft echo, depending upon antenna beamwidth and pulsewidth. To increase the target-to-clutter ratio requires high resolution in range and angle and excellent Doppler-frequency discrimination as in a moving target indicator (MTI) or pulse Doppler radar. At HF, sufficient resolution in angle and/or range to suppress completely the clutter echo is difficult to achieve. For example, a 1° beamwidth requires an antenna of the order of 2 km. Range resolution requires a wide-signal bandwidth, but it is seldom that the ionosphere can effectively support an instantaneous bandwidth greater than about 100 kHz, which corresponds to a range resolution of roughly $1\frac{1}{2}$ km. Even with

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[1] Although the HF band is defined by the ITU to extend from 3 to 30 MHz, definitions are sometimes arbitrary. Here HF is meant to include those frequencies just above the broadcast band and extending up to 40 MHz or more.

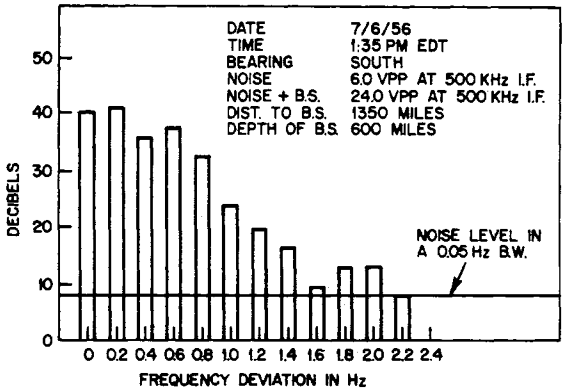


Fig. 3. A typical earth backscatter (BS) energy distribution showing the distribution of the backscattered energy and also the frequency at which this energy has diminished to the level of the noise in the 0.05-Hz bandwidth. The line structure of the graph is not due to a discrete modulation frequency since the backscatter signal is continuous with the frequency, but rather represents the average amplitude measured in a 0.05-Hz bandwidth filter over a 2-min period positioned in successive 0.2-Hz steps.

such range and angular resolution, sea clutter at a distance of 3000 km can be a target as large as perhaps 10^6 m^2. Doppler processing is thus clearly needed in an OTH radar for most targets.

In 1956 the Naval Research Laboratory concluded a definitive set of experiments that showed HF sky-wave radar could succeed for aircraft detection. First, aircraft targets were examined line-of-sight and found to give coherent echoes. The Doppler shift f_d from the radar carrier frequency f_0 is given by the relation

$$f_d = \frac{2V_r f_0}{c} \tag{1}$$

where V_r is the target relative velocity and c is the velocity of light. For aircraft targets f_d was generally a very-well-defined frequency in the slightly above 0- to 50-Hz range. Second, one-way sky-wave paths had been measured to be frequency-stable at least for the order of seconds. The conclusive experiment that indicated OTH detection was feasible for aircraft targets employed a coherent pulse Doppler radar to examine the echo from the earth, and showed that the return from the earth by a sky-wave path was well-confined in spectral content to the very low Doppler frequencies. Fig. 3 taken from an early Naval Research Laboratory report describing that experiment, shows that the amplitude of the earth backscatter frequency spectrum is reduced at least 32 dB at a frequency 2.2 Hz removed from the carrier. In this measurement, the area of earth illuminated by the coherent pulse Doppler radar was 1100 by 1300 km, and included both land and ocean surface. (This is a cell size area about three orders of magnitude greater than would be used for an OTH radar.) Data such as these, and measured aircraft radar cross sections, were used to predict that OTH detection with a Doppler radar was possible. The limits of performance appeared to be controlled by the dynamic range achievable in receivers and in the signal processors. The Naval Research Laboratory then embarked on a program to apply Doppler processing to OTH radar. The heart of the initial development was a cross-correlation signal processor that utilized a magnetic drum as the storage medium. Under Air Force and Navy sponsorship, a high-power transmitter and antenna suitable for testing aircraft detection feasibility were added, and in the fall of 1961 aircraft were detected and range tracked over the major portion of their flights across the Atlantic. Continual improvements in signal processing were made by the use of ferrite-core memory devices, capacitor-store devices, and digital processing. The signal processor has been the key element in the success achieved with OTH radar.

In this paper, the basic nature of OTH radar will be reviewed with emphasis placed on those properties and characteristics that differ from those found at microwaves. The sky-wave radar will be considered chiefly, but some brief mention will also be made of the shorter range OTH radar that utilizes the ground-wave mode of propagation.

II. Character of HF Radar

Some of the characteristics and problems of HF OTH radar can be identified by an examination of the familiar radar range equation. A form commonly used in OTH Doppler radar analysis is

$$R_{\max}{}^4 = \frac{P_{av} G_t G_r \lambda^2 \sigma F_p T_c}{(4\pi)^3 N_0 (S/N) L_s} \tag{2}$$

where

$R_{\max}$	maximum range;
P_{av}	average power;
G_t	transmitting antenna gain;
G_r	receiving antenna gain;
λ	wavelength;
δ	target cross section;
F_p	factor to account for propagation effects;
T_c	coherent processing time;
N_0	noise power/unit bandwidth;
(S/N)	signal-to-noise ratio required for detection;
L_s	system losses.

The transmitting and receiving antenna gains are shown separately since in some OTH radars it is convenient to have separate antennas for these functions. It is in F_p, N_0, and T_c that the major differences between sky-wave and microwave radar lie. The factor F_p contains ionospheric path energy loss, polarization mismatch loss, ionospheric focusing gain or loss, and losses due to the dynamic nature of the path [1], [2]. N_0 contains the noise power expected from natural sources [3] and in addition (and frequently more important) the effects of other HF band user interference. The processing time T_c [which is equal to the number of hits integrated divided by the pulse-repetition frequency (PRF)] is included in this form of the equation to emphasize that this is a Doppler radar that requires a dwell time of T_c seconds if a frequency resolution of $1/T_c$ hertz is to be achieved.

In the design of an OTH radar an adequate signal-to-noise ratio (SNR) is not the only criterion for detectability. The signal-to-clutter ratio must also be sufficient. Thus such factors as the resolution cell size may be more important in an OTH radar than in conventional radar.

