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SOME APPLICATIONS OF RADAR RETURN DATA TO THE STUDY OF TERRESTRIAL AND OCEANIC PHENOMENA*

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ABSTRACT

Exciting new possibilities for scientific and practical research will be opened by the use of imaging and altimeter-type radars mounted in orbiting spacecraft. An all-weather, day-or-night capability for high-resolution mapping and scattering cross-section studies is now recognized as being within current state of the art and sophisticated multi-frequency, polypolarization coherent imaging systems are currently under study which have the potential to greatly aid all resource-oriented sciences. Among the many new possibilities are: a) substantial contributions to unravelling the mass budgets of the Antarctic and Greenland ice caps, b) improvement of our knowledge of undulations of the geoid, c) synoptic and long-run monitoring of sea-state, with attendant estimates of wind strength and direction, of the gross-storm-derived energy flux near coastlines, and of oceanic climatology, d) monitoring of sea ice movement and remote arctic and tropical floods, e) improved geologic mapping in structurally complex areas, f) complete revision and updating of all maps of remote arid and arctic regions, and of many coastal and island areas surveyed decades ago, and substantial revision of many maps of better-known areas at scales of 1:250,000 and smaller, g) world-wide study of vegetation, including cultivated lands.

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INTRODUCTION

Very rapid advances in radar technology have taken place since World War II. While most of the advances in capabilities for air traffic control, and operational and research meteorology have become common knowledge, the scientific community has been largely unaware of the applicability of side-looking radar imaging systems to a wide range of geoscience research problems. However, the relatively few studies which have been made, together with data being accumulated in feasibility studies currently funded by NASA at the University of Kansas, GIMRADA, and other institutions leads us to the view that the wedding of radar to manned orbital spacecraft will be scientifically fruitful.

In this paper the bases for our belief are given using examples drawn mainly from our own research. Many additional applications of spacecraft-borne radars are deserving of treatment in detail, but for a number of reasons are either largely ignored here or are discussed but briefly.

We have given our attention primarily to the following topics:

a) Radar mapping

b) Characteristics of existing radar imagery

c) New capabilities to be tested in imaging systems

d) Radar altimetry

e) Terrestrial applications in geology, glaciology, geomorphology, pedology and agriculture

f) Oceanic applications related to sea-state sensing

THE DEVELOPMENT OF RADAR MAPPING CAPABILITY

Mapping with radar had its origins in 1948, when Lt. H. P. Smith[1] used radar imaging to show that the relationships of Greenland, Ellesmere Island and the Canadian Mainland were incorrect on air charts of that date. In the same year, Ensign Reynolds, U.S. Navy, flying a mission of aerial photography in Antarctica, noted in his log that he had cut off his cameras when overflying an area of dense stratus, but that he had photo-recorded his radar scope and hoped it would be useful in mapping the large bay he saw on his scope. The large bay was the west edge of the West Shelf Ice.[+] Both of these men recognized the value of WW II vintage PPI (Plan Position Indicator) radars for continental scale mapping in areas of adverse weather.

Figure I is a sketch map of a portion of Antarctica compiled by Scheps in 1957[2]. In constructing this map Scheps used radar imagery to establish the scale and horizontal control networks, and used trimetrogon aerial photography to provide much of the detail. The accurate ranging ability and the very large area of radar coverage readily permits the efficient creation of a net for such purposes. This and other studies have demonstrated that horizontal map control furnished from PPI radar is often as accurate as that of trimetrogen aerial photography for reconnaissance mapping.

Contour maps have also been compiled solely from PPI radar photos. In Fig. 2 is shown an area near Denver which was contoured with PPI imagery. These contours were derived by treating the central void or altitude hole in the middle of a PPI radar photo as an altimeter. A series of altimeter readings and shadow measurements gave elevation points between which the contours were interpolated.

