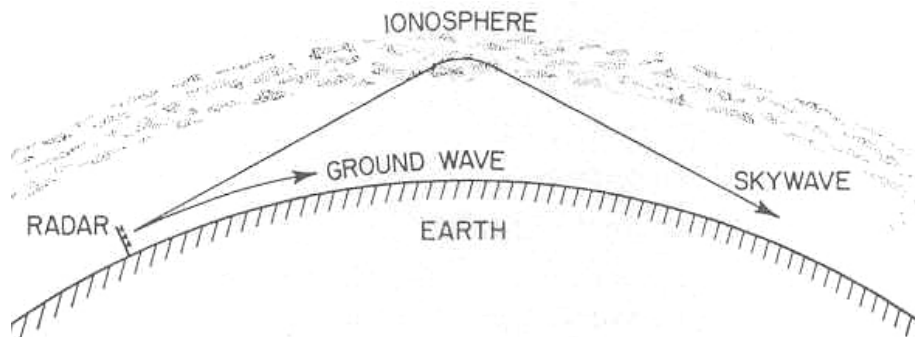


Some historical aspects of HF Band Radars

by Hans H. Jucker, June 2004

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.

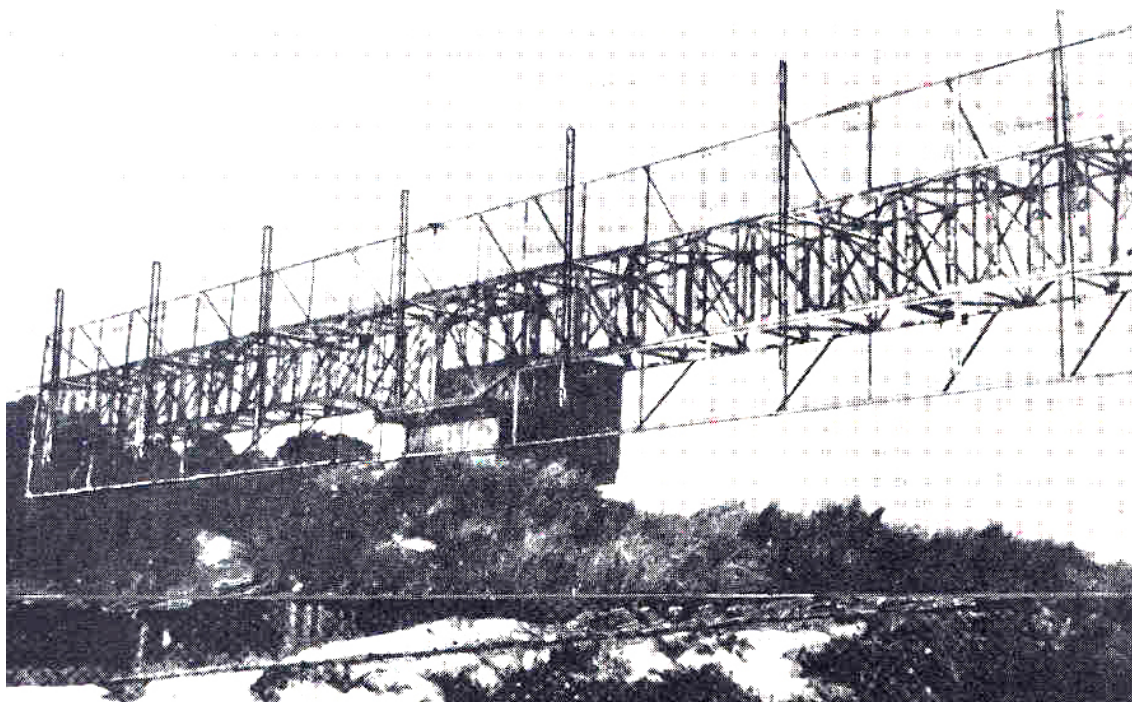


The range of ground wave HF radars typically might be of the order of 200 – 400 km, and the coverage of a sky wave radar might extend from a minimum of 1000 km to perhaps 4000 km or more. The HF over the horizon (OTH) radar can extend the 400 km range typical of a ground based air surveillance radar 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 radars and include aircrafts, missiles, and ships. The long wavelengths characteristic of HF radar also provides a means for gathering information about the sea and land, as well as aurora and meteors.

