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POSSIBLE METHODS FOR DISTINGUISHING ICEBERGS FROM SHIPS BY AERIAL REMOTE SENSING

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POSSIBLE METHODS FOR DISTINGUISHING ICEBERGS
FROM SHIPS BY AERIAL REMOTE SENSING

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SUMMARY

Methods are discussed for distinguishing icebergs from ships utilizing airborne radar and microwave radiometry. Side-looking radar is appropriate for targets off the flight path whereas radiometry may be appropriate for targets along the flight path. The radar methods are classified according to whether the target is resolved. Since targets of interest may be near or below the resolution threshold, methods which do not require target resolution are preferred. Among these methods, polarization techniques appear most feasible. Specifically, these include identification using the relatively greater depolarization by natural targets (icebergs) relative to that by man-made targets (ships), and identification by means of doubly-reversed circular polarization produced by reflecting surfaces intersecting at right angles.

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INTRODUCTION

The following report was stimulated by a U. S. Coast Guard requirement for an all-weather remote sensing system for iceberg surveillance by the International Ice Patrol and especially by work undertaken at the NASA Lewis Research Center to implement that system (ref. 1).

The objective is to determine the simplest method for locating and distinguishing icebergs from ships by means of airborne remote sensors. A combination of methods may be necessary. For precisely locating and distinguishing these targets, the selected radiation wavelength should be as short as possible consistent with the requirement for cloud and precipitation penetration. Light must be excluded because of its inability to penetrate clouds. Longer wavelength microwave radiation will penetrate clouds and precipitation and is, therefore, appropriate for sensing.

Microwave sensing systems may be active (radar) or passive (microwave radiometer). Radar incorporates a microwave transmitter as the source of radiation to be detected by a receiver after reflection from the target (iceberg or ship) and extraneous objects (the sea). The simpler microwave radiometer does not include a transmitter, but rather detects radiation emitted from or reflected by the target and extraneous objects.

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Radar is essentially a range measuring device, whereas the microwave radiometer is primarily an energy measuring device. However, radar can be used to measure reflected electromagnetic energy, whereas distance can be measured by radiometric mapping. An important advantage of radar is controllability of the amplitude and waveform of the transmitted signal allowing more freedom in methods of identifying complex targets.

Resolution is an important limitation of remote sensors in distinguishing small targets. The horizontal range resolution of airborne radar for earthbound targets is best for targets toward the horizon and poorest for targets near nadir (because the range is then essentially constant). Contrariwise, the horizontal range resolution of the microwave radiometer is best near nadir and worst toward the horizon (because of the inclination of the target-to-sensor propagation vector to the horizontal). Thus, radar is more generally used for detecting targets at depression angles (below horizontal) less than 45 degrees. Targets beneath the aircraft are not surveyed. The radiometer scans best beneath the aircraft where radar is not appropriate. Thus, the two methods are complementary.

The ability to locate and distinguish targets using radar depends upon signal characteristics and target characteristics.

Significant signal characteristics include:

1. amplitude
2. frequency
3. phase
4. polarization

There are two categories of target characteristics; namely, those which serve to locate it and those which identify it. The target is located from antenna orientation and signal propagation-time measurements, which yield azimuth and slant range, respectively. Possible significant characteristics which may be used to identify a target include·

1. size
2. shape
3. roughness

4. material

    a. reflectivity

    b. transparency

5. movement

    a. velocity

    b. acceleration

It would be most desirable to select the best target identification method by a calculation which would compare the probability of target detection and some numerical measure of target identification for different methods. Unfortunately, the variety of identification methods, the complexity of the targets, the difficulty of defining a single measure of identification common to all methods, and the lack of experimental data presently preclude this possibility. Rather, for the present, the "best" method (or methods) will be selected using qualitative arguments and a few elementary calculations.

Most of the methods to be discussed have been previously reported in declassified reports, many of which are not readily obtainable. Thus, the present report may serve to collate these methods.

RADARS, RADIOMETERS AND RESOLUTION

The desired information consists of the location and identification of the target.

At least two types of monostatic (transmitter and receiver at same location) airborne radar have been used for iceberg surveillance or to distinguish icebergs from ships. These two types are side-looking aircraft radar (SLAR) and synthetic aperture radar (SAR). SLAR transmits a fan-shaped microwave beam in a vertical plane perpendicular to the aircraft track and, hence, senses targets to the side of the aircraft. SAR records similar information by transmitting a beam with a much broader horizontal component and utilizing the translation of the antenna and interference of the return wave with a copy of the transmitted waveform to effectively synthesize a much larger horizontal aperture. This provides much greater along-track (linear azimuthal) resolution of targets, but at much greater cost. SAR is called focused, or unfocused, depending on whether or not the interference of the reflected and transmitted waveforms takes account of the variable delay of the return wavefront over the synthetic aperture.

The basic radiometer utilizes a highly directional antenna and mechanical scanning for surveillance. The scanning need not be restricted to the across-track direction.

Using radar, range and amplitude information may be recorded either in a time format or space format.

In the time format the return signal may be recorded on magnetic tape, or by some comparable means, as a function of time. In the space format, the return signal is translated into the form of a map of the region being surveyed. The spatial format not only provides a picture of the shape of the target but also includes much extraneous information about the region surrounding the target. If the target is clearly resolved, then it may be identifiable. If the target is not clearly resolved, then the spatial format may indicate the location of the target, but not necessarily its identity. Thus, for identification purposes, spatial mapping may require too much handling of extraneous data. If the temporal data contain information for identifying targets by means other than target shape, then the time format may be preferable.

If a spatial format is to be effective, the spatial resolution of the radar should be much less than the target size. The spatial resolution is the minimum separation at which two points can just be distinguished. The spatial resolution can be decomposed into two components; namely, the cross-track component, or range resolution, and the along-track component, or linear azimuthal resolution. For SLAR and SAR the range resolution is, at best, about 3 meters (ref. 2), independent of range. For SLAR, along-track resolution is determined by the angular resolution of the antenna and is, at best, about 3 meters/kilometer range (ref. 3). At a range of 2 kilometers, corresponding along-track values are claimed to be 3 meters for unfocused SAR and 1 meter for focused SAR (ref. 4). The unfocused SAR resolution along track increases in proportion to the square root of the range, whereas the focused SAR resolution along track is, in principle, independent of range.

It is evident that resolution may be a serious limitation in distinguishing all except the larger ships and icebergs by using airborne radar imagery.

Since radiometer scanning need not be across track, the radiometer resolution may more generally be decomposed into horizontal range and linear azimuthal components. Both components are determined by the angular resolution of the antenna and the range. However, because of the inclination of the target-to-receiver propagation vector with respect to the vertical, the horizontal range resolution decreases as the square of the range.

The radiometer must generally respond to much weaker signals than radar. Thus, the radiometer operates best at shorter ranges where signals are stronger and atmospheric attenuation is minimal.

