Literature Review

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Contents

Radar Basics

1.1 Uses of Radar

The advantage of radar sensing over photography is that it can penetrate clouds, and to an extent precipitation, and can provide different information. Microwaves can also penetrate deeper into vegetation than optical frequencies. Longer wavelengths will penetrate more than shorter, however shorter wavelengths can provide more information about upper layers. Microwave scattering is dependent on both the bulk-dielectric and geometric properties of the surface. We can use this scattering to infer electric and geometric properties of the surface.

1.2 Microwave sensors

The two classes of microwave sensors are passive and active. Active sensors use transmitters and receivers, while passive sensors rely on an external source of transmission. Active sensors include synthetic-aperture radar (SAR), side-looking airborne radar (SLAR), scatterometers, altimeters, and meteorological radars. SAR uses synthetic apertures (the distance the device travels between pulse and return creates a large synthetic antenna aperture). They provide the highest resolution, but it comes at the cost of complexity. Scatterometers measure backscatter with high precision but have lower resolutions.

1.3 Operation of Remote Sensing Radars

Radar can determine direction (by the direction of the antenna), distance (by the time between sent and received signals), speed (by measuring a phase change) and radar scattering cross section (comparison of the energy of the echo to that of the transmission). If a single antenna is used for both transmission and reception, a TR-switch is employed to alternate between modes.

1.4 Polarization

An E field which is polarized parallel to the medium boundary (the ground in our case) is referred to as horizontal polarization (shortened to H, also called perpendicular polarization). An E field perpendicular to this is referred to as vertical polarization (V). A radar system using these can have 4 channels; HH, VV, HV, and VH, where the first letter indicates the transmitted polarization, and the second the received polarization. A polarimetric radar uses all 4 polarizations and measures the amplitude and phase differences between the channels.

1.5 Scattering

When radar is incident on a target, it scatters in many directions. With a monostatic radar (transmitter and receiver are in the same location, usually using the same antenna), the radar measures the energy scattered directly back to the receiver. A bistatic radar utilizes two antennas in different locations. The scattered waves may be a complex function of the incident waves and the targets shape, size, orientation, permittivity, conductivity, and incident (illumination) angle. The total reflected power from the object is the product of the illuminating power density and the RCS (the radar cross section in units of area). The received power is a function of the antenna gain, effective antenna area, distance to target, and the specific RCS.

1.6 Terrain Scattering

The target can be considered a point target when the object is sufficiently far away, such that the targets size ¡¡ distance it is being measured from. Even though the object may have a complex geometry and nonuniform scattering pattern, its back-scattering strength is determined by its RCS. Point-target Monostatic radar equation:

1.7 Radiometry Emissivity

The brightness temperature of a material is the temperature at which a black body would emit the same intensity of light at a given frequency. The emissivity of a body is defined as the ratio of the actual intensity emitted to that of a perfect black body.

$$\frac{P_p^r}{P_q^t} = \frac{G^2\lambda^2}{(4\pi)^3R^4}\sigma_{pq} \tag{1.1}$$

Bistatic radar equation:

$$\frac{P_p^r}{P_q^t} = \frac{G_tG_r\lambda^2}{(4\pi)^3R_{Tx}^2R_{Rx}^2}\sigma_{pq} \tag{1.2}$$

When dealing with a monostatic radar and scattering from distributed targets (such as terrain), we can find the received power by integrating over the illuminated area. The backscattering cross section is sometimes normalized by the horizontal area. However, many seemingly uniform surfaces exhibit large variations between different areas. To compensate, we use an average radar reflectivity measurement (the average value of the back scattering cross section per unit area) [1].

1.8 RCS Statistics

The RCS of a target may be greatly dependent on the orientation (exceptions being spheres and cylinders). A distributed target will have a random scattering pattern and will exhibit large variations between small changes in position. This is referred to as image speckle. The radar reflectivity of terrain will vary with the sensor parameters such as the wavelength, incidence angle, polarization of the antennas, and the terrain parameters, such as the dielectric properties, and geometry (which may be a function of time). One way to model the surface is with the Rayleigh clutter model, which models the surface as many independent, randomly located scatterers with comparable strengths. This model allows us to write the probability distribution function of the reflected electric field as a normal distribution, known as the Rayleigh distribution [1].