Experiments with HF radars began in Germany early in WWII. The German **"Reichspost-Zentralamt"** was in charge for that program with the codename **Heidelberg Versuche**

The picture shows an antenna system as used for the early "Heidelberg" Experiments



Later in war few tactical systems with the codename **"Elefant"** were installed at different geographical locations. The table below shows some parameter of the German HF radar experimental systems. **(Dr. W. Stepp, Dissertation T.H. Darmstadt 12. Juli 1946)**

	Sender			Empfänger			Antenne				Gesamtanlage		
	λ	N_s	τ	v_{KT}	b	N_{gr}	F	$n_u \times n_v$	$\frac{\sigma}{G}$	h_r	K^4	K	
	m	Watt	sec	Watt/Hz	Hz	Watt	qm			m	m^4	m	
		10^3	10^{-6}	$4 \cdot 10^{-21}$	10^6	10^{-14}					10^{20}	10^5	
1a	20↑	300	70	150	9,7	6	1600	8.2	f	20	128 000	18,9	} Heidelberg
1b	13↑	300	70	75	9,7	3	690	8.2	f	20	47500	14,8	
1c	13→	300	70	75	9,7	3	690	8.2	f	20	47500	14,8	

The antenna and receiver of the HF radar installations were in certain cases also used for the semiactive **"Klein Heidelberg"** radar procedure. The text below is copied from a report of a CIOS/BIOS mission at the end of WWII:

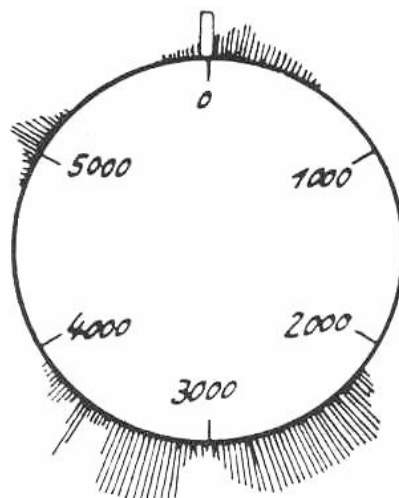
Visit of a German Elefant radar site

The enemy had originally intended to use the receiver system of the Elefant installation for Heidelberg (tracking of enemy aircraft by using the reflected signals from aircraft originating from British C.H. Stations).

However, the system was found to be inaccurate because it was not possible to receive a direct signal from the C.H. Station in order to trigger the Heidelberg equipment, owing to the fact that the ionosphere pulse was more strongly received than the ground array. The Elefant transmitting array consisted of a number of horizontally polarised wide band wire cage aerials mounted on a tower about 250 ft. high. This system also served as the receiving antenna for the range receiver. The D/F receiver was situated about a mile away on a pivoted tower about 200 ft. high and was of much the same type. D/F was obtained by maximum reading, the beam width being about 15° zero to zero. The system was essentially for early warning, the pulse length being 10 microseconds. The Elefant frequency could be easily altered from 25 to 40 MHz.

According to Dr. phys. Dieminger **(W. Dieminger, Proceedings of Physics Society B64/142, 1951)** it was occasionally the experiments realized, that if aircraft targets of interest were to be seen the extremely large undesired clutter echo returned from the ground had to be suppressed relative to the target signal.

The figure shows the typical circular range scope of the German WWII HF Radar experiments operating at 10 m wavelength, with the strong backscatter echoes from the ground.



For example, the echo from the ground might easily be 40 – 60 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 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 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 1½ km. Even with such range and angular resolution, ground or sea clutter at a distance of 1000 km can be a target easily as large as 10⁵ m². Doppler processing is thus clearly needed in an HF radar to detect aircraft targets with a typical radar cross sections of 1 - 10 m².