TARGETS

The problem is to identify the nature of a target which has been located in range and azimuth. First, each identifying characteristic is discussed separately.

Size

Determination of target size alone is sufficient for target identification only if the size exceeds that of the largest ships and, then, only if it also greatly exceeds the microwave resolution. If these conditions are satisfied, the target is assumed to be an iceberg.

Actually, there are several possible sizes which may be of interest, depending upon what is known about the target geometry. These include:

1. planform area
2. beam interception cross-section
3. image cross-section
4. radar cross-section

All except the radar cross-section are geometric cross-sections. The planform area is the area of the target at nadir. The beam interception cross-section is defined as the target cross-sectional area measured normal to a radar beam from any given direction. The image cross-section is the target area indicated by mapping the amplitude of the target return signal as a function of the horizontal range and linear azimuth. The radar cross-section is a target area derived from microwave intensity measurements.

Only the image cross-section and radar cross-section can be determined by remote sensing of unidentified targets. However, in selecting a target identification method the planform area or beam interception cross-section, obtainable from photographs of known targets, may be acceptable substitutes for the image cross-section determined operationally. For a flat target in the plane of the earth's surface the image cross-section should equal the planform area.

Assume that the radiated power incident on a target is scattered isotropically and without loss. Then, the total scattered power received at range R large compared with the wavelength and target size equals the total power incident on the target; that is,

$$I_o \sigma = 4\pi R^2 I_s$$

where I_o is the radiation intensity incident on the target, I_s is the intensity of the isotropically scattered radiation at range R, and σ is the illuminated cross-sectional area, or radar cross-section, of the target. Thus,

$$\sigma = 4\pi R^2 \, (I_s/I_o)$$

Most targets are not isotropic scatterers, so that σ is a function of the direction of view. Also, I_s is measured only at the one location of the receiver antenna. As a result, the calculated radar cross-section σ may differ greatly from and may not be simply related to any of the previously defined geometric cross-sections of the target (ref. 5, chap. 27, p. 3). Because $I_s \propto R^{-2}$, the radar cross-section σ is independent of range. For a given range, σ is a measure of the relative intensity of radiation reflected from the target to the receiver. Thus, the reflected intensity of radiation from ships and icebergs may be compared by calculating their radar cross-sections. With additional knowledge of one of the geometric cross-sections of the target it may be possible to distinguish ships from icebergs, as will be discussed.

Occasionally, an iceberg may be high enough to produce a radar shadow on surrounding sea ice. This shadow may be detected in radar imagery (refs. 6 and 2). It is not likely to be detectable if the iceberg is surrounded by sea water because of the lack of image contrast between the sea water and shadow (ref. 6).

Shape

The shape of an object with dimensions near the threshold of resolution cannot be readily determined. The radar across-track resolution of at least 3 meters implies that the characteristic dimensions of the target must be much greater than 3 meters if its shape is to be determined. The results of one mathematical analysis (ref. 7) showed that a simple target (a cross) was identifiable from its shape only when the target dimensions exceeded approximately 10 times the resolution. Thus, shape alone is not a good means for distinguishing icebergs from ships unless the target minimum dimension at least exceeds 10 meters. Even then, to differentiate these targets it must be assumed that the iceberg is not shaped like a ship.

SAR imagery has been used to identify some icebergs by their shape (ref. 2). However, an iceberg with radar cross-section comparable to that of surrounding ice clutter may not be identifiable in this manner because of lack of contrast (ref. 2).

Coherence is a factor in radar imagery, but not in radiometer imagery. Because of coherence between radar reflections from adjacent areas of a target, the resulting interference of the reflected waves at the antenna may yield a target image which is both space and time dependent. Thus, the image planforms of targets with dimensions exceeding the resolution limit may appear deformed (ref. 7). In contrast, all target points represent incoherent sources for radiometry. Hence, the interference phenomenon and the consequent image deformation does not occur. As a result, all other things being equal, target shape may be better determined using radiometry.

Roughness

For targets at ranges greatly exceeding the target size and dimensions of the radar antenna, the microwave radiation appears to be emitted from a point source and is, therefore, spatially coherent. Because the illumination of each point on the target is then effectively undirectional, the target's back-reflected intensity will depend on its roughness. Here "roughness" means any irregularity of the target configuration which affects reflection. The principal types of reflections are specular reflections, diffuse scattering, scattering by sharp discontinuities and internal reflections (ref. 8). The reflection is specular if the roughness dimensions are much greater than the radar wavelength and diffuse if the roughness dimensions are a fraction of the wavelength. The scattering at discontinuities is specular if the radius of the discontinuity exceeds the wavelength and is diffuse otherwise. Internal reflections may occur if the target is a dielectric so that radiation penetrates it. This possibility depends on the material and will be discussed under "Material."

Man-made targets tend to consist of or include structures with simple geometric shapes. Assuming that the surfaces of these structures are smooth at radar wavelengths, reflections therefrom are specular if the structure dimensions are at least 10 times the wavelength. This is the optical region (ref. 5, chap. 27, p. 21). If the structure dimensions are greater than the wavelength, resonances may occur in which the reflected intensity relative to the geometrical cross-section may be several times the optical value. This is the Mie, or resonance, region. If the structure dimensions are less than half the wavelength, then diffuse scattering occurs. The relative reflected intensity becomes only a fraction of the specular value and tends to zero with decreasing structure size.

Radar wavelengths (<1m.) are much less than overall dimensions of ships and icebergs. However, the roughness of ships and icebergs may possess any value less than the overall target dimensions, so that the backscattered radiation may include specular, resonant, and diffuse components. The reflection from a ship may occasionally result primarily from specular reflection, or glint, off a broad flat surface. However, because most ship surfaces are curved at most aspects, it is more reasonable to expect specular reflections from surface areas small compared with the overall dimensions. Resonance reflections from small structures may occur because of the simple geometry of ship structures. The intensity of diffuse reflections is expected to be much less than that of specular reflections because of the smoothness of ship surfaces. Possibly this expectation is confirmed by large fluctuations (30 dB) of individual pulse amplitudes as a function of the viewing aspect.

The expectation of glint and resonance reflections may be less from icebergs than from ships because of the random structure of icebergs. However, specular reflections may be expected from icebergs, especially from those surfaces which have been smoothed by washing with sea water. The ratio of diffuse to specular reflection may be greater for icebergs, especially the larger ones, than for ships. Not only may unwashed iceberg surfaces be rough, but also internal inhomogeneities may scatter radiation which penetrates the surface.

Specular reflecting areas contributing to the received signal are generally separated by distances large compared with the wavelength of the radiation. (Otherwise the reflection would be diffuse and associated with surface roughness.) Thus, the reflecting ship, and probably the iceberg, consists mainly of a collection of separated specular reflecting centers (ref. 9). If the extent of the ship does not exceed a resolution cell, then the net received radiation amplitude is determined by the sum of the instantaneous amplitudes of signals received from all reflecting centers within the limits of the resolution cell. The resulting coherent intensity is determined by interference between the signal contributions from each reflecting center. If the extent of the ship exceeds the resolution cell then the intensity from each resolution unit will be as just described so that the "instantaneous image" of the entire ship will be comprised of cells of varying intensity. The ship may, in fact, appear to consist of several targets rather than one (refs. 7 and 10). Hence, the ship may not be identifiable as such from its imagery. On the other hand, if the ship were a diffuse reflector, nearly all points would contribute to its image. Then, it would likely be identifiable.