A "typical" OTH radar designed for the detection of aircraft at ranges out to 4000 km might have an average power of several hundreds of kilowatts, antenna gains from about 20–30 dB, and operating frequencies from several megahertz to several tens of megahertz. Antennas must be big to obtain

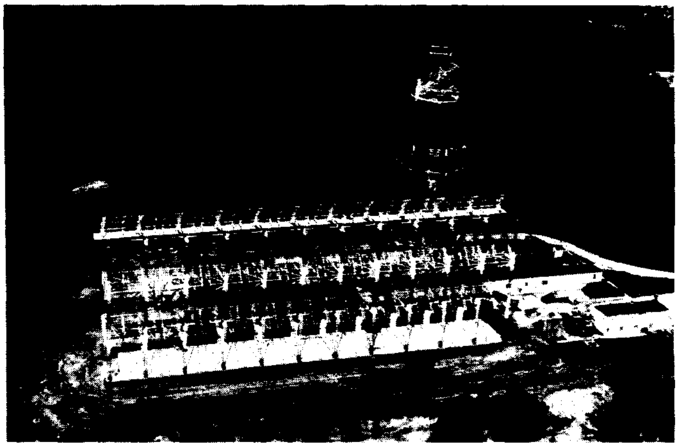


Fig. 4. MADRE OTH radar located at the Chesapeake Bay field site of the Naval Research Laboratory. The auxiliary rotatable antenna located above and behind the main planar antenna is used for experiments in directions not within the coverage of the main antenna.

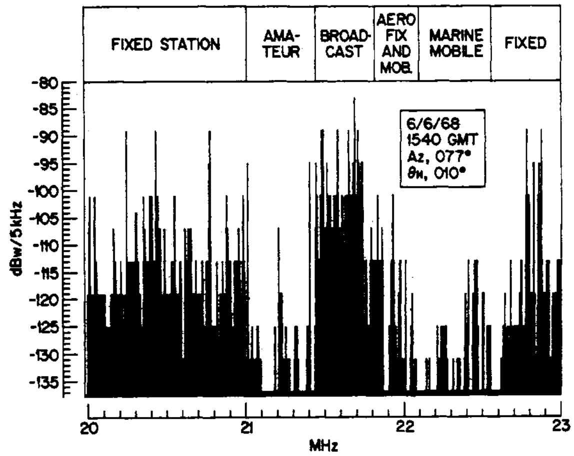


Fig. 5. Typical spectrum of the noise and interference experienced at HF as measured within a 5-kHz bandwidth. The noise due to atmospherics and cosmic sources is at a level of approximately −140 dBW (140 dB below 1 W). Note the correlation of the level with user allocations.

reasonably small beamwidths. An antenna horizontal length of 300 m might be typical.

The transmitted waveform (signal format) can be CW, simple pulse, FM–CW, chirped pulse, or other coded waveforms [5]. Pulse compression is used for the same reasons as in microwave radar. Because of the skip zone, the HF OTH sky-wave radar does not detect targets within about 1000 km so that problems of minimum range, as might occur with sophisticated pulse waveforms, do not generally exist.

The Naval Research Laboratory's MADRE OTH radar is shown in Fig. 4. This is an experimental radar that first went into operation in 1961. The antenna is 98 m wide by 43 m high and consists of twenty corner reflector elements arranged in two rows of ten elements each. The beam is steered ±30° in azimuth with mechanically actuated line stretchers. Shown above and behind this fixed main antenna is a rotatable antenna 27 m in width that is used to obtain coverage in directions other than that of the main antenna. This experimental radar has been generally operated with average powers from 5 to 50 kW.

In a microwave radar, the receiver sensitivity is usually determined by the internal noise generated within the receiver itself. External noise seldom affects the sensitivity. The opposite is true at HF. External noise due to atmospherics (lightning), cosmic noise, man-made noise, and other HF radiating sources can be significantly greater than internal receiver noise. The combined effects of interference from the many other users of the HF band is an especially major contribution to the receiver noise level. Fig. 5 plots a typical example of external noise in the HF band. The expected atmospheric and cosmic noise level would be at the bottom of the graph and is lower than the noise which is often experienced in practice. Note that the actual noise levels can be quite high and are not uniform across the band. If narrow-band operation can be tolerated (perhaps a spectral width of 5 or 10 kHz) many relatively clear regions can be found in which to operate. The nonuniformity of the ambient noise spectrum means that large-bandwidth systems might have to compete with a higher value of N_0 (noise power per unit bandwidth) than might narrow-band systems.

External noise is not the only effect that can limit receiver sensitivity. As mentioned in the preceding, an OTH radar illuminates a large portion of the surface of the earth, and the land or sea echo is generally so large that it dominates the external noise level and the target echo. Generally, some form of Doppler signal processing is necessary to extract the desired moving target from the undesired background clutter. In principle, Doppler processing in an HF radar is similar to the MTI or pulse Doppler methods employed in microwave radar but with important modifications to allow for the specific characteristics of HF radar. Doppler filter bandwidths from 1 Hz down to 0.05 Hz may be used depending upon the target's characteristics and the stability of the propagation path. The addition of noncoherent processing is generally of benefit.

Just as other users of the HF band produce interference that can limit the sensitivity of HF radar, the HF radar can cause interference to other users if care is not taken. An approach to interference minimization is to use narrow-band waveforms (in the extreme, monochromatic continuous waves) whose spectral energy can be fitted within channels where no other user can be detected. The waveform in a radar like MADRE is a compromise between range resolution, which requires wide bandwidth, and interference elimination, which requires narrow bandwidth. To properly utilize narrow-band waveforms to minimize or eliminate interference by occupying quiet regions of the spectrum, frequency flexibility is necessary.

A narrow spectrum implies a long pulse. A long pulse is important in achieving the energy required for long-range detection. It is also desirable to shape the transmitted pulse (or pulse elements in a coded waveform) so as to reduce the spectral energy contained at frequencies far from the carrier. This precaution is also true for FM–CW, thus making it equivalent to a very long frequency-modulated pulse. A cosine-squared pulse shape has been successfully used with MADRE. When proper precautions are taken, experience has proven that there are but few complaints of HF radar interference to other users of the band.

Considering radar cross section, most targets are in the *optical* region for microwave radar. In contrast, for HF radar some targets can be in the *resonance* region and when operating at the lowest frequencies, even lie in the *Rayleigh* region. The cross section decreases rapidly with decreasing frequency in the Rayleigh region [4]. Fortunately, for many targets of interest and for the usual frequency range of operation, the cross section seldom falls within this region.