1.9 Radar Types

In continuous wave radar, the transmitter sends out a continuous sine wave. The received signal is mixed with a copy of the transmitted signal and put through a low pass filter, to shift the signal down to baseband. Pulsed radar will transmit a short signal, and then listen to the return between pulses. Frequency modulation of the transmit signal allows range finding. The signal is continuously transmitted and received but varies with time. The signals are also called chirps.

Radar Signal Processing

2.1 Target detection

In an linear frequency modulation continuous wave (LFMCW) system, the reflected wave will have a time delay resulting in difference in the instantaneous frequencies of it and the transmitted wave. We can then use this frequency difference to determine the range of the target. Alternatively, we can consider the phase difference and the magnitude of the echo. If the target has a velocity with respect to the radar, the return signal will have a doppler shift. This will shift the instantaneous frequency either up or down, depending on direction. The return signal will also be attenuated. With range identifiable, and parameters of the antennas known, we can determine parameters of the target based on the returning amplitude. The maximum range of the radar is that such that the old echo is indistinguishable from a recent one. That is, the delay between the chirp and echo is greater than the interval between chirps. The signal should be sampled at a rate greater than twice the bandwidth, following the Nyquist sampling theorem.

2.2 Gain Correction

Signals received earlier during the period will be much stronger than those received later, due to the increased travel distance. In order to distinguish features from later in the period, we can increase the amplitude the further into the period the echo is received. This does tend to be bounded by a maximum value.

2.3 Stacking

If we repeat the same transmission multiple times, we can average the received data. This will reduce the random noise and improve interpretation.

2.4 Smoothing

Smoothing is a technique that can be used to detect small signals in a high noise environment by reducing the amplitude of the incoherent noise. One algorithm used is the moving average.

2.5 Persistent Scattering

This technique involves looking at which pixels stay coherent across all scans in the stack.

2.6 Matched Filtering

We would like to implement a filter that will maximize the signal to noise ratio (SNR) of the radar. The impulse response of the filter that maximizes the SNR is the correlation of the received signal with a time delayed copy of the transmitted signal. This is valid for non-interrupted radar.

2.7 Windowing

Since the radar signal is of finite duration, it is often necessary to truncate the signal to avoid high frequency components due to the discontinuities. Choosing the window is a trade off between decreasing the side lobes and keeping the main lobe narrow. The window may also cause a reduction in the power, and so called spectral leakage.

Ground Penetrating Radar

3.1 Operation

GPR may be either continuously moved across a surface, or set up, measurements taken, and then moved. The systems provide a cross section of the target. GPR emits in the microwave frequency band, and may utilize a variety of and is commonly used to detect buried objects, changes in materials, and voids. The antenna should be in contact with the ground to maximize signal strength. The emitted signal is scattered off boundaries and non-homogeneities within the soil itself. When depth is to be determined, the velocity through the medium must be considered to calibrate the instrument. The conductivity of the target and the transmitted frequency affect the effective depth range. An increase in the transmitted frequency will increase the attenuation of the signal but provides greater resolution. Penetration depth tends to decrease in wet soil compared to dry soil, due to the increase in the electrical conductivity. In a bistatic GPR system, there will initially be a combined response at the receiver due to the wave travelling laterally through the air and the ground. Point targets tend to produce a characteristic hyperbola on B-Scans. There are some disadvantages of the system. High energy consumption may be problematic for field work. Performance is limited in high conductivity soils that are salt contaminated as well as signal scattering in heterogeneous conditions. Sea ice falls under both conditions.

3.2 Applications

GPR can be a cost effective, portable, and durable radar device, suitable for harsh arctic environments. It has found many uses in the Earth sciences and proven to be effective in measuring the thickness of sea ice with a layer of snow above. The combination of low microwave and higher radar frequencies so identify snow and sea ice characteristics. The depth of the sea water beneath the layer of ice is unable to be measured due to its high conductivity.

3.3 Basic Data Processing

Unwanted low frequencies should be removed from the data. This may be a de-wow filter, which runs an average filter, or simply through applying a DC shift. Since the signals attenuate with time (propagation to be specific), the gain should increase with time. This allows the retrieval of data from deeper depths.

3.4 Properties of Sea Ice

On top of sea ice, snow is typically found. This snow differs from terrestrial snow due to the salinity and oceanic heating. Snow can be categorized as either wet or dry. Both contain ice crystals and voids. Sea ice contains brine, air pockets, and solid salt. The permittivity of the ice is a function of the pure ice, brine (dielectric constant, volume, and shape), ice temperature, and ice salinity. Solid salts may be ignored, since they are not a large portion of the whole and are similar in structure to the ice. In addition, the scattering due to air bubbles is notable only at frequencies above 2-3 GHz, and above 20-30 GHz for brine pockets. The GPR used will operate below these frequencies. The sea ice is also anisotropic the bottom of the ice exhibits strong reflection when the GPR antenna is polarized parallel to the grooves but will not reflect when perpendicular to it.