Since coherence is not a factor in radiometry, each point of a target radiates independently in all directions. The variation of target radiation from adjacent areas results from temperature differences, but more predominantly, from emissivity variations and reflections from other emitters. For these reasons the measured radiometric intensity from any target may vary widely as a function of the viewing aspect and time of day.

Because of the nonsphericity of most targets, their radar image intensities are strongly dependent on orientation. This results from the relative shift and exchange of reflecting centers as the direction of observation changes.

The complexity of ship and iceberg geometries makes theoretical identification of target configuration from its roughness characteristics most difficult.

Material

Depending on its transparency to microwaves, the target material may contribute to distinguishing icebergs from ships. The transparency is determined primarily by the conductivity of the material and the radiation frequency. In the present problem the material may be a significant factor because ice and water are poor conductors relative to metals.

In Table I, conductivity σ_c, refractive index n, skin depth d, attenuation A, and attenuation index κ are listed for the appropriate materials, steel (St), salt water (SW), salt-water ice (SWI), fresh water (FW) and fresh-water ice (FWI) at the frequency $\nu = 1.59 \times 10^8$ Hz (159 MHz) in the VHF band, a very low radar frequency. A low frequency was chosen to provide an estimate of the maximum penetration of the material that could be expected. Generally, calculated and experimental results are in good agreement, except in the case of salt-water ice where the experimental attenuation in decibels is about 10 times the theoretical value. (The listed theoretical skin depth would be too large, hence, would be much greater than the experimental value.)

It is evident from Table I that the microwave transmittance of steel and salt water is negligible, is poor in salt-water ice, but is good in fresh water and fresh-water ice. Thus, microwave penetration might be used to distinguish ships from fresh-water ice, but possibly not from salt-water ice. Icebergs, which originate from glaciers, consist of fresh-water ice, but might be at least partially coated with sea water or sea-water ice as a result of the wave action of sea water in which they are partly immersed.

In radiometry, the emissivity, which influences the thermal radiation, is determined partly by the material, as well as its roughness.

Reflectivity

The microwave reflectivity characteristics of ships and icebergs are so different that reflectivity might contribute in distinguishing targets by radar.

The normal reflectivity $\mathcal{R}$ at air-water, air-ice, and ice-water boundaries is given in Table II for the low radar frequency 159 MHz. The normal reflectivity of an air-steel or air-water interface is high, whereas that at an air-ice interface is low. However, the reflectivity at an ice-salt water interface is also high. Thus, airborne microwaves will be strongly reflected off a steel or salt water surface, but will penetrate fresh-water ice and may be more strongly reflected off the back (ice-salt water) interface (ref. 11). Of course, the relative intensity of the front and back surface reflections depends upon the thickness and absorption of the ice.

In general, reflectivity is a function of polarization of the radiation. However, for normal incidence, as often may be required for reception using a monostatic radar, reflectivity is independent of polarization if the reflector dimensions greatly exceed the wavelength. Otherwise, polarization may be a significant effect.

Radar cross-section measurements of both ships (ref. 12) and ice blocks (ref. 13) have been found to be independent of the plane of polarization for HH and VV polarization*. For ships at 45 degrees illumination depression angle, the VH cross-polarization cross-section was about 10 to 20 dB less than the VV cross-section. For ice blocks at normal incidence, the HV cross-section was about 10 dB less than the VV or HH cross-sections. Thus, the cross-polarized return tended to be less than the parallel-polarized return. It has been found that the ratio of parallel-polarized return to cross-polarized return tends to be greater for man-made targets than for natural targets (ref. 14). This difference has been used to detect submarine periscopes and snorkels in the presence of sea clutter (ref. 14). Possibly, it can also be used to distinguish icebergs from ships.

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* H means polarization plane parallel to the earth's surface. V means polarization plane perpendicular to the earth's surface. Given VV, HH, HV or VH. The first letter represents the polarization plane of the transmitted wave. The second letter represents the polarization plane of the receiver antenna.

For circularly polarized radiation both same and reversed polarization signals have been intermittently received from the same ship (ref. 15). This implies that both double and single reflections, respectively, have occurred. The effect may not be the same for icebergs. Thus, polarization reversal might be used to distinguish ships from icebergs.

Because icebergs tend to be more irregular than ships, there exists the possibility that the two targets might be distinguished by differences in their spectral reflectance at wavelengths corresponding to target subdimensions. Specifically, the reflectance spectrum of an iceberg may be smoother than that of a ship, which might exhibit relatively intense discrete frequency lines (associated with discrete subdimensions of the target) on an otherwise smooth spectrum.

Movement

Sometimes icebergs and ships may be distinguished by their movements. The mode of detecting radial movement is Doppler frequency shift. Using SLAR and spatial format, visible wakes may disclose movement. Both ships and icebergs may possess a wake. However, ships in motion generally display a well-defined wake with apex at the target, whereas icebergs will only occasionally exhibit a wake of near constant width and with no defined apex (ref. 6).

Using SAR, movement of the target during the observation period may result in various forms of defocusing, attenuation and image shift, including:

1. "blur" due to radial acceleration and cross-range target velocity.

2. "smear" due to relative radial velocity.

3. attenuation due to blur and Doppler-frequency shift beyond the azimuth passband of the radar, and

4. cross-range image shift due to radial velocity (refs. 16, 2).

Although these image defects might appear to make SAR useless for identifying targets which move during observation, in principle, spatial filtering of the image might, on the contrary, not only be used to detect moving targets but also be used to identify them by virtue of their velocity and shape.

METHODS OF IDENTIFYING TARGETS

Individual characteristics or combinations of the cited characteristics of a target might be used for target identification. Whatever the choice, the signal (target) must be detectable in a noise (sea clutter) background. The signal may be recorded as a function of spatial dimensions or time, or their respective Fourier transforms, spatial frequency and frequency. The spatial format is most useful if the target is resolved. If the target is sufficiently resolved, its image cross-section may be measurable. This cross-section constitutes a potentially useful variable in identifying the target. The "roughness" of the target relative to the radar wavelength affects the reflection characteristics of the target. The reflectance is, in general, specular, resonant, or diffuse depending, respectively, upon whether the wavelength is less than, approximately equal to, or greater than the surface roughness of the target. If the incident radiation is plane polarized, then backscattered radiation will also be plane polarized if the reflectance is specular. However, if the reflectance is diffuse, then depolarization of the backscattered radiation will occur (ref. 17). This and the preceding characteristics may all be useful in categorizing methods of target identification.

