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A study of sea surface influence on radar reflectivity of ships

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Abstract
A theoretical and numerical method is presented for the analysis of sea surface influence on the radar reflectivity of ships. The method of analysis is based on presentation of the field density scattered by the ship as a sum of echoes from different back Scatterers located on the surface of the ship. The influence of sea surface is accounted for under the physical optics assumption. An analytical expression is obtained for the propagation factor with the ship in line-of-sight (LOS) range. Plots are illustrated for the dependence of the propagation factor on ship range for different heights of the radar antenna. The effect of microwave backscattering amplification from the ship is predicted for grazing angles of observation within LOS range.

Keywords: Line-of-sight, weather formations, microwaves domain, spacecraft

Introduction
Radar is a detection system that uses radio waves to determine the range, angle, or velocity of objects. It can be used to detect aircraft, ships, spacecraft, guided missiles, motor vehicles, weather formations, and terrain. A radar system consists of a transmitter producing electromagnetic waves in the radio or microwaves domain, a transmitting antenna, a receiving antenna (often the same antenna is used for transmitting and receiving) and a receiver and processor to determine properties of the object (s). Radio waves (pulsed or continuous) from the transmitter reflect off the object and return to the receiver, giving information about the object's location and speed.

Radar was developed secretly for military use by several nations in the period before and during World War II. A key development was the cavity magnetron in the UK, which allowed the creation of relatively small systems with sub-meter resolution. The term RADAR was coined in 1940 by the United States Navy as an acronym for Radio Detection and Ranging. The term radar has since entered English and other languages as a common noun, losing all capitalization.

The modern uses of radar are highly diverse, including air and terrestrial traffic control, radar astronomy, air-defense systems, antimissile systems, marine radars to locate landmarks and other ships, aircraft anticollision systems, ocean surveillance systems, outer space surveillance and rendezvous systems, meteorological precipitation monitoring, altimetry and flight control systems, guided missile target locating systems, and ground-penetrating radar for geological observations. High tech radar systems are associated with digital signal processing, machine learning and are capable of extracting useful information from very high noise levels. Radar is a key technology that the self-driving systems are mainly designed to use, along with sonar and other sensors.

Other systems similar to radar make use of other parts of the electromagnetic spectrum. One example is LIDAR, which uses predominantly infrared light from lasers rather than radio waves. With the emergence of driverless vehicles, radar is expected to assist the automated platform to monitor its environment, thus preventing unwanted incidents.

There are many places in which a knowledge of the electrical reflectivity of natural surfaces is used-radio communications, missile guidance, and radar detection and tracking of targets, among others. The new emphasis on space research brings with it a need for additional data on the reflectivity of planetary surfaces.

There are distinct similarities between reflection phenomena in the microwave region and at optical, infrared, and the longer radio wavelengths. In addition, certain common features are exhibited in the scattering of sound and the scattering of radio waves from irregular surfaces.

While the subject of scattering from rough surfaces has been studied since the publication of Rayleigh's classical work on reflections of acoustic waves, there remains much to be done before a complete understanding is available. There are current efforts to solve the problem theoretically, and with the mathematical tools developed recently in noise theory large strides can be expected soon. At the same time, in order to answer certain practical questions, much experimental work on scattering is being done. We have been involved in research on scattering for applications in radar map-matching and in missile guidance. A need is now developing to expand our emphasis to encompass some broader aspects of the problem.

It is our intent to present a simplified treatment of many of the experimental results available to date and to suggest some of the newer trends. To understand the scattering phenomenon more completely, one needs reflectivity as a function of the angle made by the field vector with reference to some fixed angle for both the transmitter and receiver over the, entire possible range of angles.

First experiments

As early as 1886, German physicist Heinrich Hertz showed that radio waves could be reflected from solid objects. In 1895, Alexander Popov, a physics instructor at the Imperial Russian Navy school in Kronstadt, developed an apparatus using a coherer tube for detecting distant lightning strikes. The next year, he added a spark-gap transmitter. In 1897, while testing this equipment for communicating between two ships in the Baltic Sea, he took note of an interference beat caused by the passage of a third vessel. In his report, Popov wrote that this phenomenon might be used for detecting objects, but he did nothing more with this observation.