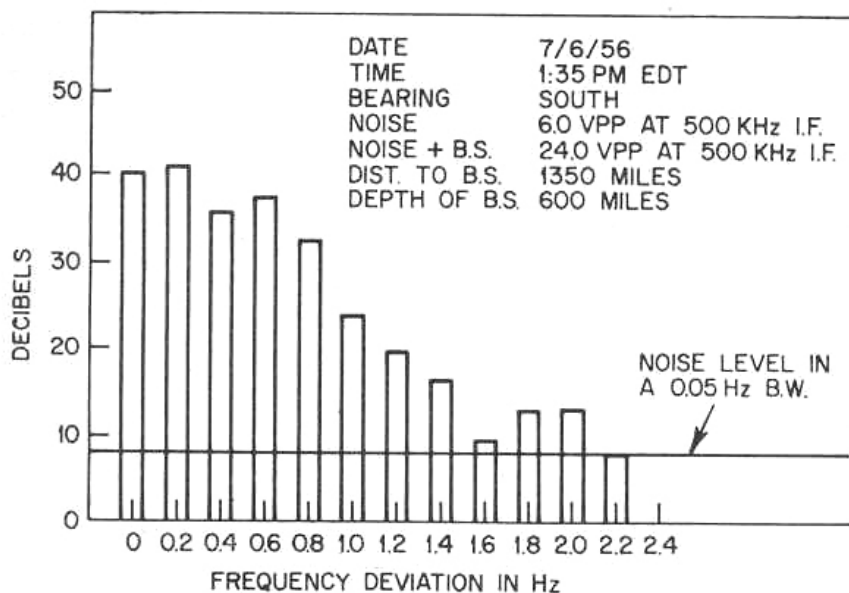
However, an advanced Doppler processing technique did not exist in the early 1940's, so according to Dr. phys. Dieminger, the German HF Radar experiments weren't very successful! (Frankfurter Fachtagung 1953, Die Bedeutung der Rückstreuung von Erde und Ionosphäre in der Funkortung). The obtained results, were a valuable base for the post-war research in the United States. (**W. Stepp's Dissertation T.H. Darmstadt 1946**).

Experiments with HF radars began in the **United States at the Naval Research Laboratory (NRL)** early in the 1950's. The NRL could take advantage from the exploitation of the German experiments, collected by the Combined Intelligence Objectives (CIOS) at the end of WWII. In 1956 the NRL 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_c is given by the relation