A sky-wave OTH radar utilizes the ionosphere to refract the energy back to the earth's surface. The ionosphere determines the range of operation and introduces an additional path loss. The motions inherent in the ionosphere can limit the Doppler processing and the accuracy of the angular measurement. It is important in a radar of this type that the frequency of operation and the signal parameters be chosen to minimize the adverse effects of the ionosphere. It is generally easier to operate a radar to compensate for ionospheric propagation effects than it is with HF communications. In communications, two parties—the transmitter and receiver—must cooperate in order to have an effective path. In radar, there is only one party. Communicators usually operate with a limited set of frequency allocations. For the radar, it is assumed that the best frequencies are available, provided they do not interfere with others. The nature of the radar clutter echo can be used to determine the proper mode of operation. The effective use of frequency and signal waveform flexibility to operate successfully in spite of the vagaries of the ionospheric propagation path is an advantage of radar, as described in Section III.

The waveform repetition frequency of an OTH radar is generally low so as to avoid range ambiguities. A pulse-repetition frequency (PRF) of 50 Hz, for example, corresponds to an unambiguous range of about 3000 km. Because the PRF is low, Doppler ambiguities can result and a compromise is generally required between the range and Doppler ambiguities. Typical pulsewidths might vary from tens of microseconds to several milliseconds.

The magnetoionic part of the transmission path rotates the plane of polarization so that fading of the echo can occur if linear polarization is transmitted and received [1], [2]. Polarization fading can be reduced by receiving on two orthogonal linear polarizations when a single linear polarization is transmitted. Circular polarization can eliminate fading due to polarization rotation; however, it is expensive to achieve in a practical HF radar antenna. Because of the proximity of the antenna to the earth (relative to the wavelength), the ground must always be considered part of the antenna. The ground effects are generally different for horizontal and vertical polarization so that an initially circularly polarized wave might actually be launched as elliptical polarization and the ellipticity will be a function of the vertical radiation angle.

Multipath interference and dynamic irregularities in the ionospheric propagation path are two other sources of fading. Multipath effects with sky-wave radar are important and some will be identified. First, the previously mentioned polarization rotation can be considered a multipath effect. This rotation is due to the birefringement nature of the refracting medium (electrons in the presence of the earth's magnetic field). An incident linearly polarized wave can be thought of as decomposing into two circularly polarized components, one right handed and the other left handed, each traveling by its own distinct path and path length through the ionosphere, and upon emergence the combination of the two components can again give a linearly polarized wave, in general rotated from the incident wave. Second, waves refracted by an increasing electron density with height will generally have two paths from the radar to the target, a high ray and a low ray. The high ray experiences more loss and in analysis is frequently neglected. Third, the structuring of the ionosphere, especially in the daytime, into separate height bands of high-charge gradient provide, for some operating frequencies and distances, up to four paths between radar and targets. Fourth, for some operating frequencies and target distances both one- and two- (or more) refraction paths exist. All of the preceding sources of multipath can be multiplicative and the separate paths will either interfere causing fading or give distinct separate responses depending upon the radar's resolving capability in range, Doppler, and elevation radiation angle.

The antenna for an HF OTH radar is probably more demanding than for any other radar application. The antenna should be of high gain, cover an extremely wide-frequency range, be steerable in elevation, be rapidly steerable over a wide azimuth, and handle high power. Such an antenna will be of large size and require a large ground screen to keep the elevation launch angles low if vertical polarization is used. For example, if a vertical monopole element is used over a ground of poor conductivity and it is desired to put the maximum of the first lobe at 4°, a ground screen extending about 150 wavelengths (3000 m at 15 MHz) in front of the antenna is required.

The coverage of the radar on the earth's surface depends on the ionosphere. A "typical" patch of the ground illuminated by a single frequency might be 1000 km in the range dimension. The region from 1000–4000 km might, therefore, require three different frequencies for proper coverage. On the other hand, ionospheric conditions might be such that a single frequency could cover this range or perhaps five or six frequencies might be required. This illustrates the necessity for flexible radar management that senses the environment and adjusts the parameters of the radar for optimum operation. This subject will be treated in Section III.

If Doppler processing is used, the antenna beam must dwell on the target area for a time sufficient to achieve the Doppler resolution required and the degree of clutter attenuation needed. In MADRE, this dwell period might typically be 10 s.

The wide-area coverage of an OTH radar, the need to employ more than one frequency to cover the range interval under surveillance, and the need to dwell a sufficient time for Doppler processing means that a single-beam radar might require a relatively long time to scan a large surveillance area. The scan time can be reduced, if necessary, by the use of multiple simultaneous transmit and receive beams at the expense of increased equipment complexity. Another approach is to transmit with a broad beam and receive with multiple narrow beams covering the same area as the broad transmitting beam. This allows the more expensive transmitting antenna to be relatively small. (The transmitting antenna must be capable of high power so that it generally will be more costly than a receiving antenna of the same size.) The burden of providing narrow beams for resolution and accuracy then rests with the receiving antenna.

A problem confronting HF OTH radar is the clutter from meteors and aurora. Both phenomena can produce strong radar echoes that can hinder detection of desired echoes. Meteor and aurora clutter can be strong enough at times to enter the radar via the antenna sidelobes and from ranges greater than the maximum unambiguous range so that they are folded-over in range and can appear where targets might be expected. Again, by proper management of the flexible radar operation, limitations due to these effects can be minimized or eliminated.

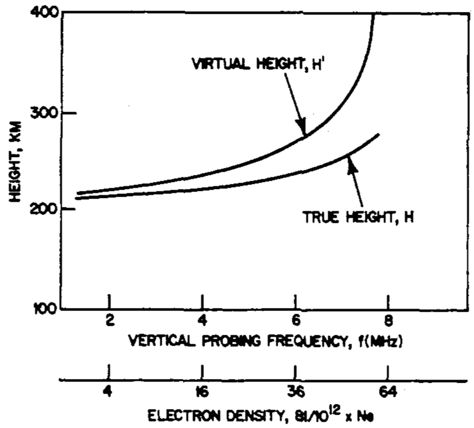


Fig. 6. Two vertical profiles of reflection height versus probing frequency are given. The upper trace is as would be derived from a vertical sounder and the H is a virtual height, generally identified by a prime: $H' = (c\Delta t/2)$, where c is the speed of light, Δt is the time delay for the signal to return from the ionosphere. The lower trace is the true height profile. The abscissa scale can be in terms of electron density because of the relationship $Ne = f^2/81$, where Ne is free electrons per cubic meter and f is the frequency in hertz.

