Seeing Beyond:
Over the Horizon Radar Systems and HF Propagation

ECE-5635: Radar System Design

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Introduction

Radar (RAdio Detection And Ranging) is a system by which electromagnetic waves are used to locate targets and determine target characteristics such as elevation, range, speed, azimuth, and size. Radar does this with greater accuracy, flexibility, and range than optical techniques, and thus has great applicability in a wide variety of situations. Most radars that operate today utilize frequencies greater than 300 MHz; however, it is sometimes desirable to have a system that operates in the high frequency (HF) band. This paper examines the history, theory, and current usage of HF radar systems.

History

Many advances had taken place since radio was first discovered in the late ninetheenth century, and radar took full advantage of these developments. Many radio communications systems in the 1920s and 1930s operated using HF equipment. The HF band is the range of radio frequency that extends from 3 to 30 MHz that became a viable method of worldwide communication at this time. This is because HF waves can travel beyond the horizon due to reflection and refraction from the ionosphere, a region of ionized gas in the upper atmosphere. This method of communication was less expensive and easier to deploy than long distance telegraph cables, and therefore became widespread in usage. HF radio equipement and parts became readily available, which engineers adapted for use in early radar designs.

Numerous countries had radar development programs during the early twentieth century, including the United States and the United Kingdom. Many of the original radar designs operated in the HF range. In the United States, radar development was initially conducted at the Naval Research Laboratory. Albert Taylor and Leo Young began working on radar design in 1922 during routine communication experiments. Robert Page and Leo Young furthered radar technology by developing pulse radar, which was demonstrated in 1934. Pulse radar operates by transmitting all the energy of the signal in a short pulse, which increases the strength of target reflections. Stronger reflected signals increase the probability of signal detection above naturally occurring white noise.

In the United Kingdom, Robert Watson-Watt was the early innovator of radar. Watt, an established figure in the area of radio communications, was approached by the Air Ministry to develop a death ray out of radio waves. Watt's initial work demonstrated that a RF death ray was not feasible, but suggested the possibility of RF target detection. The Air Ministry then funded Watt and his assistant, Arnold Wilkins. They successfully demonstrated radar in February 1935 with the Daventry Experiment. Watts and Wilkins used a receiver to detect a 6 MHz BBC signal reflected by a passing airplane. As a result of this experiment and the growing threat of German air attacks on Great Britain, Watts led the development of the Chain Home system to detect the German airplanes. The Chain Home system was a series of HF radars placed on the eastern and southern coasts of Britain; its success thoroughly proved the usefulness of HF radar systems.

In 1949, engineers in the Soviet Union developed a system based off of long distance HF radio propagation. This system, known as Over the Horizon (OTH) radar, allowed for the detection of targets at long ranges. The OTH radars were built to track missile launches between the USSR and the USA. A prototype was successfully constructed in 1949, called the Veyer; however, little more was done in the USSR until the 1970s. Starting in the 1950s, the US also had an active OTH radar research program This was led by Dr. William Thaler of the NRL. He supervised the first successful American prototype, MUSIC (Multiple Storage, Integration, and Correlation), in 1955. It was improved upon and through the development of MADRE (Magnetic-Drum Radar Equipment) in 1961. Additional radars include the Russian Steel Yard OTH radar created in 1976, which caused noticeable amounts of interference for ham radio operators in the US, who nicknamed it the Russian Woodpecker. Development picked up in earnest in the early 90's, but with the fall of the Soviet Union there was little need to detect missile launches from long range. Even so, HF radar still has applications in national defense, in addition to scientific research and law enforcement.

HF Propagation

While history is important to understanding where HF radar came from, knowledge of the underlying physics is required to actually design and operate OTH radar. The underlying propagation processes and interactions are what make HF signals different than other forms of EM propagation, and in some cases, much more desirable. The signals can propagate long distances, even over the horizon as a result of these processes. In modern day systems, these distances range from about 1000 to 3000 km [Colegrove, 2000; Greenwald, et al., 1995]. Various names have been given to this type of propagation, including ionospheric skip, sky wave, and multi-hop propagation [Lusis, 1983]. Figure 1 illustrates this type of propagation.