Among the ways of classifying target-identification schemes, classification according to the ability of the method to resolve targets seems appropriate because targets of interest are likely to be detected near the threshold of resolution. Using this classification scheme, some possible methods for distinguishing icebergs from ships are listed as follows:

A. Geometric cross-section determinable

   1. Radar cross-section differences

B. Target resolved, but shape indeterminate

   1. Two-frequency differential penetration

   2. Spatial spectrum difference

C. Target not resolved

   1. Discrete components in frequency spectrum

   2. Doppler spectrum difference

   3. Depolarization difference

   4. Doubly reversed, circular-polarization difference

Each of the listed methods is applicable to targets larger than those for which it is listed. Methods listed under A and B involve measurements of the target geometry, whereas those under C do not. The first two methods under C are spectral methods, whereas the other two are polarization methods. Whereas all other methods require one receiver antenna, the polarization methods in C may require more than one antenna. Each of the listed possibilities is now discussed in more detail

A1. Radar Cross-Section as Function of Geometric Cross-Section

In this method it is assumed that because ice, especially freshwater ice, reflects microwaves poorly relative to the steel in ships, the radar cross-section of an iceberg should be less that that of a steel ship having the same geometric cross-section (ref. 1).

Microwave reflections from ships are more intense and steadier than those from ice (ref. 18). It has been reported (ref. 15) that ice typical of that in icebergs on the Grand Banks has a reflection coefficient of approximately 0.33 and reflects microwaves 60 times less than a steel ship of equivalent cross-sectional area. Thus, differences in reflected microwave intensities from targets with known geometric cross-sections should be sufficient to distinguish between ships and icebergs. Unfortunately, it may not be possible to determine with sufficient accuracy the geometric cross-section of the target using radar if the target dimensions are not at least an order of magnitude greater than the spatial resolution of the radar.

Radar cross-sections of ships are listed in Table III. For ships the size of a two-man raft, or larger,

$$-12 < \sigma_{dbsm} < 80$$

where the cross-section σ_{dbsm} is in decibels (re. 1 m.^{2}). These are median values obtained from many reflected pulses. For a given ship the median value as a function of azimuth may vary by 20 dB., the minimum being obtained for bow illumination and the maximum for broadside illumination. The median value may also decrease 5 to 20 dB. as the depression angle of illumination is increased. "Instantaneous" (single pulse) values of radar cross-section may deviate from the medians by ± 15 dB., or more.

In Table III, radar cross-sections for ships included in reference 19 were computed from near-field cross-sections σ_n by using the relation $\sigma = \sigma_n/4$ (ref. 20).

Radar cross-sections of ships are usually, but not always, independent of polarization and radiation frequency (ref. 12).

If ships are to be unmistakably distinguished from icebergs on the basis of radar cross-section, the radar cross-sections of the two targets must not overlap; that is, for the same geometric cross-section the radar cross-sections of all ships must exceed those of all icebergs. Radar cross-section data for blocks of ice and icebergs are available for testing this hypothesis. The ice-block data is "laboratory" data, whereas the iceberg data was obtained under operational conditions.

The data for blocks of ice indicate that the radar cross-sections of ships and ice may overlap. For a block of ice (geometric cross-section, 44 in. x 22 in.) resting on a snow surface, it was found that

$$\sigma_{dbsm} = 16$$

or more, at normal incidence with 10 G Hz (X-band) radiation and VV polarization (ref. 13). For other angles of incidence $\sigma dbsm$ was as much as 50 dB below this maximum value although values within 10 dB of the maximum were not uncommon at other angles of incidence. Cross-sections were essentially the same for both fresh-water ice and salt-water ice and were also independent of polarization. Nor was wavelength significant unless the surface roughness was comparable. However, it was found that $\sigma \propto A^2$ when the reflection was specular (λ much less than surface roughness = smooth block) and $\sigma \propto A$ when the reflection was diffuse (λ comparable to surface roughness), where A is the geometric cross-section of the ice surface normal to the radar beam. For 10 G Hz radiation frequency the reflection was specular.

To calculate the radar cross-section for normal incidence and other values of geometric cross-section

$$\sigma^{(2)}_{dbsm} = \sigma^{(1)}_{dbsm} + 20 \log (A_2/A_1)$$

where the superscript denotes the target. Thus, if the geometric cross-section of the iceblock mentioned above were increased to equal the plan-form area of the picket ship listed in Table III, the maximum radar cross-section of the ice block, $\sigma^{(2)}_{dbsm}$, would be

$$\sigma^{(2)}_{dbsm} = 16 + 20 \log \frac{2339}{0.6245} = 87$$

whereas the maximum radar cross-section of the picket ship was σ_{dbsm} = 47. Thus, the ice cross-section exceeds that of the picket ship by 40 dB. To see whether this is a reasonable number, the radar cross-section of the ice block may be compared with that of a perfectly conducting disk with the same geometric cross-section illuminated at normal incidence. The radar cross-section of a perfectly conducting disk at normal incidence is given by

$$\sigma^{(d)} = (4\Pi/\lambda^2)(\Pi a^2)^2$$

where a is the radius of the disk (ref. 21, p. 513). For $\Pi a^2 = 2339\ m^2$ and $\nu = 10$ G Hz; $\sigma = 7.6388 \times 10^{10} m^2$.; that is,

$$\sigma^{(d)}_{dbsm} = 109$$

for the disk, which exceeds that for the equivalent ice block by 22 dB. Hence, relative to a perfect conductor, the power reflection coefficient for the ice block is 0.0068, which is a reasonable, if not slightly low, value for ice.

The preceding results show that the radar cross-section of the ice may exceed that of a ship by 40 dB, or so. If the smooth ice is not illuminated by a monostatic radar at normal incidence, its radar cross-section may be as much as 50 dB below the value at normal incidence. However, if the ice roughness is comparable to the radiation wavelength, then the radar cross-section may be much closer to the maximum value for smooth ice at normal incidence (ref. 22). Thus, laboratory data indicate that ships may not always be distinguished from icebergs on the basis of reflected intensity (radar cross-section), range and geometric cross-section determinations.

The preceding case of normal incidence on a large, smooth, flat block of ice likely possesses low probability of occurrence. Radar cross-sections of icebergs are expected to be much lower generally.