The German inventor Christian Hülsmeyer was the first to use radio waves to detect "the presence of distant metallic objects". In 1904, he demonstrated the feasibility of detecting a ship in dense fog, but not its distance from the transmitter. He obtained a patent for his detection device in April 1904 and later a patent for a related amendment for estimating the distance to the ship. He also got a British patent on September 23, 1904 for a full radar system, that he called a telemobiloscope. It operated on a 50 cm wavelength and the pulsed radar signal was created via a spark-gap. His system already used the classic antenna setup of horn antenna with parabolic reflector and was presented to German military officials in practical tests in Cologne and Rotterdam harbour but was rejected.

In 1915, Robert Watson-Watt used radio technology to provide advance warning to airmen and during the 1920s went on to lead the U.K. research establishment to make many advances using radio techniques, including the probing of the ionosphere and the detection of lightning at long distances. Through his lightning experiments, Watson-Watt became an expert on the use of radio direction finding before turning his inquiry to shortwave transmission. Requiring a suitable receiver for such studies, he told the "new boy" Arnold Frederic Wilkins to conduct an extensive review of available shortwave units. Wilkins would select a General Post Office model after noting its manual's description of a "fading" effect (the common term for interference at the time) when aircraft flew overhead.

Smooth Surface Scattering

Scattering from a smooth, partially conducting surface has been worked out to a high degree of approximation for linear and circular polarizations; these derivations may be found in the literature. Specular reflection takes place, with the angle of incidence equal to the angle of reflection. If the complex index of refraction of the surface is known, the amplitude reflection coefficient ρ and the change of phase on reflection ϕ can be computed for any incident wavelength and polarization. As an illustration, the reflection coefficients for horizontal and vertical polarization, ρ_v and ρ_h respectively, for C-band (5 cm) radiation incident upon a smooth sea surface. (As show in Fig. 1)

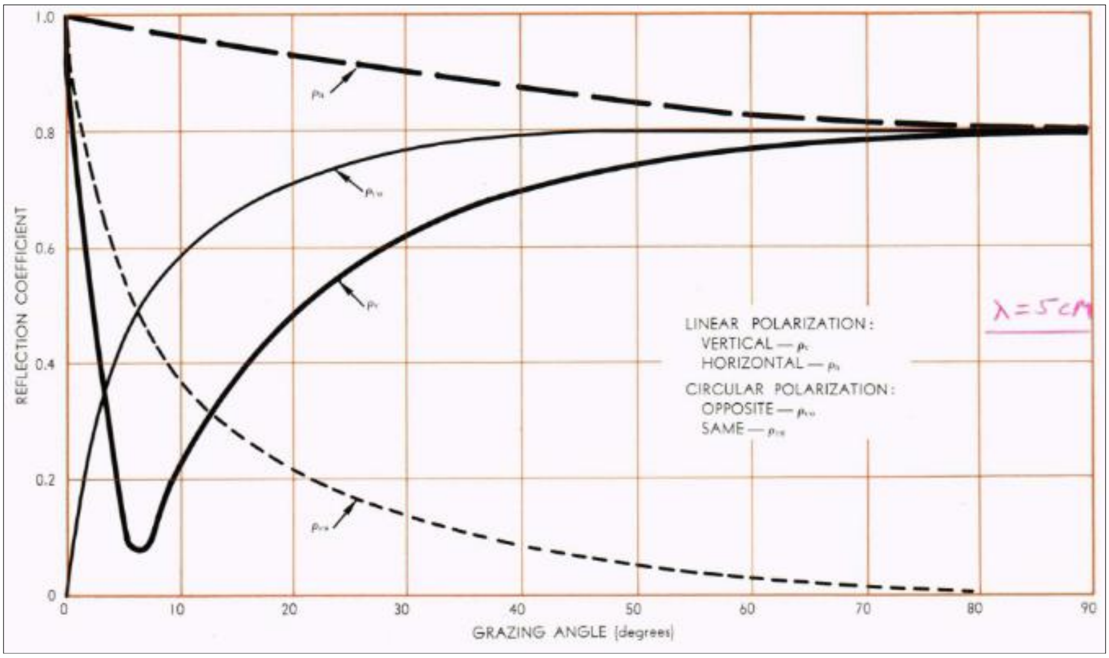

Fig 1: Sooth-sea reflection coefficient for linear and circular polarizations**.**

When considering circular polarization, we must take the sense of receiver polarization into account. A right-hand circularly polarized wave normally incident on a flat conducting plate becomes left-hand circularly polarized on reflection. This same wave incident on the same surface at small grazing angles retains its sense of polarization; the angle at which this transition occurs is called the Brewster angle. Thus, when we speak of the reflectivity of a circularly polarized wave, we must state the sense of polarization; this is done by subscript, ρ_{cs} meaning reflection coefficient "circular, same," and ρ_{co} meaning "circular, opposite." To detect a circularly polarized wave in free space we use identical antennas at the transmitter and receiver. If, on the other hand, we wish to detect a circularly polarized signal reflected from a flat conducting surface, we use antennas polarized with opposite sense.