The early 1950's saw the birth of side-looking radars. Their earliest development integrated PPI radar with side-looking radar to obtain a mapping capability.[3] This system used the inherent data redundancy from successive PPI radar images to form the control net on which to orient the higher

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[+]Map of the West Shelf Ice, U.S. Geological Survey, Map #E-1-66-12, 1957.

resolution detail of the side-looking radar. About the same time, computer techniques for making block adjustment of control were devised. Then, in the late 1950's, systems configurations were simplified in response to military needs, and mapping techniques were devised to utilize side-looking radar along with supplementary navigation data.[4] These techniques have been thoroughly tested and the accuracies attainable are a function of navigation system accuracies, a constantly improving technological area. With this development, block adjustments of control are now made by computer from navigation inputs, and distance measurements from the radar imagery.

In addition to this planimetric mapping capability, radar developments to obtain relief information have also progressed rapidly. The early example in this paper (Fig. 2) of contouring near Denver was more a tour de force than a practical capability. However, recent work has looked into several promising techniques. One of these, radar stereoscopic photography, can be obtained by flying overlapping imaging runs.[5] Appropriate flight height versus flight line spacing proportions are chosen to optimize parallax relations so that heights relative to a datum can easily and unambiguously be obtained from the radar photography. Techniques for employing rather normal stereo-mapping techniques have also recently been suggested by Levine.[6] Another approach investigated has been the use of interferometric principles,[7,8] in which the path length difference to two vertically stacked (active and passive) antennas from points on the terrain varies with angle. By mixing the two received signals an interference signal displaying peaks and nulls may be recorded. Thus the interferometric technique adds angle data range data and permits unambiguous description of three-dimensional terrain. Figure 3 illustrates the principles involved.

Along with side-scan radar and three-dimensional techniques, instruments have been developed in prototype to aid radar mapping. These include a radar-sketching device (Fig. 4), a radar-viewing measuring instrument (Fig. 5), and a side-looking radar restitutor (Fig. 6). Other, more advanced instruments are being developed as a result of tests on these prototypes. Such instruments are needed for block adjustment of control and rectification of image geometry.[9] As examples of current developments, three figures are given here. The first is a radar-derived contour map (Fig. 7) covering the Harper's Ferry, West Virginia area which may be compared with the standard U. S. Geological Survey sheet of the same area (Fig. 8). The second (Fig. 9) is the Dyersburg, Mississippi 1:250,000 map sheet. Portions of the Mississippi River on this sheet were derived from radar photos by employing the radar sketching device shown in Fig. 4. The final example (Fig. 10) is a map of Abilene, Texas, produced solely from side-looking radar. To maximize the geometric fidelity of radar imagery, indications of which are given in the above examples, objective test procedures and test areas have been developed. These include grids of radar corner reflectors laid out on Wilcox Dry Lake, Arizona as reported by Scheps.[10]

To summarize these developments, it is fair to say that the current mapping capabilities of radar and ancilliary instruments are such as to meet requirements for mapping at a scale of 1:250,000. A series of comparisons of unrectified AN/APQ-56 radar images with 1:250,000 maps of the Mobile, Vicksburg, Boulder and Birmingham areas, U.S ., by Simons and Beccasio[11] led them to conclude that scale variations on radar imagery are "somewhat better than maps at the same scale, provided that one restricts measurements to a small segment of the imagery."

CHARACTERISTICS OF EXISTING SIDE-LOOKING RADAR IMAGERY

Side-looking radars have the following features:

a) highly directional transmitting and receiving capability

b) very short pulse length of the order of 0.1μ sec, which reduces the dimensions of a ground resolution patch, by reducing the dimensions of resolvable range elements

c) very narrow frequency range of operation in comparison to conventional panchromatic aerial film

d) optimized signal to noise ratio, by varieties of radar parameters (e.g. pulse repetition frequency)

e) unusually precise time-determined range measuring capability

f) resolution inferior to that of conventional photography, so that the clutter of redundant details is reduced

g) a substantially planimetric, non perspective, equivalent ground range imagery display

h) broad aerial coverage up to 40 miles wide with high-flying aircraft

i) with normal commercial film-packing densities, areas of 40 x 40 miles can be displayed in film 5 miles square. Consequentely, radar imagery of this type is a remarkable generalizing tool for reconnaissance study of the natural landscape.

j) all-weather capability for obtaining imagery, except for short wave length systems and these are restricted only by deep precipitating cloud masses.