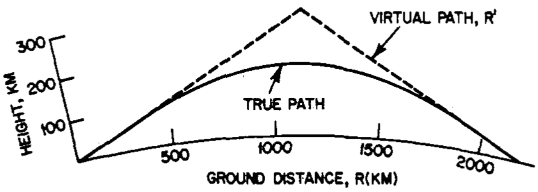


Fig. 7. A true path and virtual path are shown for the ionosphere as described in Fig. 6. It is frequently convenient to work with virtual paths. The virtual path length $R' = (c\Delta t/2)$ is similar to the concept of virtual height. Below the ionosphere the true path and virtual path are identical.

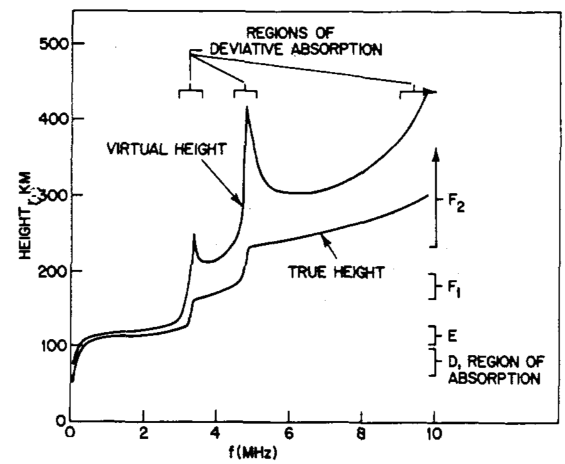


Fig. 8. A daytime vertical profile of the ionosphere is shown. This is a median profile based upon past soundings made at the particular location and time. The lower trace indicates the electron density structure with height as being other than smooth. The commonly used designators of height regions (F_1, F_2, E, and D) are approximately bracketed and regions of absorption are indicated.

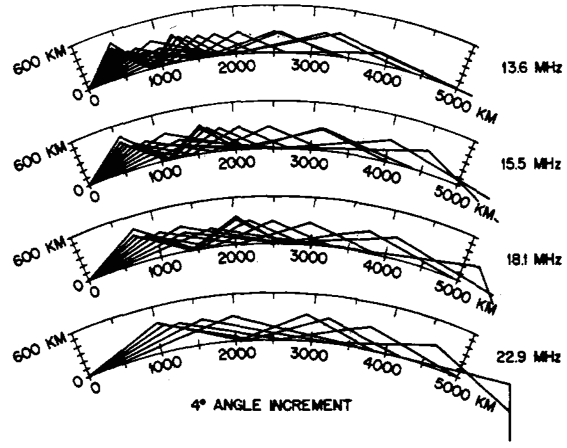


Fig. 9. This set of virtual path traces is based upon the ionospheric description given in Fig. 8. It would be more precise if each reflection from the ionosphere had used its own vertical profile. Although ionization changes with distance have been ignored, the general picture of radar range coverage achieved as a function of operating frequency is shown.

III. Radar Management and the Ionosphere

Sky-wave propagation provides transmission paths from a station on the earth's surface to any other point on the earth's surface and to a large volume above the earth. A high-frequency EM wave launched at some oblique angle to the horizontal will bend away from the vertical as it travels into a region of increased electron density. The magnitude of this bending increases with decreasing radio frequency. Thus achieving a path back to the earth is just a matter of choosing the correct radio frequency to match the existing electron density distribution. The electron density distributions are caused by solar radiation exhibiting diurnal and seasonal variations. Since solar behavior is not precisely predictable, a future electron density distribution is not exactly predictable either. Effective radar operation requires that the electron density distributions be sensed in real time. Fig. 6 gives an example of an electron density profile and a vertical sounding profile, either of which is a common method of describing ionospheric parameters. This example shows a smooth increase of electron density with altitude typical of summer nights. Such a profile can be used to describe the ionosphere at each location on the earth. Fig. 7 shows a ray path for a frequency that gives refraction back to the earth. Earth reflections and successive ionospheric refractions can extend the path to any distance, including complete encirclement of the world. A complicating factor is that the vertical (altitude) profile of electron density may not be a smoothly varying function. Also electron density vertical profiles vary with time and geographic location. Fig. 8 is an example of daytime electron density profile and the virtual height as a function of the probing frequency. Fig. 9 shows the virtual ray paths associated with this ionospheric description for several radio frequencies. It can be seen that at some target distances a variety of paths are available.

Propagation losses are identified by three different processes. The first is in the lower part of the ionosphere (D region) where collisions of the free electrons (excited by the radio wave) with neutral particles absorb energy. This is called nondeviative absorption [1], [2]. The second is in the E region at an altitude a little over 100 km, where thin patches of high-density ionization may exist giving obscuration to the higher ionosphere. This has been called sporadic-E obscuration. The third is the region where the true and virtual heights of the radio wave differ greatly, and this is called deviative absorption. In addition to these losses, there can be loss due to

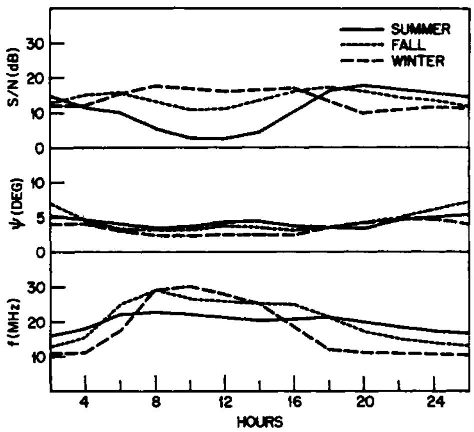


Fig. 10. The average performance calculated for a radar is used to show the variations in signal-to-noise ratio S/N, vertical radiation angle ψ, and operating frequency f versus time of day for three seasons but a single sun spot number. These computations are for a single target size and range, the range being about the maximum that can consistently be reached by one hop. A three-to-one frequency spread is required with the lowest frequency requirement being at winter night. The worst SNR occurs during the middle of summer day. Required radiation angles vary between 3° and 6°. Operation over an entire solar cycle requires more variation in launch angle and frequency.

polarization mismatch, ground reflection, and focusing or defocusing due to irregularities in ionization.