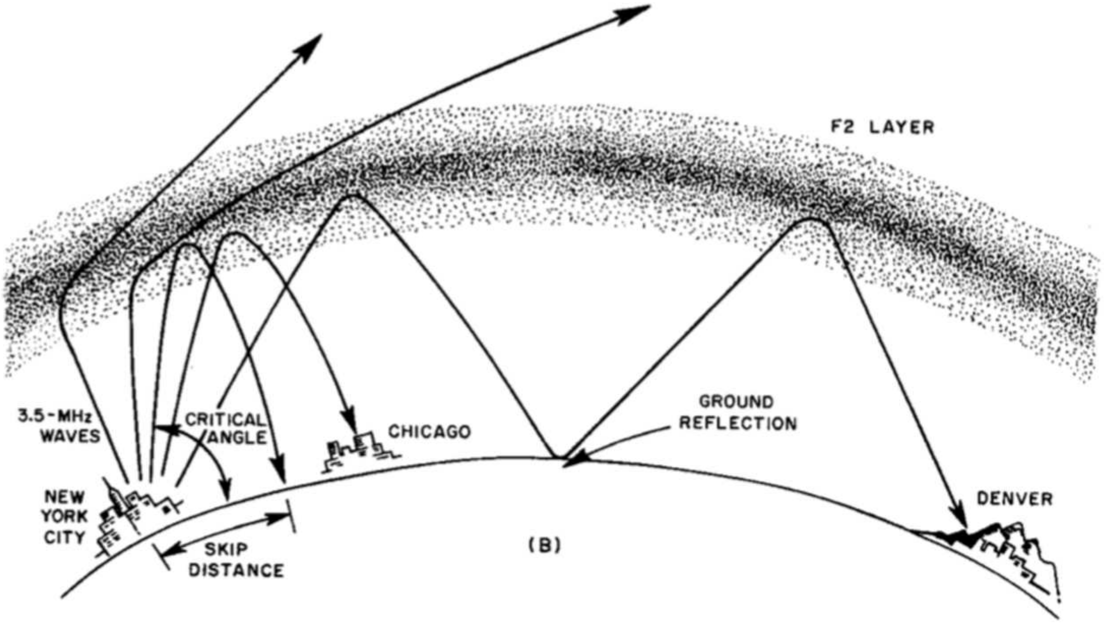

Figure 1: Effect of Incident Angle on Refractivity of the Ionosphere on HF Waves [Lusis, 1983]

The ionosphere is a region of the upper atmosphere that contains charged particles. This region exists because ultra violet rays from the sun ionize atmospheric gases. HF propagation is heavily dependent upon the ionosphere because the ionosphere can bend radio waves back to earth, making sky wave propagation possible. It is important to note that the ionospheric effect on radio waves varies greatly depending on the frequency. Low frequencies, such as those below the HF band, tend to be absorbed by the ionosphere. Frequencies above the HF band tend to cut through the ionosphere. [Lusis, 1983] Thus, OTH radar using sky wave propagation is only feasible using the HF band.

The ionosphere is a highly variable system, and its current conditions dramatically impact its ability to support HF sky wave propagation. The Maximum Usable Frequency (MUF) and Least Usable Frequency (LUF) characterize its variability. The MUF indicates the highest frequency that will be refracted back to Earth, while all frequencies below the LUF will be absorbed by the ionosphere. The MUF and LUF do not necessarily span the entire HF band; rather, it is common that only a portion of the band supports long-distance propagation at any given point in time or space. In general, both of these numbers increase with greater levels of ionization.

Numerous variations in ionospheric ionization level are observed because of ionization dependence on solar energy. The first is the diurnal, or day-night, variation. This creates a strong ionosphere during the day and a weak one at night. It also turns out that ionization is correlated with the number of visible sunspots, which are relatively small, dark regions on the sun's visible surface. Sunspots numbers increase and decrease in an eleven year solar cycle. [Lusis, 1983] Figure 2 illustrates this by plotting the sunspot number for most of the 20th century. In general, the ionosphere will support refraction of the highest possible frequencies during daytime hours in a period of solar maximum.