Measurements on icebergs at near-zero depression angle have shown that, for equal echo amplitudes, the ratio of the beam interception cross-section to that calculated for a perfectly conducting sphere ranges from 10 to 400 with an average of 67, independent of range (ref. 23). Thus, on the average, if $I^{(sph)}/I^{(b)} = 1$,

$$I^{(sph)}/I^{(b)} = \sigma^{(sph)}/\sigma^{(b)} = (67\ A^{(sph)}/A^{(b)})^2$$

where A is the beam interception cross-section, and the superscripts b and sph refer to iceberg and sphere, respectively. Consequently, in decibels,

$$\sigma^{(b)}_{dbsm} = \sigma^{(sph)}_{dbsm} + 20 \log (A^{(b)}/A^{(sph)}) - 36.5$$

relative to a perfectly conducting sphere. The data previously discussed were related to calculations for a perfectly conducting disk, rather than a sphere. The radar cross-section of a sphere with radius a is given by

$$\sigma^{(sph)} = \Pi a^2$$

so that, for a disk with the same radius,

$$\sigma^{(d)} = (2\ \Pi a/\lambda)^2 \sigma^{(sph)}$$

Therefore, relative to a disk at normal incidence,

$$\sigma^{(b)}_{dbsm} = \sigma^{(d)}_{dbsm} - 10 \log (ka)^2$$

$$+ 20 \log (A^{(b)}/A^{(d)}) - 36.5$$

for an iceberg, where $k = 2\Pi/\lambda$.

For an iceberg having a beam interception cross-section equal to the planform area of the picket ship, the preceding formulas and data indicate that

$$\sigma^{(b)}_{dbsm} = 109 - 75.1 - 36.5$$

$$= -2.6$$

on the average, with lower and upper limits of -18.1 dbsm and 13.9 dbsm, respectively. These values for icebergs are considerably less than (-73 dbsm) those interpolated from the ice-block data, and are more realistic. The minimum median value for the picket ship is approximately 47-20 = 27 dbsm for bow illumination. The minimum instantaneous value for bow illumination would be approximately 12 dbsm. Therefore, the iceberg data indicate that, as long as ship planform area is not much less than its beam interception cross-section, then there is little likelihood that icebergs and ships having the same interception cross-section would be confused. However, to be accurately measured, the geometric cross-section must exceed the spatial resolution of the radar by at least two orders of magnitude. This implies that the geometric cross-section of the target must exceed 900 m^2/km. range when using SLAR, or 300 m^2, independent of range, when using SAR. Since the mass of an iceberg is primarily submerged, these cross-sections may be associated with objects hazardous to navigation.

The accuracy requirements in measuring geometric cross-section may not be severe. Since $\Delta_A\sigma/\sigma \propto 2\,\Delta A/A$, where Δ denotes error, and Δ_A denotes error due to the error of A, the error of σ is relatively sensitive to the error of A. For example, if $\Delta A/A = 1$, then $\Delta_A\sigma_{dbsm} = 3$; whereas, if $\Delta A/A = 5$, then $\Delta_A\sigma_{dbsm} = 10$. This larger error is quite plausible for target sizes near the resolution limit. However, the corresponding error of σ is only comparable to other variations due to aspect and signal averaging. Therefore, even these large errors in measuring geometric cross-section may still permit icebergs to be distinguished from ships.

If the target cannot be resolved but its radar image dimensions exceed those of a point, it may still be possible to estimate the image cross-section of the target. The excess breadth, ℓ_e, of the image indicates the target dimensions along track, and the excess duration, t_e, of the target return yields the target dimension r_e across track according to the relation $r_e = ct_e/2$, where c is the speed of light. The geometric cross-section of the target is given by

$$A \approx \ell_e r_e$$

If the target is effectively a point or a line, then this cross-section technique cannot be used. The target is a point if its dimensions are small compared with the dimensions of a resolution cell. The resolution in range, δ_r, is given by

$$\delta_r = (c/2)\delta_t = c/2B$$

where δ_t is the time resolution, and B is the modulation bandwidth of the radiation (ref. 24). The linear azimuthal resolution, δ_s, for SLAR is given by

$$\delta_s = \lambda R/D$$

where D is the horizontal aperture of the antenna (ref. 4). If the corresponding target dimensions are small in comparison with these components of resolution, then the target is effectively a point.

Consider a pulse modulated radar with $\lambda = 3.2$ cm., pulse width $\Delta t = 2 \times 10^{-7}$s., D = 5 m. The bandwidth is approximated by $B \approx 1/\Delta t = 5 \times 10^{6}\text{s.}^{-1}$. At range $R = 5 \times 10^{3}$m., $\delta_r = \delta_s \approx 30$ m. For target dimensions much less than this, say 5 m., or so, the target appears to be a point. These dimensions correspond to targets of appreciable size.

At best, relative to the preceding data, an order of magnitude improvement in linear azimuthal resolution is practically attainable using SLAR. Note that, in the above example, $\delta_s > 30$ m. if $R > 1$ km. Thus, although the resolution may be sufficient to distinguish ships from icebergs at close range, say 1 km., it is not likely to be sufficient at long range, say 10 km., or more.

It seems worthwhile to search for other radar methods which might work better for barely resolved or unresolved targets.

For radiometer imagery near nadir the angular resolution should be similar to the azimuthal resolution of SLAR with the same antenna beamwidth and operating at the same wavelength.

However, because the radiometer image is for the area beneath the aircraft, on the same mission the target ranges for the radiometer are less than for the radar. Thus, the linear resolution of the radiometer may be better than the linear azimuthal resolution of the SLAR.

Radar cross-section is not a factor with radiometry. Rather, the radiometer senses the brightness temperature of the area scanned. The contrast in brightness temperature exposes targets. Because of the many factors (temperature, emissivity, roughness, extraneous sources) which affect brightness temperature, there is no guarantee that brightness temperature of ships and icebergs will not overlap on occasion so that the two targets may be identified. For example, can an ice-covered ship be distinguished from an iceberg?

If radiometry were to prove unsatisfactory, then forward looking radar might provide an alternative for coverage along the flight path.

B1. Two-Frequency Differential Penetration

This method utilizes the difference in microwave penetration of ice and metals as a function of frequency in order to distinguish icebergs from ships. Specifically, the penetration of metals by microwaves is negligible at all frequencies, whereas the penetration of ice, especially fresh-water ice, is frequency dependent. The longer the wavelength, the greater the penetration. For fresh-water ice the skin depth d is about 10 m. at frequency 10 G Hz (wavelength $\lambda = 3$ cm.) but increases to more than 100 m. at frequency 1 G Hz ($\lambda =$ 30 cm.) (ref. 25).

Basically, radar measures time durations. Thus, it might be possible to distinguish icebergs from ships by measuring propagation time differences of radiation at two different frequencies as a result of differences in the penetration of and reflection from icebergs and ships. For example, assume that two different frequencies are identically pulse modulated and simultaneously transmitted. By measuring the time from final transmission of a pulse to final decay of the return pulse to some preset level and then comparing this duration for both frequencies, the target may be identified and the range of the target may be determined. Specifically, if the two durations are the same, the target is presumed to be a ship, whereas if the two durations differ, the target is an iceberg.

Alternatively, icebergs and ships might be distinguished by comparing the durations of the return pulses. Any significant difference would imply that the target is an iceberg.