In practice, a system would be designed on the basis of the available information about the statistical behavior of the ionosphere. Since the electron density always increases with altitude (in the lower portion of the ionosphere), the existence of an ionospheric path can be considered certain but unpredictable in its detailed character. The reliability of performance that can be realized depends upon the antenna aperture size, radiated power, and the span of frequencies that can be used. One controlling limit is absorption in the lower atmosphere during summer days when the ionization extends to lower heights where the neutral particles are more dense. The result is increased path loss. A second controlling limit occurs on winter nights when the electron density is comparatively sparse and a low operating frequency is required to provide a path. Thus the first limit affects the long-range performance and the second, the short-range performance. Violent, but relatively infrequent, solar activity may result in short periods of similar behavior that can sometimes be more extreme. Fig. 10 shows the predicted performance of a hypothetical radar design.

In short, the sky-wave path can be made reliable if one is willing to pay the cost.

In addition to the question of path loss in HF sky-wave propagation, there are other aspects of the OTH radar environment that can be described as detrimental to radar operation. These may be classified as follows.

1) A multiplicity of paths from radar to target can exist causing either fading or multiple responses from a single target as has been previously discussed. There also may be patches of electron density in the lower ionosphere that are semitransparent causing a ray to be refracted to the ground as well as permitting rays to be transmitted to a higher layer where they are likewise refracted back to the ground.

2) The ionosphere is dispersive in that the velocity of propagation depends on the frequency. Hence there are limits upon the information bandwidth that may be employed, and extremely short pulses will be distorted, placing a limit on range resolution.

3) The nature of refraction by the ionosphere allows a specific area to be illuminated by only a limited band of frequencies.

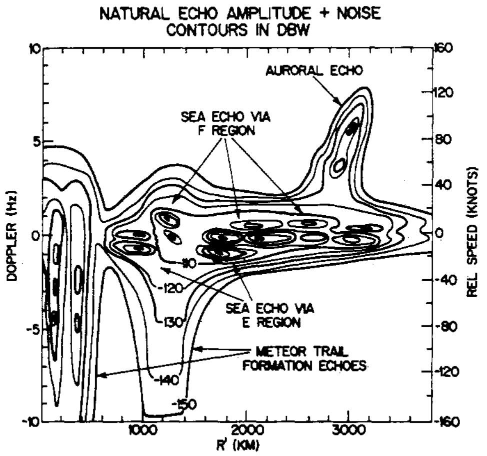
4) The electron-density distribution in the ionosphere is in a state of continuous change so that the nature of the propagation path is subject to change with time.

5) The propagation space is studded with unwanted clutter echoes such as the earth, auroral ionization, meteor-caused ionization, and other large scattering areas that compete with the desired target echoes.

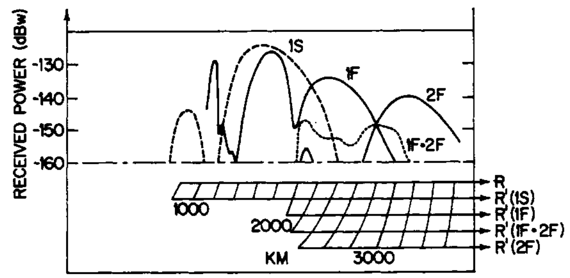
6) The part of the frequency spectrum appropriate for OTH radar is noisy due to cosmic, solar, and natural terrestrial sources, all of which, though not exactly white, extend smoothly across the band. The spectrum of man-made relations, both from radio transmissions and electrical machinery, tends to be colored. It is emphasized that the HF spectrum is crowded with users.

All of the preceding discussion shows that for successful HF OTH radar operation it is essential that the environment be sensed in real time and the radar be optimally matched to the environment. The operating frequency and the vertical radiation angle are the parameters available for securing desired illumination power density at a particular point on the earth. Monitoring of the occupancy of the HF spectrum can assist in the selection of the precise frequency and the emission bandwidth to minimize the interference level at the radar and to avoid interference to other users. The waveform repetition rate can be adjusted for the best compromise between range ambiguities, Doppler ambiguities, and obscuration by natural targets (clutter). It is evident that narrow antenna beamwidths in both the horizontal and vertical planes can provide discrimination against natural targets that obscure, and at the same time minimize interference with other users. Widening the emission bandwidth to achieve greater range resolution also can help reduce the echo from distributed natural targets.

All of the preceding serves to emphasize that for effective sky-wave radar operation it is important to have a real-time description of the transmission path and the band occupancy, and that the radar waveform and signal processing must be matched to the existing conditions. All of the common methods to determine the best operating conditions that have been developed for HF communications can be used with radar. These include vertical soundings of virtual height versus frequency, oblique soundings of virtual range versus frequency between the radar and fixed points, oblique soundings of backscatter amplitude versus frequency, estimates of the effect of solar activity, and HF band occupancy obtained from a search receiver. The sky-wave radar has a capability not available with HF communications that should always be used and which can provide additional description of the transmission path. The radar backscatter from the earth at a particular frequency can be used to infer the character of the ionosphere for all heights up to the height of maximum ionization. Thus normal radar operation has, as a byproduct, the data from which the transmission path can be described. The essential requirements for using these data are a knowledge of the scattering properties of the earth and some method of correlating virtual ranges with ground ranges, or virtual ranges with elevation radiation angle. If the earth has identifiable natural localized scatterers such as islands on the sea,



(a)



(b)

Fig. 11. In Fig. 11(a) Doppler range space is shown in contours of received power level in decibel-watts. Such descriptions of the earth (sea) echo can be used to determine the radar transmission path parameters. This analysis has been done and in Fig. 11(b) the received power for a 1000-m² target has been plotted for the several paths versus both great circle ground range R and virtual range R'. The paths drawn are: one refraction by sporadic ionization in the E region (1S); one refraction in the F region (1F); two refractions in the F region (2F); and the combination of the latter two (1F–2F). The ranges that permit multiple responses are evident. To indicate performance (either SNR or signal-to-clutter ratio) the noise or clutter power level from the appropriate range and Doppler on Fig. 11(a) must be divided into the signal power from Fig. 11(b). Performance is a decided function of target location in Doppler range space as well as power received from the target.

sea–land boundaries, or mountains or cities on land, these can be used to determine the correspondence between the virtual and ground range. If the radar has directive beams that can be readily steered in elevation, ground ranges can be associated with virtual ranges and ionospheric heights can be deduced. The earth echo provides a signal of sufficient quality to be used for automatic analysis of the transmission path. Even if the radar has no elevation angle control and there are nc identifiable ground targets, the earth backscatter can still be useful in confirming estimates of the transmission path made by other means. The earth backscatter amplitude as a function of virtual range may not uniquely define the propagation path but it can be used to test the correctness of a particular assessment of the path. If the predicted backscatter distribution is similar to that observed, it gives confidence that the assessment is correct. Fig. 11 gives an example of performance assessment that has been deduced from an operating radar's earth (sea) echoes [6].