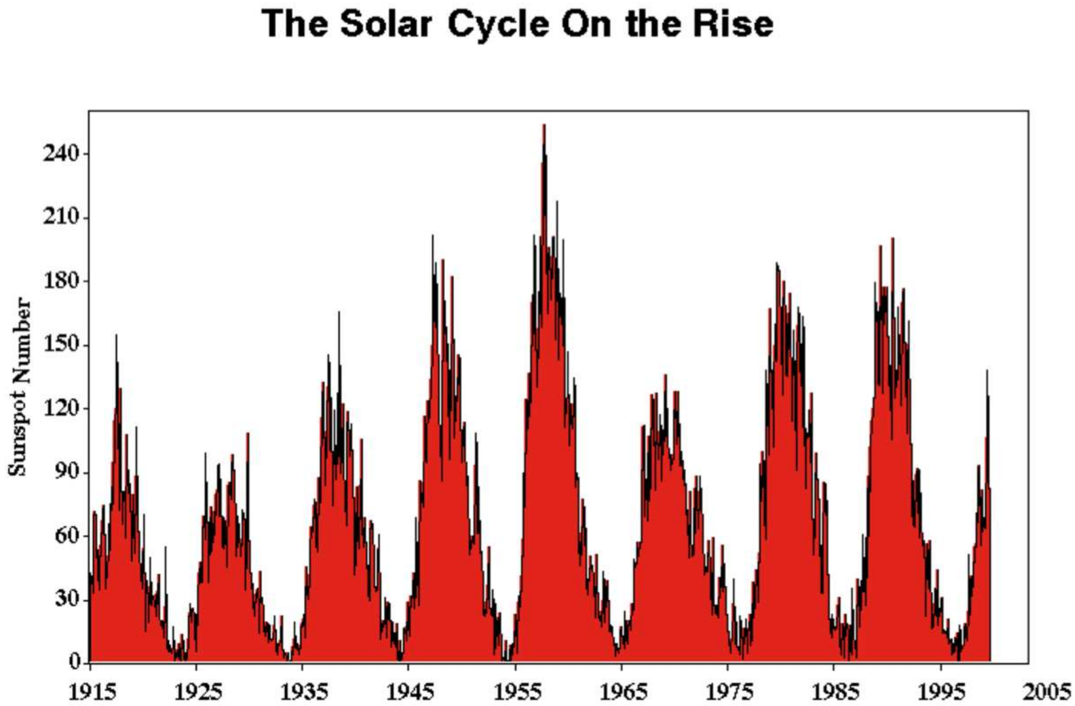

Figure 2: Sunspot numbers from 1915 -2000 [NASA SWPC - http://www.swpc.noaa.gov/Media/graphics/SolarCycle.gif]

Non-cyclical solar and space weather processes also affect HF propagation. Processes such as solar flares, coronal mass ejections (CMEs), coronal holes, and geomagnetic storms can disrupt HF propagation on earth. These events cannot be reliably predicted, and some of them disrupt propagation with no advanced warning.

Technical Considerations for Design and Operation of HF OTH Radars

When operating a radar, it is necessary to use a frequency that is optimal for current ionospheric conditions. Because of ionospheric variability, it is not possible to create a system that will have reliable range coverage. The range of an HF OTH radar may decrease from a long range of about 3000 km to tens of km in only a few minutes. Therefore, steps must be taken to adapt to constantly changing ionospheric conditions. In order to accomplish this, engineers design frequency agile HF radar systems. This allows operators to change the operation frequency based on current ionospheric conditions. Designing an antenna system that will operate over the entire HF band with features desirable for radar use is a difficult problem. This is because the system ideally should change from 10 meter wavelengths up to 100 meters. Due to such large wavelengths, physical steerability in the radar is not feasible; however, phased array implementation allows an electronically steered beam. Some modern systems, such as SuperDARN, restrict their operation to portions of the HF band and use phased array systems to as a compromise between cost, complexity, and usability [Greenwald, et al., 1995; Chisham, et al., 2000].

Engineers and operators need a method for determining the optimal frequency for radar operation for frequency agility to be useful. Frequency choice depends on ionospheric conditions, and thus radars require current information regarding the ionosphere. This information can be obtained in a number of ways. Numerous government, commercial, and scientific agencies measure ionospheric properties and create data products suitable for this application. Examples of such agencies include NASA and the Space Weather Prediction Center (SWPC). Ionospheric data can also be obtained by implementing measurement instruments as part of the radar system itself. The Jindalee radar in Australia uses this approach [Colegrove, 2000; Wise, 2004].

Two approaches exist for obtaining ionospheric measurements. The active approach involves radar soundings taken directly by a radar system. This approach provides good localized measurements. The passive approach involves receivers listening to natural white noise generated by the sun or a network of beacons with known frequencies, locations, and transmitting power levels. The 10.7 cm flux is a measure of radio noise at 2800 MHz. The amount of noise measured correlates with ionization, and therefore serves as an indicator of HF propagation. The Penticon Radio Observatory in British Columbia takes this measurement daily. It ranges in value from about 50 to 300, with higher numbers indicating more ionization [Poole, 2002]. Beacons provide excellent information regarding the quality of the propagation path between the beacon site and the measurement site. Some radar systems include beacon transmitters in their design.

Ionospheric modeling also serves as a tool in HF radar operation. Models accept inputs of current and past data on ionospheric conditions and provide outputs that predict propagation conditions for both current and future times and locations. Both statistical and physics based models exist.