The above combination of characteristics is the core of radar mapping abilities insofar as systems geometry is concerned. The remainder of this capability stems from the ability of radar interpreters to unambigously identify natural and cultural objects in radar imagery. This is by no means always easy, for the radar return signal from a given resolution patch of terrain is a composite related to surface roughn ess parameters, dielectric properties, polarization, volume scatter of penetrating waves, and the angular dependence of the above.

Much existing radar imagery has been obtained with systems operating between 8 gigacycles (8×10^9 cps) and 35 gigacycles (gc). Within this frequency range the contributions of the above parameters to the return signal may be summarized as below:

a) roughness parameters of the surface. Radar theory recognizes that there is a relationship between radar wave length and the nature of surface scatter. A commonly used relation[12] is that surfaces with roughness less than $\lambda/10$ are likely to appear smooth to the wave length in question. For a 35 gc system (wave length 8.6 mm) this means that height variations of the order of 3 or 4 mm per cm are likely to be "rough" as far as the radar is concerned, and the scatter will be that of a rough surface. Indeed, surfaces which appear smooth to that wavelength are likely to be rare--a cement road, a pond at dawn unruffled by breezes, but relatively little else. The degree to which the geometric properties of the surface are organized within a ground resolution patch for the radar is probably a major component of the return signal for these frequencies. In the absence of unequivocal evidence, it is our guess at this time that a good deal of the interpretation which is made with K_a band radar (35 gc) rests on variations in geometry of surfaces.

b) Dielectric properties. Variations in electrical characteristics[13] (conductivity, permittivity and permeability) of natural and cultural objects affect the return signal. Wet versus dry ground along the edges of marshes are sharply differentiated; water is clearly separated from land, probably largely on its dielectric properties. The significance of variations in dielectric or lesser order than these examples is unknown. As a component of the return signal it is probably swamped much of the time by variations in surface roughness, at least with short wave-length systems.

c) Polarization of the surface. The effects of various degrees of anisotrophy of the surface are suspected as being of importance, but are as yet undocumented for geoscience purposes. Many side-looking systems in the 35 gc frequency use a horizontally-polarized pulsed energy source, with a receiver designed only to receive the horizontally-polarized return signal. The degree of depolarization, if separable from the other components of the return signal, should be a valuable parameter to aid in identification of surfaces.

d) Penetration of surface. Penetration of objects is wave length dependent, and is also a function of the dielectric. Watt, Mathews, and Maxwell,[13] indicate that penetration at 35 gc is likely to be very limited (the relevant skin depth,[13] is certainly less than a centimeter except for dry sand).

e) Back-scattering cross-section (σ_o vs. Θ). A number of studies[14,15,16] have indicated that for certain types of natural objects the energy return varies only a few db for a wide range of beam-incidence angles (in the range 20 to 70°), while for others, the return varies widely and shows a strong angular dependence in the 20 to 70° range. These variations between different surfaces in this respect when adequately documented should prove useful in aiding identification. At present, however, it still remains very much an unknown in analysis of radar imagery, though continuing studies at Ohio State University with truck-mounted equipment and at the University of Kansas and GIMRADA using aircraft are directed towards quantitative evaluation of σ_o vs. Θ for a variety of known, documented surfaces.

NEW SIDE-LOOKING RADAR CAPABILITIES

NASA is supporting feasibility studies at present at The University of Kansas, GIMRADA, Ohio State University and Waterways Experiment Station and a number of other institutions which are devoted to evaluating the value of sophisticated multi-frequency, polypolarization, coherent imaging systems for geoscience purposes. These studies (in which data has yet to be received in an imaging mode) in effect rest on experience with multi-spectral photography (Colwell et al[17]), and multi-band infra-red imagery (Holter[18]) which strongly suggests that a four or five-frequency system will give a substantial information gain over that from a single frequency.