Suppose that two frequencies modulated by identical pulses are transmitted simultaneously from the same location. Consider two targets consisting of plane plates, one of steel and the other of ice, at the same range R_1 to the front surface nearest the transmitter. For normal incidence, the steel plate yields this range at both frequencies. Assume that, for ice, the radiation at the higher frequency reflects mostly off the front surface, whereas that at the lower frequency penetrates the ice and reflects mostly off the back surface. Hence, the plate of ice yields the range R_1 at the higher frequency and R_2 at the lower frequency. The difference in range is

$$R_2 - R_1 = c\Delta t/2$$

where c is the velocity of the radiation in the plate, and Δt is the two-way propagation time between the plate surfaces.

In order to detect and measure small values of $R_2 - R_1$, say $R_2 - R_1 = 1$ m., small time resolution δ_t is necessary, since the range resolution is given by

$$\delta_r = (c/2)\ \delta_t$$

The time resolution is given by

$$\delta_t \approx 1/B$$

Thus, the resolution of small space and time differences necessitates large bandwidth signals. If $\delta_r \leq 1$ m. is desired, then $\delta_t \approx 10$ ns., so that $B \approx 0.1$ GHz.

In order to satisfy the preceding requirements, the simplest transmitted waveform, which also contains sufficient energy for detection of the target and permits unambiguous measurement of range, is a long pulse. However, the bandwidth requirement implies that a short pulse should be used. This conflict can be resolved by modulating a frequency-modulated signal, or "chirp" with a long pulse. This yields a wide bandwidth signal. In addition, the range resolution can be greatly increased by means of pulse compression, in which the received signal is passed by a filter whose impulse response is the time inverse of the transmitted signal.

At least two features of real icebergs, namely three-dimensionality and inhomogeneity, will tend to make the time difference less than Δt. For example, if the plate of ice is replaced by a rough block of ice and the radar beam is slightly inclined to the thickness dimension, so that returns from the far edge are received both by transmission through the block (low frequency) and through air (high frequency), then the duration of the received pulse having a transmitted duration T will be $T + \Delta t_1$ at high frequency and $T + \Delta t_2$ at low frequency, where

$$\Delta t_1 \approx 2\ (R_2 - R_1)/c_o$$

is the two-way propagation time in air from the front surface to the back surface, and

$$\Delta t_2 \approx 2n\ (R_2 - R_1)/c_o$$

is the corresponding two-way propagation time in ice. Also, c_o is the speed of light in vacuum. The difference in propagation times is

$$\Delta t_2 - \Delta t_1 \approx 2\ (n-1)(R_2-R_1)/c_o$$

which is to be compared with the corresponding result

$$\Delta t \approx 2\ n(R_2-R_1)/c_o$$

for the plate of ice. For example, if $n = 1.7$, then $\Delta t_2 - \Delta t_1 \approx 5$ ns/m. target thickness which is about 1/2 the time difference for the plate. However, this reduction is likely to be an extreme value for homogeneous ice because the extent of the iceberg beneath the sea surface is much greater than its extent above the surface. For inhomogeneous ice, reflecting or scattering surfaces may prevent appreciable penetration to the rear side and, thus, decrease the time difference. However, it seems unlikely that the time difference would vanish. Moreover, in at least one test (ref. 11) penetration was not a problem, but multiple internal reflections may have occurred. If the time difference for inhomogeneous ice cannot be resolved, it is still possible that the iceberg can be distinguished by noting the difference in decay of the penetrating and nonpenetrating radiation. For ships, the decay should be similar at both frequencies, whereas for icebergs, it should be quite different.

B2. Spatial Spectrum Difference

If a target is resolved, so that information is obtained regarding its shape, then the target image may be Fourier transformed to obtain its spatial spectrum. The spatial spectrum may provide a sensitive test not only for identifying a target but also for estimating its dimensions and orientation.

In general, the resolved image of a ship cross-section mapped by airborne radar or radiometry might tend to possess axial symmetry. The corresponding cross-section of an iceberg should generally not possess axial symmetry.

If the cross-section is axially symmetric, then the spatial spectrum is also axially symmetric. For example, the well-known spatial spectrum of a rectangular cross-section is essentially a "barred" cross with its most closely spaced intensity maxima in the direction of the length of the rectangle. In the ship-iceberg problem, this spectrum would imply a ship target. The relative spacing of the spectrum intensity maxima would indicate the ship orientation. The minimum spacing y_i $(i = 1,2)$ of maxima permits calculation of the ship dimensions x_i using the simple relation

$$x_i \approx k/y_i$$

where k is a constant for specified maxima. (This formula is easily derived from the optical problem of the spacing of extrema in Fraunhofer diffraction by a rectangular aperture.) Note that as the target gets smaller, the spacing of the maxima gets larger. This accounts for the sensitivity of the method. The major dimensions of the ship are determined by the minimum spacing of selected orders of diffraction extrema along and normal to the symmetry axis.

Assuming that the radar image of a ship is axially symmetric, the potentiality of the method can be tested by optical means. Although the radar return from a target contains information on both amplitude and phase, in determining symmetry of the image cross-section of the target, intensity information is sufficient. Thus, radar images of targets can be photographed on film, so that the target is represented by a transparent aperture on an opaque background. Each aperture may be illuminated by a collimated laser beam to obtain the spatial Fourier transform (spatial spectrum) of the aperture at the back focus of a lens placed behind the aperture (fig. 1). The target may then be identified by observing whether the the transform is spatially symmetric about an axis (ref. 26).

Although it may be easy to identify the nature of the target by visual inspection of its spatial spectrum, the identification may be more difficult to accomplish by automatic means. One possibility is to orient the target major axis perpendicular to a split slit located at the transform plane (fig. 1) and centered on the target axis. Two equal photocells, one behind each slit, detect all illumination transmitted through the slits. The split slit scans the entire spectrum by moving parallel to the target major axis. If the output voltages of the two photocells are equal throughout the entire scan, then the spectrum and associated target must be symmetrical about the translational axis. Hence, the target must be a ship. If the photocell outputs do not remain equal throughout the scan, then the target is asymmetrical and is presumed to be an iceberg.

C1. Discrete Components in Frequency Spectrum

This and the following methods are intended to apply when the target appears to be a point.

Man-made targets such as ships are generally simple geometric shapes or include substructures having simple geometric shapes. On the other hand, icebergs possess nonsimple shapes. For target dimensions and microwave wavelengths corresponding to the resonance regime, large fluctuations of reflected amplitude may occur as a function of wavelength. This is particularly the case for rectangular plates exposed edge-on and for spheres (ref. 21, p. 526 and ref. 5, p. 21). However, plates face-on do not display resonances (ref. 21, p. 524). Thus, it is possible that the spectra of ship targets in the resonance regime may have intense discrete components, whereas those of icebergs do not. Radars operate at wavelengths ranging from 10^{-2} meters to 10 meters. Target dimensions equal to or exceeding these wavelengths may potentially produce resonance reflections.