Unwanted backscatter is another problem associated with HF OTH radar. Because of the nature of sky wave propagation, much of the backscatter received in an HF OTH radar system comes from ground reflections. By using a moving target indicator (MTI) technique, desired targets can be separated from undesired backscatter. Figure 3 illustrates this property. Target velocities colored gray indicate probable radar returns due to ground scatter reflection. Ground scatter return has both low Doppler shift and low spectral width, which is used as a criteria in computer analysis to automatically remove the returns.

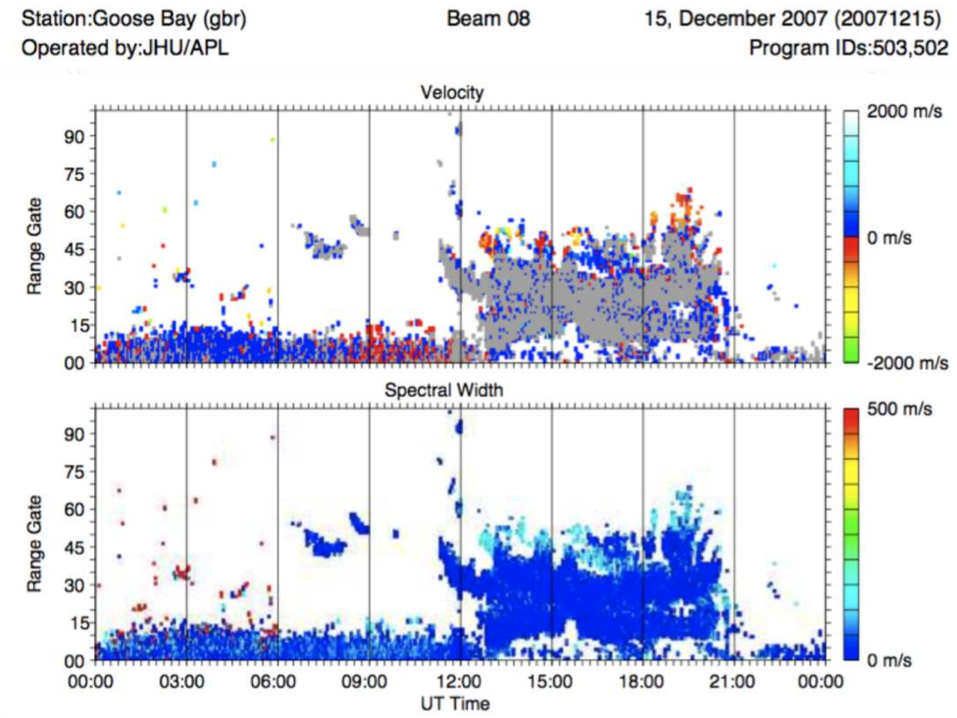

Figure 3: SuperDARN Data Showing Automatic Determination of Ground Scatter

Modern Implementations

The Jindalee radar is an OTH radar used for national defense along Australia's coastline. This radar is the result of a research project that began in 1974 due to the Cold War. Like most OTH radars used in defense scenarios, Jindalee is a bistatic radar. This is because Jindalee uses very large antenna systems and FMCW instead of pulse techniques, which would produce a high probability of interference between transmit and receive signals in a monostatic system. Transmit arrays are on the order of 400 m in length, while receive arrays are on the order of 3200 m in length. Jindalee is a frequency agile system, and incorporates a frequency management system (FMS) that measures ionospheric properties and selects appropriate operating frequencies. The FMS uses both active sounding techniques and passive beacon measurements to gather its data [Colegrove, 2000; Wise, 2004].

SuperDARN is a network of HF radars designed ionospheric convection for scientific research. The network consists of 21 radars, each pointed toward either the North or the South Pole. SuperDARN radars are coherent, and therefore require less power than the incoherent scatter radars that are used for ionospheric research. This network is frequency agile across a range of 8 to 20 MHz.

SuperDARN requires OTH radar for a number of reasons. First, it is desirable to take measurements across the largest area possible. OTH radar is the most cost effective means to accomplish this. Secondly, it is necessary to measure velocities in the highest regions of the ionosphere, the F region. This is because velocities of particles in the F region directly map to magnetic field line velocities, which is of great interest to space scientists. For geometric reasons, sky wave systems can make these measurements in the Polar Regions while line of sight systems cannot. [Greenwald, et al., 1995; Chisham, et al., 2007]

Conclusion

Over the horizon radar is a long range radar system that typically uses high frequency radio waves propagating using ionospheric skip. In order to effectively design and operate HF OTH radars, it is important to understand HF propagation and the variables that affect it. One variable, the condition of the ionosphere, is entirely outside of human control. Radars that are frequency agile across the HF band and sensitive to ionospheric variations can be effective in spite of highly variable conditions. OTH radar systems incorporating these techniques operate effectively today in both defensive and scientific roles.

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