Bistatic Reflectivity

The bistatic geometry is pictured. Here we see two aircraft, one containing the transmitter and the other the receiver. Ideally, these aircraft are equipped with narrow-beam antennas in order to illuminate or receive from a narrow angular region. The indicated depression angles ψ_T and ψ_R are not usually the same. For a given surface condition, all possible combinations of angular values are scanned. In practice, for practical reasons, it is likely that a wide-beam antenna model would be used with the transmitter and a narrow-beam with the receiver. Experiments using this procedure are visualized for the future. (As show in Fig. 2)

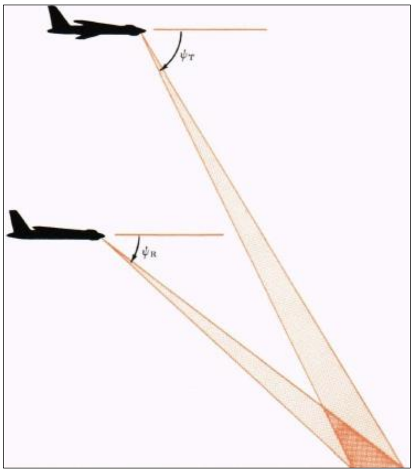

Fig 2: Geometry of bistatic reflectivity problem; ψ_T = transmitter depression angle, and ψ_R = receiver depression angle.

A program is now being conducted to obtain data from missile flights by using the Doppler shifted frequency of the returned signal. With the transmitter aboard ship and the receiver on an aircraft or missile, the bistatic reflectivity for a somewhat limited, but useful, range of transmitter depression angles can be obtained. The ship transmits a continuous-wave signal that illuminates a target airplane and the sea surface. Signals reflected from the target and the sea contain Doppler frequencies that depend on aircraft speeds and geometry. The receiver airplane or missile should have a wide-beam antenna, and its pattern must be accurately known over a wide angular region. Areas on the surface at different depression angles ψ_R contribute different Doppler components to the received signal. If the reflectivity of the target airplane or calibrator is known and the received signal spectrum is measured, the reflectivity of each of the areas on the sea may be determined. A program to obtain bistatic reflectivity is continuing at APL, and it is hoped that a dependable set of bistatic curves may be obtained. Clearly, with the transmitter mounted on shipboard, the maximum ψ_T will be restricted to less than several degrees.

Sea Surface Measurements

It was mentioned earlier that before a complete solution of rough-surface scattering is obtained, we must find an adequate description of the surface. Present methods for measuring ocean waves are not applicable to the present problem. We can, at any point in water and to any desired sensitivity, determine the height of water as a function of time. Although from height-time recordings a spectrum can be computed, this spectrum is not the one required. The spectrum obtained from a measurement of height versus distance along the surface is the one needed. If all waves moved with constant speed and direction, we could transform the time spectrum into the desired space spectrum. Unfortunately, waves of different lengths move with different speeds and not necessarily in the same direction; thus, the transformation from the time to the space spectrum cannot be made.

To obtain the description of the surface, a joint program sponsored by the Office of Naval Research and APL is in progress to develop a stereo–photogrammetric method to measure surface structure. A special pair of stereo cameras is being mounted aboard a ship to determine the feasibility of making wave measurements with the desired sensitivity. The present goal is to measure wave heights with a sensitivity of ±0. l in. From these photographs, three-dimensional space spectra are to be obtained for times during which radar reflectivity measurements are made.

Conclusions

Progress is being made in our understanding of reflectivity of electromagnetic waves from rough surfaces. Ultimately, we hope, radar observation of surfaces will permit computations of satisfactory descriptions of the surface states. Over land it will provide an all-weather navigation system. Over water we will be able to measure wave height with a remote probe, and our ability to detect targets amid sea clutter will be improved.

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