3.5 Oil in young sea ice formations

The resulting structure is non-homogeneous. However, there were some patterns that emerged. Most of the oil was contained in the top 5cm of ice, which was 6.5 cm. The oil may have also displaced some of the brine in the ice as well. In the uncontaminated ice, the top had the greatest salinity, while in the contaminated ice, the top had the lowest salinity. The oil seems to surround the regions of air in the ice. Oil rising to the top of the ice decreases the effective permittivity of the ice, decreasing the normalized radar cross section (NRCS). It was observed that with time, the NRCS tends to decrease, due to the oil pooling on the surface as well as rising within the sea ice. This may be useful in detection methods [2].

3.6 pulseEkko GPR Device

This system utilizes a bistatic radar [3]. It also includes a digital video logger to display the results and a control module. It is suitable for up to -50 ℃, and therefore should be adequate for arctic conditions. The device supports a range of frequencies available, from 12.5 to 1000 MHz. The high frequency antennas (250, 500, and 1000 Mhz) are also electrically shielded. The antennas are dipoles polarized in the HH orientation. The device will store the data without any gain applied. However, there are four different gain modes available: AGC, SEC, constant, and none. These are applied to the displayed data. AGC will attempt to equalize all signals by applying a gain inversely proportional to its strength. However, applying this method means that the reflectivity of the various targets cannot be deduced. The user can also set a maximum to the gain applied, preventing very small signals from producing large gains. SEC (Spreading and Exponential compensation) compensates for the spherical spreading loss and exponential dissipation of energy. It is essentially an exponential function, where the user specifies the attenuation value. It also implements a user specified gain limit. Constant gain and no gain operate as the name suggests.

Scattering Models

4.1 Coherent and Incoherent scattering

The total bistatic scattering coefficient in a co-polarized system will include a coherent and incoherent component. A cross-polarized system will have no coherent component. However this coherent component will only exist when the transmitter and receiver are very close together. As the roughness of a surface increases, the coherent portion will decrease, and the depolarization will increase.

4.2 Mie Scattering

The scattering and absorption due to dielectric spheres are dependent on two parameters. The normalized circumference and the relative index of refraction. When a wave is incident on a dielectric sphere, some power will be absorbed by the sphere, while some other fraction will be scattered. Additionally these values can be approximated further using the Rayleigh approximations with around a 1% error [1].

4.3 Volume Scattering Models

In a 3-layer medium, such as snow on top of the ground, there will be scattering at the air-snow boundary, the snow-ground boundary, and within the snow layer itself. When modelling the scattering properties of a medium, we must consider the size of the scatters relative to wavelength, the orientation of the scatterers, the shapes of the scatterers, and the dielectric constants of the scatterers. These following factors should be considered. Large scatterers relative to wavelength have distinct scattering patterns while small scatters can be approximated using the Rayleigh phase function. It should be determined whether scattering should be limited to single scatterings instead of multiple. The composition of the attenuation (extinction) coefficient (whether it is dominated by absorption or scattering) and the azimuthal symmetry of the target should also be considered.

4.4 Rayleigh Scattering

Rayleigh scattering is scattering which occurs without a change in wavelength. This means that the scattering particles are much smaller than the incident wavelength. This allows for the modelling of non-spherical particles small compared to wavelength as equivalent spheres with the same size and mass.

4.5 Backscattering of Dry Snow

The backscattering coefficient of dry snow will consist of the reflection at the air-snow boundary, the attenuated contribution from the snow-ground boundary, and direct back scattering from the snow layer.

Since dry snow has similar dielectric properties to air, the initial reflection and all consecutive reflections may be ignored at the air-snow boundary. The backscattering of dry snow tends to be insensitive to the surface roughness. The most important parameter in the volume scattering of dry snow is the ratio of the radius of the crystals to the wavelength. If the depth is not two orders of magnitude greater, the layer appears invisible. However, if there are many scatterer interactions, the layer may appear semi-infinite [1].

4.6 Single Scattering Models

A single scattering radiative-transfer (S2RT) model will account for scattering contributions that involve single scattering by the canopy, as well as double, single, or no scattering by the ground underneath.