Radar performance depends on the geographical location. When the refracting part of the ionospheric path is in an auroral region, path losses and instabilities can be great. Even when the propagation path does not traverse the aurora, unwanted echoes from aurora and other intense sources of field-aligned ionization can obscure targets by entering the radar via the antenna sidelobes.

Furthermore, OTH radar capability abruptly changes across the transition from one-hop to two-hop coverage. These transitions are somewhat variable with both time and location and nominally they are 2000–2200 km via the E region and 3000–4000 km via the F region. Thus when performance out to 4000 km is required, part of the time it must be achieved by a two-hop path.

IV. Capabilities

A complete and detailed description of the capabilities of OTH radar cannot be fully discussed in a paper of this scope. Nevertheless, it is possible to indicate the following nominal performance characteristics that might be achieved:

range coverage	1000–4000 km; longer ranges are possible with multihop propagation, but with degraded performance;
angle coverage	can be 360° in azimuth, if desired; 60°–120° is more typical;
targets	aircraft and ships; also nuclear explosions, prominent surface features (such as mountains, cities, and islands), sea, aurora, meteors, and satellites below the ionosphere's altitude of maximum ionization;
range resolution	could be as low as 2 km, but is more typically 20–40 km;
relative range accuracy	typically 2–4 km for a target location relative to a known location observed by the same radar;
absolute range accuracy	10–20 km, assuming good real-time path assessments are made;
angle resolution	determined by the beamwidth; it can be less than 1° which corresponds to 50 km at a distance of 3000 km;
angle accuracy	beam splitting of 1–10 should be possible with sufficient SNR; ionospheric effects might limit the angle measurement accuracy to some fraction of a degree;
Doppler resolution	resolution of targets whose Doppler frequencies differ by 0.1 Hz or less is generally possible; at a radar frequency of 20 MHz, 0.1 Hz corresponds to a difference in relative velocity of about 1.5 knots.

V. Applications

The order of magnitude increase in range possible with an HF OTH radar as compared with conventional radar makes it attractive for those geographical areas where it is not convenient to locate conventional microwave line-of-sight radars. Radar coverage of the sea is such an example. By way of illustration, two applications will be briefly mentioned:

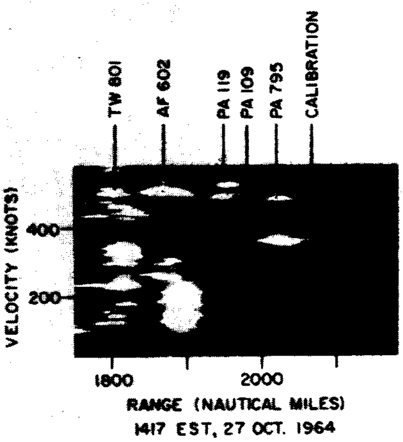


Fig. 12. Transatlantic aircraft targets on a Doppler-range display. In this example a clutter filter has been used to reject relative velocities up to about 100 knots, and approach and recede targets have been folded upon each other so that direction is not obtained. The vertical smears are meteor trail formation echoes. They persist but a short time. The aircraft echoes have been identified with flight information furnished by the FAA.

1) air-traffic control over the sea; and 2) the remote observation of sea conditions and the accompanying weather. Other applications are certainly possible.

1) Air-Traffic Control: An OTH radar with 120° angle coverage and a range coverage from 1000–4000 km can survey an area of almost sixteen million square kilometers. Aircraft within this area can be detected, located, and tracked by such a radar.

Fig. 12 shows a range-Doppler display of aircraft targets flying the North Atlantic air corridor between the United States and the United Kingdom. These data were taken with the MADRE radar. The azimuth measurement accuracy of this radar is not sufficient to track in angle, but excellent Doppler resolution permits targets to be separated in the frequency domain and measured in range. Fig. 13 is a plot of the ranges of these targets as measured by the radar (shown by the circle points) compared with the aircraft tracks (straight lines) obtained from the FAA. The agreement is quite good. Fig. 14 shows a Doppler-range display of aircraft targets made with the smaller MADRE rotatable antenna (see Fig. 4) looking West. Note how this radar is able to resolve in the Doppler domain targets that are unresolved in range alone.

Target height is not obtained with this OTH radar. It is possible to install HF transponders on each aircraft and relay back to the radar the height of the aircraft as determined by the on-board altimeter, as well as the identity of the aircraft. Limited communications can also be effected by this means.

An example of the possible OTH coverage of the North Atlantic air lanes is shown in Fig. 15 for two arbitrary radar sites.

Thus OTH radar offers a new capability for improving the safety and quality of over-ocean air traffic.

2) Remote Sensing of Sea Conditions: The extent of the Doppler frequency spectrum of the sea or land clutter is much less than the Doppler shifts expected from aircraft. Hence to separate aircraft echoes from sea or land echoes, the low-frequency portion of the spectrum is filtered out and only that region is passed in which aircraft or missile targets are expected. The lower portion of the spectrum that is filtered out, however, contains significant information about the nature of

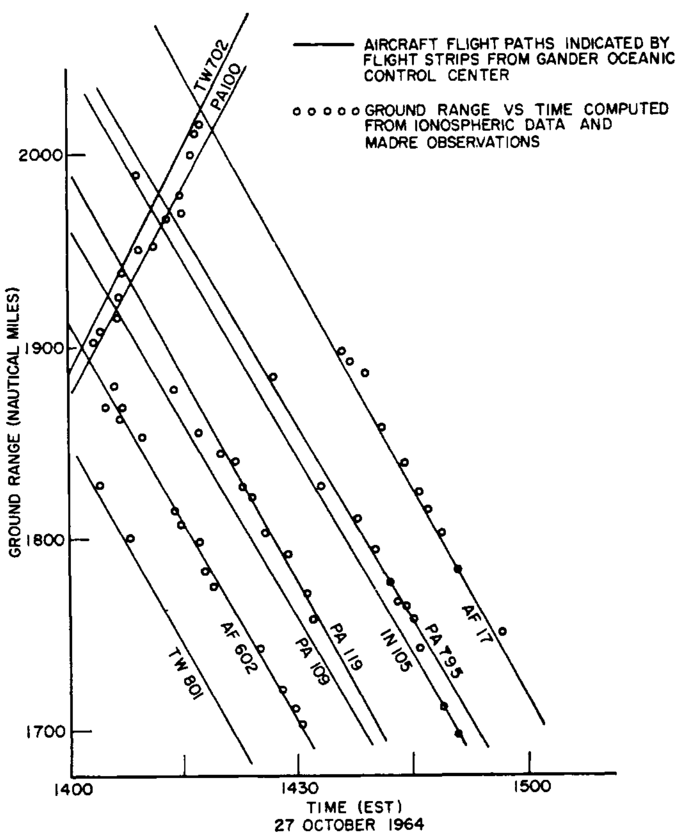


Fig. 13. FAA flight paths compared with radar data for a 1-h period.