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

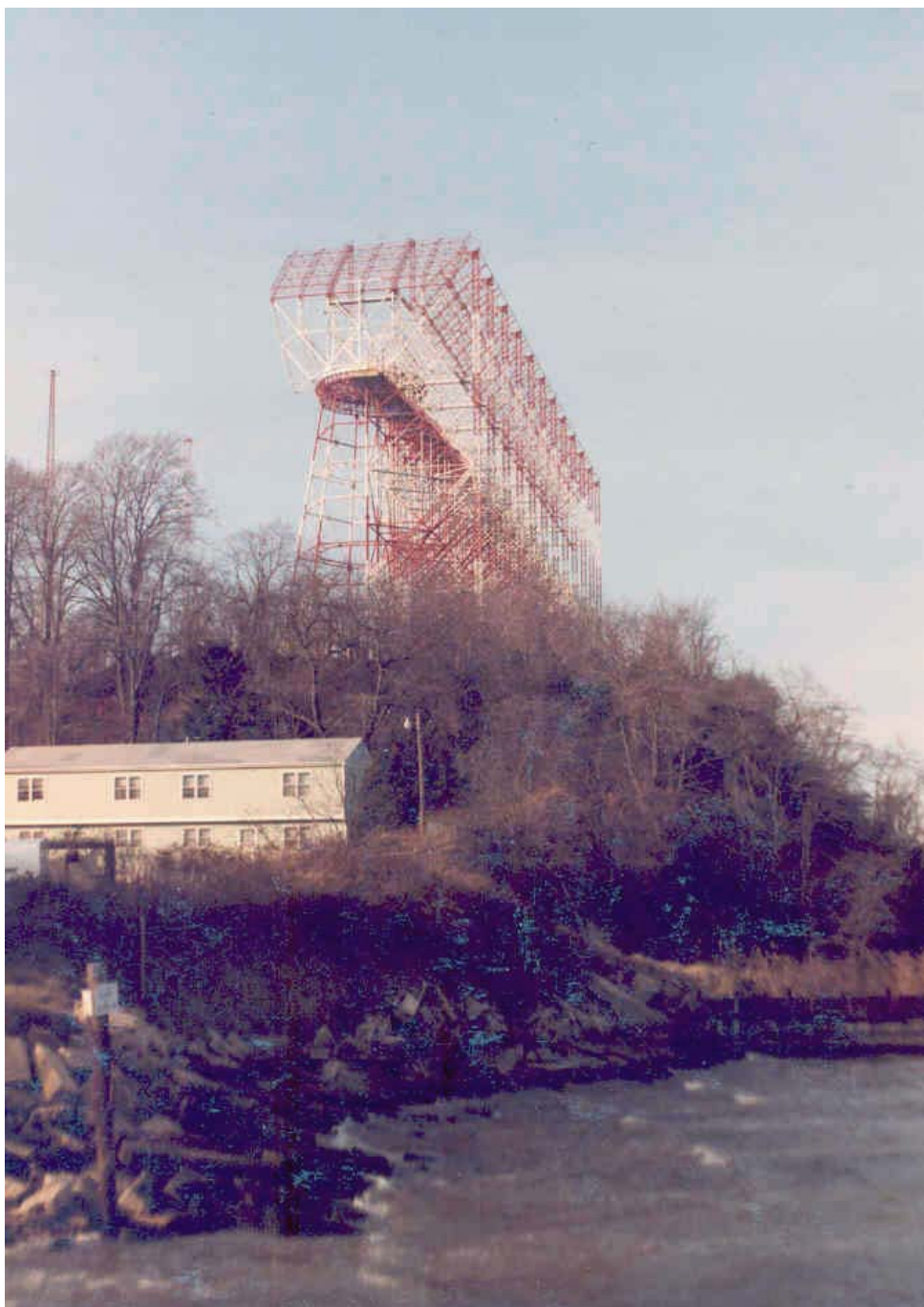
where V_r is the target relative velocity and c is the velocity of light. For aircraft targets f_d was generally a very well defined frequency in the slightly above 0 - 50 Hz range. Second, one way sky wave paths had been measured to be frequency stable at least for the order of seconds. The conclusive 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.

A typical earth backscatter energy distribution showing the distribution of the backscattered energy and also the frequency at which this energy has discriminated to a level of the noise in the 0.05 Hz bandwidth.



The figure taken from an early NRL 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.

The Naval Research Laboratory HF Radar Experimental site at Cheasapeake City MD is shown in this photography. The antenna is 98 meter wide by 43 meter high and consists of twenty corner reflector elements arranged in two rows of ten elements each. The beam is steered $\pm 30^\circ$ in azimuth with mechanical actuated line stretchers. This experimental radar has been operated with average powers of 5 – 50 kW. The photography was shut occasionally my visit in the early 1980's.



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 receiver and in the signal processors. The NRL 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 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, and digital processing. The signal processor has been the key element in the success achieved with OTH radar.

Capabilities

The NRL trials in the early 1960's indicated the following nominal performance characteristics:

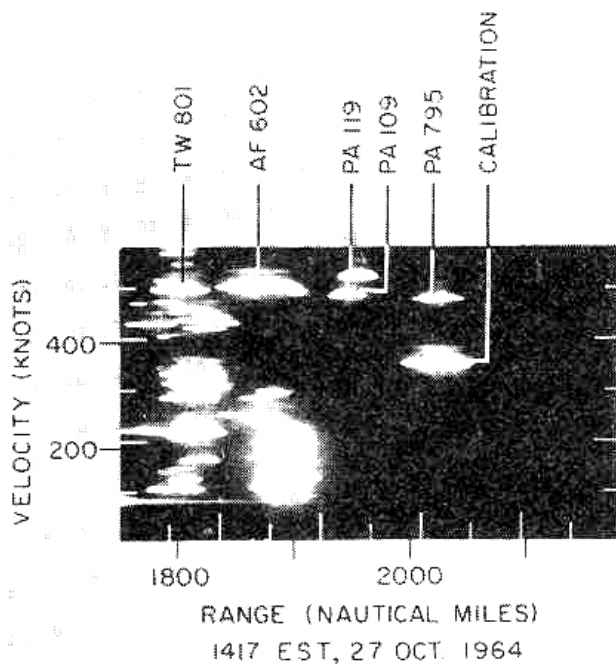
Range coverage:	1000 - 4000 km; longer ranges are possible with multi-hop propagation, but with degraded performance
Angle coverage:	can be 360° in azimuth, if desired; 60° - 120° is typical
Targets:	aircraft and ships; also nuclear explosions, prominent surface features such as mountains, cities, and 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 typical 20 - 40 km
Relative range accuracy:	typically 2 -4 km for a target location relative to a known location observed at the same radar
Absolute range accuracy:	10 -20 km, assuming good realtime 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

Applications

The order of magnitude increases 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 at sea is such an example. By way of illustration, two applications will be briefly mentioned:

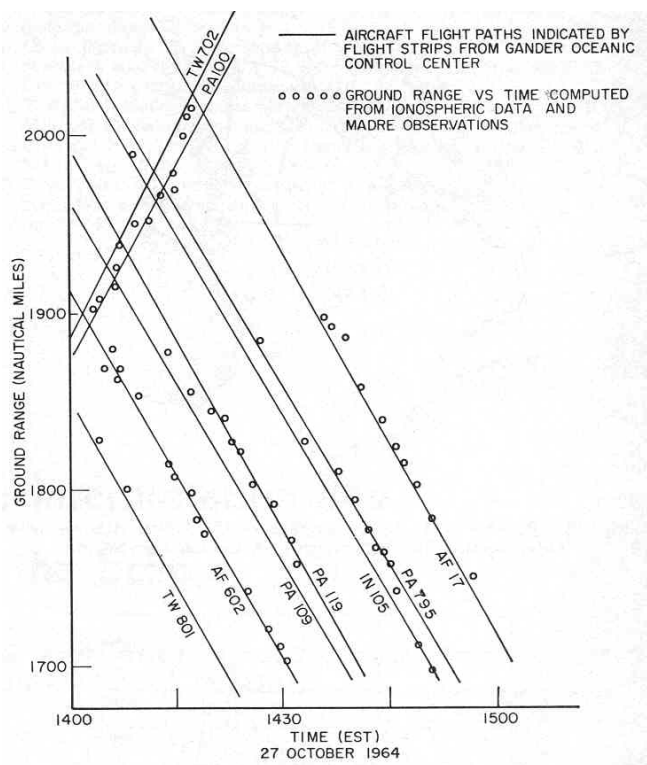
- 1. Air Traffic Control:** An OTH radar with 120° angle coverage and a range of 1000 -4000 km can survey an area of almost sixteen million square kilometres. Aircrafts within this area can be detected, located, and tracked by such a radar.

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 identified with flight information furnished by the FAA.