4.7 Isotropic Scatterers

If a scatterer is isotropic, the scattering pattern is uniform in all directions.

4.8 Radiative Transfer Theory

There are two approaches for modelling multiple scattering by an inhomogeneous medium: either analytical theory (solving Maxwells equations, which should account for all multiple scattering), or radiative transfer theory. This assumes that there is no correlation between the fields scattered by different particles. This requires that scatterers are randomly distributed in location, and the spacing between them is large enough (in terms of wavelength) to ignore mutual inductance.

Permittivity of Heterogeneous materials

5.1 Conventions

The substance with the greatest volume fraction is called the host material, with the other substances called inclusions. Inclusions may be modelled as disks, spheres, and needles. Models typically ignore interactions between inclusions (assuming a low concentration), and assuming an effective dielectric constant surrounding an inclusion to account for this.

5.2 Polder-van Santen/de Loor (PvS/dL) model

This is one of the heterogeneous dielectric mixing models applicable to the oil-sea-ice problem. For small volume fractions, short range particle interactions may be ignored, changing ϵ^* to ϵ_h. At larger volumes, this is partly accounted for by changingϵ^* to ϵ_m . For intermediate volumes, using ϵ_h tends to underestimate the permittivity, while using ϵ_m tends to overestimate the permittivity of the mixture. This model considers pure ice as the host medium, and brine and oil as separate inclusions. Air is also neglected [1].

5.3 Tinga-Voss-Blossey (2-TVB) model

This model considers inclusions as ellipsoids with a constant dielectric, surrounded by another elliptical shell of the host material having a constant dielectric. The ratio of the volumes of the two ellipsoids is the same as the ratio of the volumes of inclusions to host material. This model generally falls in between the two PvS/dL models. This model (when applied to oil contaminated sea ice) approximates the permittivity by considering sea ice as the host medium, and oil as the inclusions. The sea ice permittivity is calculated using the standard TVP method [1].

5.4 Permittivity and Reflectivity of Sea Ice

In sea ice, the brine inclusions greatly affect the complex permittivity of the mixture. The salinity of the mixture, in psu (g of salt/ kg of water) varies with temperature. Ice age affects the brine concentrations, with salinity decreasing with age. The permittivity of sea ice also varies significantly with temperature. Thin ice has a relatively large RCS, but this decreases as it grows beyond a couple centimeters. Older ice tends to be rougher, which will increase the RCS. During the winter, while some volume scattering occurs due to the snow, since the snow is dry the effect is not significant. In the summer months, the snow on top of the ice melts, and the RCS slightly decreases. At higher frequencies, volume scattering becomes much larger than surface scattering. This is due to the smaller wavelengths, where the size of the air bubbles becomes comparable to the wavelength. The contrast between new ice and old ice is smaller at low frequencies due to this effect. Smooth surfaces will not depolarize much, meaning that the cross polarization of old ice will be greater than that of new ice. At low frequencies, the radar will penetrate deeper into the ice resulting in most of the scattering being due to surface and possibly sub-surface ice-ocean scattering. At high frequencies, sea ice scattering will become dominated by volume scattering. This will also result in a flat roll-off of backscattering with incidence angle. MY ices backscattering remains relatively constant throughout the winter months, while FY ice tends to vary significantly throughout its growth [1].

5.5 Differentiating between Sea and Ice

It is easiest to discriminate between the two at large incidence angles. The back scattering of the sea is typically less than that of ice in the winter. In the summer, when the ice is covered in wet snow and melt ponds it is more difficult. At certain bands, the angular roll off (decrease of scattering due to an increase of angle) is greater for water than it is for snow under calm conditions. However, the scattering increases for moderate incidence angles under large winds, making it more difficult to differentiate between the two. While identification under a range of conditions is possible using polarimetric data (with HH being the best method but thin ice and water appearing similarly), the largest distinction between sea ice and water can be found in the entropy measurements [1].

5.6 Detection of Oil Spills

The presence of oil is generally detectable through its change in the back scattering of the ocean. This is identified as a decrease in the backscatter. This usually requires wind of a moderate strength to detect. Weak winds will not generate waves while stronger winds will mix the oil with the water. This is more detectable at shorter wavelengths. Other phenomena may also produce low backscatter, such as rain cells and low wind conditions. Oil may also reduce the emissivity of the surface by affecting the transmission of energy emitted by the water, and damping small waves, reducing the roughness of the surface [1].

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