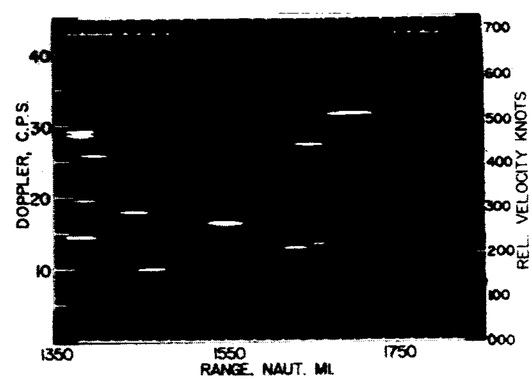


Fig. 14. A Doppler range of aircraft targets to the west of the MADRE site. Among the targets there is quite a spread in relative velocity. Notice that multiple targets at the same range are readily resolved by Doppler discrimination.

the clutter. Fig. 16 shows an example of the spectrum of the sea echo. Such spectra can be interpreted to give sea roughness and direction. Ionospheric effects, especially multipath, cause complications. Nevertheless, it has been possible to determine the direction of the waves, to estimate their magnitude, and to infer something about the winds that drive the waves. An example of radar derived wind direction is given in Fig. 17 [7]. Other papers in this issue of PROCEEDINGS treat this subject [8], [9].

VI. Ground-Wave Radar

Almost all of the preceding has been concerned with an OTH radar that utilizes the refractive properties of ionospheric sky-wave propagation to reach out and detect targets

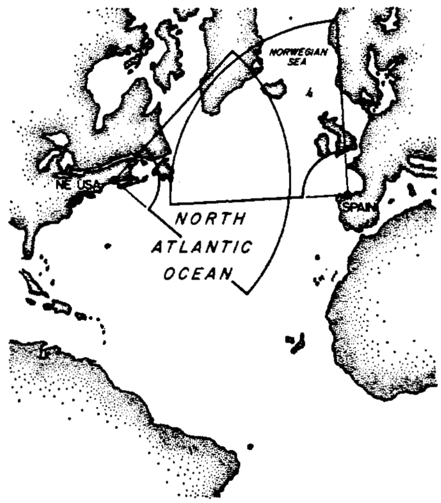


Fig. 15. Possible OTH radar coverage of the North Atlantic from radar locations in northeastern USA and northern Spain.

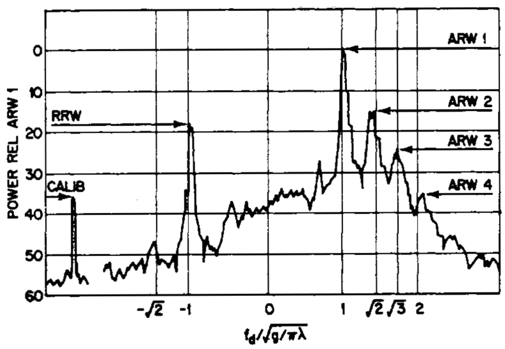


Fig. 16. A spectrum of the radar echo from the sea obtained from an area about 9.5 by 7.5 km via ground wave. The sea was developed by a 25-knot approaching wind and the operating frequency was 13.4 MHz. The Doppler f_d scale has been normalized so that the major returns occur at ± 1. The major returns are the Approach Resonant Wave ARW 1 and Recede Resonant Wave RRW. The difference in amplitude between ARW 1 and RRW can be used to calculate the sea (and exciting wind) direction. The amplitude of the other peaks, ARW 2, ARW 3, ARW 4, and of the continuum between peaks can be used to indicate sea state (or driving wind speed).

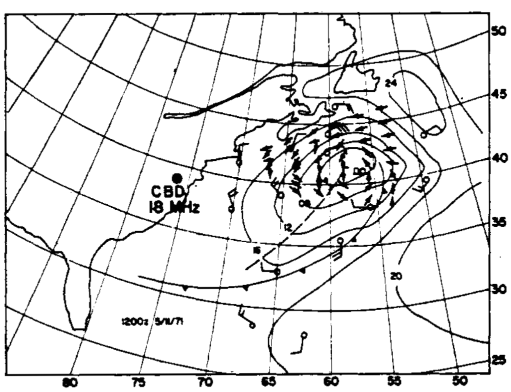


Fig. 17. Radar-derived wind direction has been plotted on a standard surface weather map in order to effect a comparison. The radar data are in good agreement with the weather map. The radar data can be obtained with a high density over the sea area surveyed.

beyond the horizon. It is also possible at HF to propagate energy around the curvature of the earth by diffraction. This is commonly called ground-wave propagation. The loss beyond the horizon in this ground-wave mode increases exponentially with range. Also the higher the frequency the greater the loss. A ground-wave radar can detect the same kind of targets as discussed for the sky-wave radar. Detection is somewhat easier than with sky-wave propagation since ionospheric effects are not present as they are with the sky-wave radar, and clutter returns from aurora can generally be eliminated by time gating. Furthermore, at night it may be possible to operate a ground-wave radar at a frequency too high for sky-wave transmission so that interference from distant sources that would normally propagate by sky wave is not present.

A ground-wave radar of a size and frequency comparable to the sky-wave radar discussed in this paper might have a range against aircraft targets of perhaps 200–400 km. Thus its capability is far less than that of the sky-wave radar. Detections are generally easier, for the reasons previously cited, but the ground-wave radar might not prove cost effective for general use. Unfortunately, the maximum range of ground-wave radar is considerably less than the minimum range of the sky-wave radar unless the sky-wave radar can operate at frequencies down to the broadcast band. However, the antenna dimensions would become large, and many targets of interest would certainly be in the Rayleigh scattering region where the cross section would be small. Thus it is impractical for ground-wave radar to fill in the skip zone of the sky-wave radar.