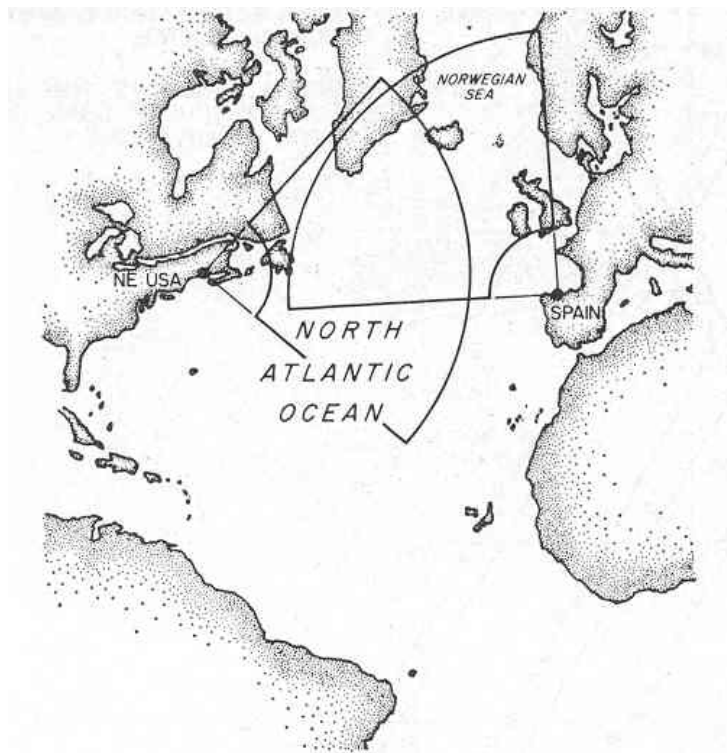


The figure shows a range Doppler display of targets flying the North Atlantic air corridor between the United States and the United Kingdom. These data were taken with the NRL HF radar located at Chesapeake City MD. The azimuth measurement accuracy of this radar is not sufficient to track in angle, but excellent Doppler resolution permits targets to be separated in the frequency domain and measured in range. Target height is not obtained with this OTH radar. The figure below shows 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 by the FAA. The agreement is quite good.

FAA flight paths compared with radar data for 1 h period

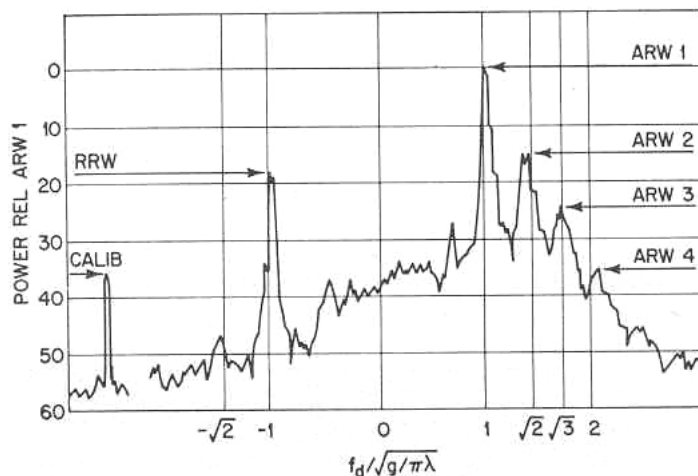


An example of the possible OTH coverage of the North Atlantic air lanes is shown in the figure below for two arbitrary radar sites.



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 the clutter. Such spectra can be interpreted to give sea roughness and direction. Ionospheric effects, especially multi path, cause complications. Nevertheless, it has been possible to determine the direction of waves, to estimate their magnitude, and to infer something about the wind that drive the waves.