The signal at a given wavelength may be scattered, resonantly reflected and optically reflected, depending on the size, shape and orientation of the various reflecting structures comprising the entire target. For a given structure, material, and imposed radiation amplitude, the amplitude of the resonantly reflected radiation always exceeds that of the scattered radiation, but may be either greater than or less than that of the optically reflected radiation. Except in special cases, such as a rectangular plate exposed edge-on, the resonantly reflected intensity likely exceeds that optically reflected by less than 10 dB (cf. refs. 5 and 27). Unfortunately, the resonance reflection occurs only for precise orientations of the target and tends to decline drastically for other orientations.

Usually in the optical regime the radar cross-section tends to increase as the target area increases. Therefore, a target substructure must be comparable in size to the entire target if there is to be a reasonable expectation of detecting resonance. For most resonance-inducing geometries, the resonances are most likely to occur if the significant structure dimension ranges from 1 to 10 times the wavelength. (The rectangular plate viewed edge-on is a notable exception in that the resonance maximum continues to increase as the ratio of target dimension to wavelength increases beyond 10.) Thus, for target dimensions in the interesting range from 3 meters to 30 meters, a wavelength of 3 meters (100 MHz.) might be appropriate. Unfortunately, the antenna size required to obtain sufficient resolution, say $\delta_r =$ 10 meters, at this frequency is of an impractical size for both airborne and spaceborne operation. In summary, for the targets of interest the resolution is poor if resonance is to be obtained.

One possible way to overcome the preceding problems would be to transmit two pulsed frequency-modulated carrier frequencies centered at, say, 100 MHz and 10 GHz (λ = 3 cm). The former carrier would be used to study the resonance spectrum, whereas the latter would be used to locate targets. The 100 MHz. carrier would be transmitted and received inefficiently, which would have the desired effect of reducing the maximum detection range toward that of the 10 GHz. carrier. One problem with this system would be that of distinguishing ships from icebergs among a mixed array of targets because of poor resolution.

Because of the critical conditions required to obtain resonance reflections and because the resonances are not likely to be intense relative to the background, it would appear that a pulse-by-pulse analysis of the return spectrum might be necessary to detect the resonances.

C2. Doppler Spectrum Difference

This method might be used to distinguish among targets by measuring their differential velocities relative to the radar. These velocities are characterized by Doppler frequency shifts of reflected radiation. For a transmitted frequency f, the received frequency f' is given by

$$f' = f + f_D$$

where the nonrelativistic Doppler frequency f_D is related to the target closing velocity v and radiated wavelength λ by

$$f_D = 2\ v/\lambda$$

The Doppler frequency is measured by evaluating $f' - f$ in the receiver. Each target (ship, iceberg, or waves) produces an individual Doppler frequency shift as a result of its radial velocity relative to the radar. A ship may have radial components, hence a Doppler shift, due to ocean currents, ocean swells and buffeting by ocean waves, but also due to its propulsion and wake. An iceberg's motion, except for the propulsion component, will be similarly affected, although not by the same magnitude, so its Doppler shift may be different. Finally, the ocean's reflected return, called "clutter," results from its own motions; that is, currents, swells, waves, and also wind-induced spray. Due to the nonuniformity of target motions, the Doppler spectra are somewhat broadened. Ships and icebergs are likely to possess narrow-band spectra, say 10 to 20 Hz. wide, whereas sea-clutter spectral bandwidths are more nearly 50 to 100 Hz. Because of the different mean motions, each spectrum may peak at a different frequency so that the desired target can be detected by filtering its spectrum out of the clutter spectrum.

Early versions of Doppler radar yielded at X-band (10 GHz.) a Doppler resolution of 10 Hz., corresponding to a radial velocity of one-third knot (refs. 28 to 30). Submarine snorkels were detectable in sea clutter if the Doppler-spectrum peaks corresponded to a radial velocity difference as small as 1 knot. For radial velocity differences greater than 3 or 4 knots, there was no interference between the snorkel and clutter spectra. More sophisticated, coherent, continuous-wave (CW), Doppler radar in the form called moving target indication (MTI) radar and pulsed Doppler radar has since been developed (refs. 31 and 32, chaps. 17, 18, 19). In coherent radar the return signal is compared with the transmitted signal so that both amplitude and phase information are recovered in the reflected signal. The CW radar sacrifices range accuracy for velocity resolution, whereas, for pulsed radar the converse is true. These radars may yield more refined data on target motion and aid in target identification.

In flying a constant course relative to the direction of wave motion, it should be relatively easy to extract the target Doppler spectrum from that of the clutter. The most difficult target to detect (neglecting questions of signal-to-noise ratio) would be one moving with the waves at a speed such that the target and clutter Doppler spectra peak at the same frequency. This target could not be an iceberg. A side-looking Doppler radar would not detect targets moving parallel to the aircraft. However, if the aircraft radar scans in azimuth, then targets moving in a straight line will have a radial component of motion at some scanning angles. In calm water, ships and icebergs are probably not distinguishable if both are drifting. However, if there is appreciable wave action the two targets may be distinguishable by virtue of differences in their motion. For example, since the mass and volume of an iceberg is mostly submerged, whereas that of a ship is not, the iceberg motion may be less subject to surface wave action than that of a ship of similar displacement. Thus, an iceberg Doppler spectrum may be narrower than that of a ship because the iceberg may exhibit less rolling motion than a ship. Because of its submerged mass, the Doppler spectrum of the iceberg may exhibit greater attenuation at higher frequencies than that of a ship with a similar cross-section. Finally, certain icebergs, called "growlers," submerge momentarily. "Growlers" might be distinguished by slow scintillation of signals as the target periodically submerges.

C3. Depolarization Difference

Radar cross-sections of ship targets are often independent of the plane of polarization of the incident radiation. However, for any plane of polarization of the incident radiation a certain portion of the radiation reflected from most targets may generally have components of polarization in other planes; that is, will be depolarized. For singly-reflected backscatter this depolarization of plane polarized incident radiation will not occur if any of the following conditions apply (ref. 17):

1. The radiation is imposed at grazing incidence.

2. The plane of polarization of the incident radiation lies in, or is perpendicular to, the local plane of incidence.

3. The target is a perfect conductor.

4. The incident radiation is normal to the target surface.

The specular components add coherently, whereas the diffuse components add incoherently. Only the diffuse components contribute to depolarization (ref. 17). Thus, if the surface roughness exceeds the radiation wavelength, depolarization may be minimal. Since the surface roughness of man-made targets tends to be less than for natural targets, relative depolarization of backscattered radiation tends to be less for man-made targets (ref. 14).

Relatively little depolarization is produced by ships (about 10 dB, or 10 percent, for transmitted horizontally polarized radiation and slightly greater for vertically polarized radiation) (refs. 33 and 34). In addition to depolarization by diffuse scattering, specular back-reflection off mutually perpendicular surfaces may produce depolarization. In particular, depolarization occurs if the plane of polarization is neither parallel to nor perpendicular to the line of intersection of the reflecting planes. If this line of intersection is rotated through an angle Θ about the axis of propagation of the incident radiation, then the plane of polarization of the reflected radiation will be rotated through an angle 2Θ (ref. 33). Rotation of the plane of polarization of reflected radiation might occur in this manner from a ship as a result of its pitch and roll.