VII. Discussion

OTH radar offers a new and exciting means for sensing the environment and the detection of targets at distances an order of magnitude greater than conventional microwave radar. The technology has been developed and the capabilities demonstrated. The cost of the HF OTH radar might be expected to be high, but on the basis of cost per square mile of coverage it is probably comparable to other radar types. Its chief advantage is that it can cover areas not feasible with conventional radars.

VIII. Note

In the United States, significant work on OTH radar using HF frequencies and both ground-wave and sky-wave propagation started in the late 1940's. The organizations engaged in this early work included the Watson Laboratories of the Army Air Force, the Lincoln Laboratory of the Massachusetts Institute of Technology, the National Bureau of Standards, the Raytheon Company, RCA, and Stanford University. In the early 1950's, the Naval Research Laboratory started a program to demonstrate the feasibility of sky-wave radar for aircraft targets. Later many other groups have significantly contributed to the advancement of HF OTH technology.

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Sea Backscatter at HF: Interpretation and Utilization of the Echo

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***Abstract*—Theories and concepts for utilization of HF sea echo are compared and tested against surface-wave measurements made from San Clemente Island in the Pacific in a joint NRL/ITS/NOAA experiment. The use of first-order sea echo as a reference target for calibration of HF over-the-horizon radars is established. Features of the higher order Doppler spectrum can be employed to deduce the principal parameters of the wave-height directional spectrum (i.e., sea state); and it is shown that significant wave height can be read from the spectral records. Finally, it is shown that surface currents and current (depth) gradients can be inferred from the same Doppler sea-echo records.**

I. Introduction

TWENTY YEARS ago Crombie [1] observed sea echo with an HF radar, and he correctly deduced the scattering mechanism which accounted for the peculiar and unique dominant peaks in the observed Doppler spectrum. This gave rise to further research and suggested the exciting possibility of measuring sea state at great distances with HF sky-wave radars. A current joint program involving NOAA, NRL, and ITS on San Clemente Island has provided data for testing three possible applications of HF sea echo: 1) as a standard or reference target for calibrating the sensitivity of sky-wave radars; 2) as a means of deducing sea state (viz., the dominant features of the wave-height directional spectrum); and 3) as a method for measuring surface-current features. HF, as considered here, extends from the broadcast band to VHF, including radar wavelengths between 10 and 200 m.

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Although the heights of ocean waves are generally small in terms of these radar wavelengths, the scattered echo is nonetheless surprisingly large and readily interpretable in terms of its Doppler features. The fact that these heights are small facilitates the analysis of scatter using the perturbation approximation. This theory [2] produces an equation which 1) agrees with the scattering mechanism deduced by Crombie from experimental data; 2) properly predicts the positions of the dominant Doppler peaks; 3) shows how the dominant echo magnitude is related to the sea wave height; and 4) permits an explanation of some of the less dominant, more complex features of the sea echo through retention and use of the higher order terms in the perturbation analysis. Hence the dominant spectral features explained by the simple, lowest order terms of the perturbation analysis are referred to as "first-order" sea echo, while the remaining, less dominant features are termed "higher order" because they arise from the smaller (i.e., second-order, third-order, etc.) terms.

By way of introduction to the basic type of HF echo records upon which the discussion in this paper is based, we show a typical received Doppler spectrum in Fig. 1. This plot represents the received signal power versus normalized Doppler shift from the carrier (the carrier being located at zero, and the predicted positions of the dominant peaks at positions ± 1). Details of the conditions and system behind this spectral record will be discussed later, but for now we refer to it to illustrate how the three previously claimed applications will be subsequently developed from data such as these. 1) The dominant, first-order peak (near $+1$) will be tested for use as a standard or reference echo. 2) The higher order Doppler features (i.e., their shapes, peak positions, and amplitudes) will be used to deduce sea state. 3) The overall shift of the first-order echo peaks from ± 1 will be used to deduce

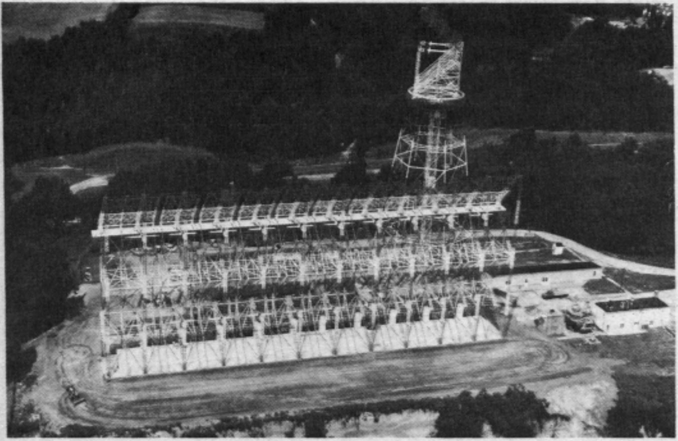
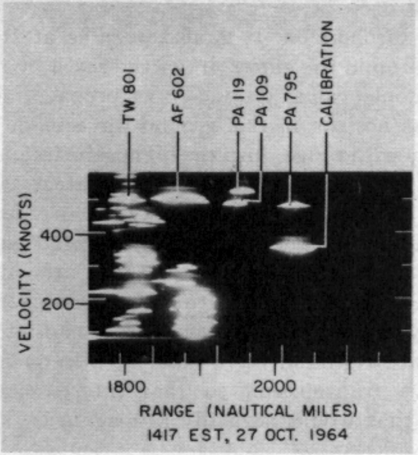


Fig. 4. MADRE OTH radar located at the Chesapeake Bay field site of the Naval Research Laboratory. The auxiliary rotatable antenna located above and behind the main planar antenna is used for experiments in directions not within the coverage of the main antenna.



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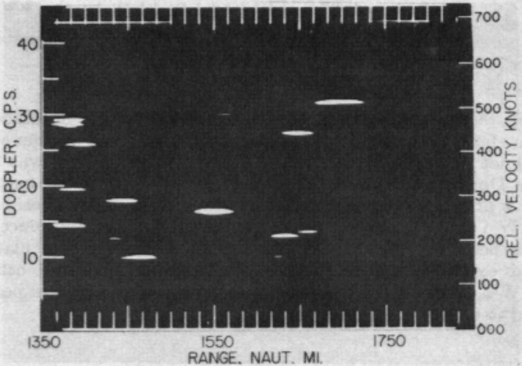

Fig. 14. A Doppler range of aircraft targets to the west of the MADRE site. Among the targets there is quite a spread in relative velocity. Notice that multiple targets at the same range are readily resolved by Doppler discrimination.