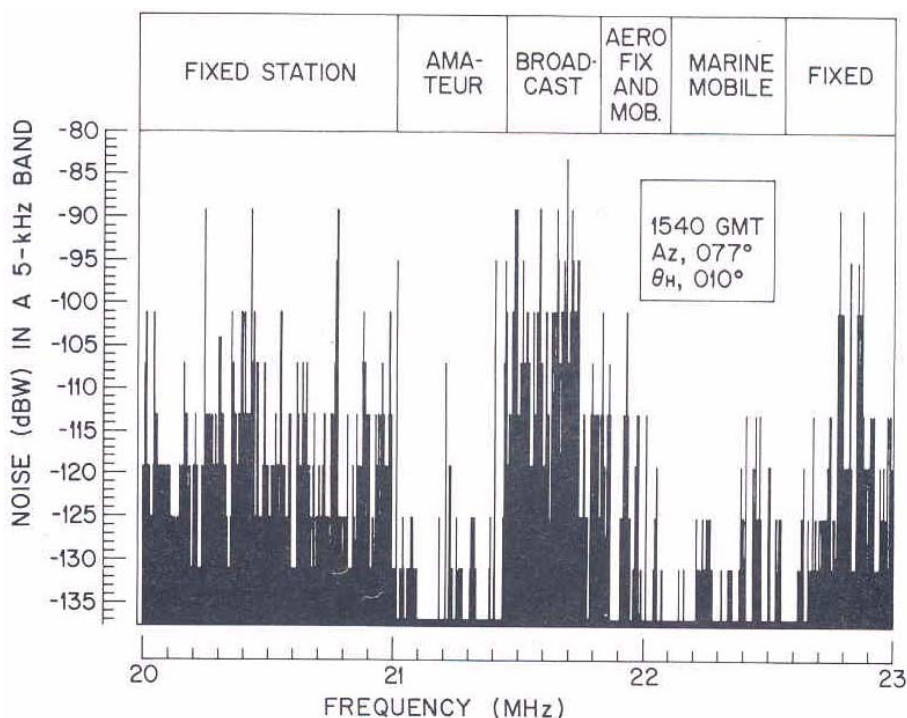
The figure shows a spectrum of the radar echo from the sea obtained from an area about 9.5 by 7.5 km via ground wave. The sea was developed by a 25 knot approaching wind and the operating frequency was 13.4 MHz. The Doppler f_d scale has been normalized so that the major returns occur at ± 1 . The major returns are the Approach Resonant Wave ARW1 and Recede Resonant Wave RRW. The difference in amplitude between ARW1 and RRW can be used to calculate the sea (and exiting wind) direction. The amplitude of the other peaks ARW2, ARW3, ARW4, and of the continuum between peaks can be used to indicate sea state (or driving wind speed)



Environmental Parameter

For effective OTH radar operation, environmental parameters need to be determined in real time; transmission path information must generally be derived from adjunct vertical and oblique sounders as well as by using the radar itself as a sounder. In addition, other users in the spectrum must be observed continuously and operating frequencies selected to avoid interference. The part of the spectrum that is useful for sky wave propagation is densely populated.

An example of spectrum occupancy shows the figure below, it examines one particular segment and time. These observations were made with 5 kHz bandwidth filters at the Chesapeake Radar site



References

- W. Dieminger, Die Bedeutung der Rückstreuung von Erde und Ionosphäre in der Funkortung, Ausschuss für Funkortung, Frankfurter Fachtagung 1953
- W. Dieminger, Proceedings of Physical Society, Volume 64, 142, 1951
- W. Stepp, Ueber die Reichweite drahtloser Anlagen, insbesondere von Funkmessanlagen im Wellengebiet von 1 cm bis 20 m, Dissertation T.H. Darmstadt 12. Juli 1946
- W. Stepp, Physikalische Grundlagen der Funkmessortung, Ausschuss für Funkortung, Hamburger Fachtagung 1952
- J. M. Headrick Over The Horizon Radar in the HF Band, Proceedings of the IEEE, Special Issue on modern radar technology, June 1974
- J.M. Headrick HF Over The Horizon Radar, Radar Handbook, Second Edition 1990

Radar Cross Section vs. "Ersatzdipolzahl"

It is an interesting detail how the quantification of the radar back scatter phenomena was defined in Germany during WWII.

It was chosen to be the scattering power of an optimally oriented, shorted, resonant dipole. A backscattering body can therefore be characterized by a dimensionless number z called "Ersatzdipolzahl" which simply means that the body produces z -times the field intensity compared to that which a dipole would produce at the same distance.

It seems that some practical experiments were undertaken at the Baltic Sea for establishing a comparison between the "Ersatzdipolzahl" z and the radar cross section of different real radar targets.

W. Stepp is describing the relation "Ersatzdipolzahl" z vs. the radar cross section of a shorted resonant dipole as:

$$z = \frac{4 \pi}{9} \frac{\text{RCS}}{\lambda^2}$$

David Barton, R.E. Kell and R.A. Ross are describing the RCS of a shorted resonant dipole as:

$$\text{RCS} = 0.88 \lambda^2$$

The figure shows the "Ersatzdipolzahl" of the German JU52 aircraft vs. wavelength for vertical and horizontal polarization