The depolarization by icebergs may be somewhat greater that that by ships. Plane polarized, ultra-high frequency (440 MHz), pulse-modulated radiation penetrating glacier ice has displayed polarization rotation up to 85 degrees and a polarization ellipticity ratio as great as 6 dB (ref. 35). The latter implies ratios of depolarized to polarized power as great as 25 percent, although most values were lower than 1 percent. Nevertheless, the possibility of obtaining relatively large values of depolarization and/or large values of rotation of the plane of polarization by icebergs indicates that they may, in this manner, be distinguishable from ships.

As a possible way to detect and identify a target, a plane-polarized wave is transmitted, whereas both parallel- (to the transmitted wave) and cross-polarized waves are received. All return signals whose parallel-polarized amplitude or whose ratio of cross- to parallel-polarized amplitude exceeds preset values determined to, at least, exclude clutter are recorded. Any signal which exceeds these preselected thresholds is assumed to be from a target. Any signal which exceeds the polarization ratio threshold is assumed to be from an iceberg since this threshold has presumably been preselected to exclude man-made targets, as well as clutter. All non-iceberg targets are assumed to be ships.

The radar wavelength may be optimized by evaluating roughness spectra of ships, icebergs and the sea. It is to be expected that the roughness spectrum of a ship will be a maximum at low discrete spatial frequencies corresponding to ship structure dimensions. The iceberg roughness spectrum should not include discrete components. The sea roughness spectrum may be broader and more uniform than the other two. By choosing a radar wavelength which is shorter than the wavelength range of the dominant part of the ship roughness spectrum but is located well within the dominant part of the iceberg and sea roughness spectra, the depolarization of the iceberg and sea returns relative to that from ships will be maximized.

As noted under "Reflectivity," the polarization ratio technique has been used successfully to detect periscopes and snorkels. For calm sea and grazing incidence, vertically-polarized transmitted radiation gave a stronger return, whereas if the sea were rough, horizontally-polarized transmitted radiation gave a stronger return (ref. 14). In general, horizontally-polarized transmitted radiation was preferred.

C4. Doubly Reversed Circular Polarization Difference

When a circularly polarized wave is specularly reflected by a simple plane surface, the sense of rotation of the reflected wave is the reverse of that of the incident wave. If the incident wave is doubly reflected off two plane, mutually perpendicular surfaces, then the back reflected wave is circularly polarized in the same sense as the originally incident wave. If the incident wave undergoes three reflections, as in a right-angled corner, then the sense of rotation is reversed again and is the same as that for one reflection. Thus, the sense of rotation of back reflected radiation is the reverse of that of the incident wave for odd numbers of reflections and is the same for even numbers of reflections.

In the far field, single reflections cover a solid angle of measure zero and, hence, are detectable only at isolated points. For a monostatic radar, back reflection occurs only if the reflecting plane is perpendicular to the propagation direction of the incident radiation. Double reflections off two mutually perpendicular planes yield back reflection along an arc lying in a plane perpendicular to the line of intersection of the reflecting planes and bounded by the reflecting planes. Triple reflections off three mutually perpendicular planes produce back reflection over a solid angle bounded by the planes themselves.

Since man-made targets tend to be smooth, whereas natural targets generally are not, the double polarization reversal might be used to distinguish ships from icebergs.

DISCUSSION AND CONCLUSIONS

Since the objective is to distinguish between ships and icebergs in the simplest manner and since some of the methods cited herein may prove satisfactory, more complex possibilities involving tests of statistical quantities (ref. 36), symmetry considerations affecting polarization (ref. 37), target reconstruction from Doppler spectrum recordings (ref. 38) or interferometry (ref. 39) have not been considered.

Among all possible methods for target identification, those which do not require resolution of the target are preferred because, in practice, many targets of interest, especially those off the flight path, are likely to be near or beyond the limits of resolution of radar (and radiometers). The polarization methods utilizing radar may require more than one antenna. However, the depolarization method has already been found effective for detecting small targets in a sea clutter background. Therefore, this method is preferred among those listed. The method of doubly reversed circular polarization may also prove satisfactory. The

Doppler spectrum method has also been used to detect targets in a sea clutter background. However, there is a question as to whether Doppler spectra of ships and icebergs would always be sufficiently different to permit target identification. Among the methods for unresolved targets, the frequency-spectrum method appears least satisfactory because resonance reflections are not likely to be sufficiently intense to be clearly distinguished from the background continuous spectrum of the target.

Because of the wide variety of geometries possessed by ships, and especially by icebergs, little attempt has been made to predict the usefulness of any of the methods by computations. The possible situations are too varied and the computations too difficult to reach any general conclusions as to which, if any, method proposed will work and is best. It appears that the most desirable course of action is to select one of the methods, preferably one of the polarization methods first, and to try it experimentally while simultaneously proceeding with detailed calculations to optimize the system.

Microwave radiometry may be used for target surveillance beneath the aircraft, where radar resolution is poorest; whereas, elsewhere, radar may be used for scanning out to the horizon.

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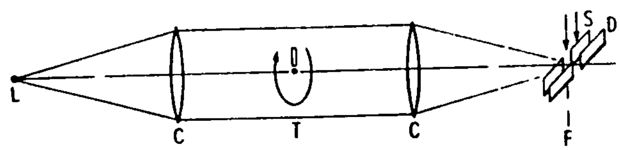
Table III - Radar Cross-Sections of Ships

Ship type	Planform Dimensions, Meters	σ_{dbsm}	Polarization	Frequency, GHz	Depression angle	Ref.
Picket	134.4x17.4	27 to 47	VV, VH	X-band 10(?)	5 - 45	40
Small submarine, Large freighter (1944)	----------	-8.6 to ·11.7	------	10	0	2
$\geq$ LST's	----------	30 - 80	------	3	0	19
Wooden Minesweeper	43.9x8.5	19	VV, HH	X-band 10(?)	0	12
Cargo ship	84.7x13.4	40 $\pm$ 20	------	X-band 10(?)	16 - 22	42
Submarine	93.3x8.4	15 $\pm$ 5	------	X-band 10(?)	10 - 15	42
Small landing craft & rafts	----------	-13 to 18	HH	X-band 9.38	0	43,44



L - Light source
C - Collimating lens
T - Rotatable target plane
F - Fourier transform plane (spatial spectrum)
S - Translatable split slit
D - translatable twin photo-detectors

Figure 1 - Target-symmetry dectector

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16 Abstract

Summary of the simplest methods for aerial remote sensing which are least affected by atmospheric opacities. Radar is preferred for targets off the flight path and microwave radiometry for targets along the flight path. Radar methods are classified by ability to resolve targets Techniques which do not require target resolution are preferred Among these techniques, polarization methods appear most promising, specifically those which differentiate the expected relatively greater depolarization by icebergs from that by ships or which detect doubly-reversed circular polarization

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