In the same manner the use of multiple polarizations rests on the knowledge that many objects in nature (trees, crops, rocks, soils) are anisotropic in their dielectric field, crystal orientation, bedding and foliation and so on, and hence are potentially separable by combining frequencies and polarizations.

It is expected that the first results from aircraft with these capabilities will be available for analysis in the late summer of 1965, and within a year or two we should have enough information to give NASA a firm basis for evaluating the contribution to the geosciences of polychromatic radars on manned spacecraft in earth orbit.

THE DEVELOPMENT OF RADAR ALTIMETRY

Along with imaging radars on manned spacecraft, we anticipate a significant series of roles for radar altimeters, particularily in sea-state sensing and for profiling the Antarctic continent.

Radar altimeters, as altimeters, were developed prior to World War II[19] and during and since that conflict, both military and commercial versions have been refined considerably in both size and accuracy. In this paper, however, altimetry is given a broader definition, since it is used for a downward pointing radar illuminating a relatively wide area to obtain information both on altitude and on the scattering properties of the surface within, say, 45° of the vertical. Both pulsed and frequency-modulated altimeters have been used widely for altitude measurement; for scattering coefficient measurement pulsed, narrow-beam continuous, and Doppler measuring wide-beam continuous systems have been used.

Altimeter accuracy depends both on instrumental factors and on the variation in elevation of the illuminated patch. Instrumental errors may be capable of reduction to a foot or two for a unit designed for scientific use (not operational use), with adequate calibration, and with averaging over a large number of independent fading return pulses as suggested by Godbey.[20] Fluctuations in terrain level over the illuminated patch may make such accuracy quite impossible over land, but over sea, the mean surface may be measured to this precision, although it has not been experimentally verified.

Measurements of scattering coefficients as a function of angle of incidence for numerous terrains have been made since the beginning of World War II.[21] These have had as their objective: 1) determination of design parameters for radar systems including altimeters, 2) correlation with scatter theory, 3) determination of the detectability of military targets in ground or sea clutter. Only recently has any attempt been made to use the "signatures" so obtained for remote sensing of information of geoscience value. Major past programs involving aircraft flights with near-vertical measurements have been reported by Davies and Macfarlane,[22] Campbell,[23] Edison, Moore and Warner,[24] and others.[25] Careful laboratory measurements from grazing to within 10° of vertical were reported by Cosgriff, Peake, and Taylor.[26]

Results of all the measurement programs are difficult to evaluate because of lack of adequate ground control information on most programs. It is clear, however, that for a given material the "smoother" the surface, the more the scatter increases near the horizontal and the more rapidly it falls off with angle near the vertical. Thus smooth sea gives a stronger echo near the vertical than rough sea, but at angles of 10° or so it falls off to a lower value than that for rough sea. The same applies to other material, such as sand. Also clear is the fact that, at the vertical, water surfaces give the strongest echoes found for any natural environment, while deserts and forests usually tend to give the weakest--deserts because of the material, and forests because of their roughness.

EXAMPLES OF POSSIBLE TERRESTRIAL APPLICATIONS OF SPACECRAFT RADARS

Many applications are possible for attempting hitherto infeasible experiments in a number of fields. We have chosen a few areas for special emphasis here, both because of our own interests or radar publications in these areas and because spacecraft-borne radars seem peculiarly apposite for the experiments or mapping in question. The use of radar for high latitude studies very much fits the latter category.

Glaciology

One of the most significant challenges presented to glaciologists is to define the mass budget of the Antarctic and Greenland ice sheets. Analyses such as those of Meier and Post[27] and Weertman[28] on the rates of growth and shrinkage of glaciers and ice sheets could be altered or bolstered with data on the budget of these ice sheets. We would suggest that a two or three-frequency radar altimeter system coupled with a polychromatic, polypolarization imaging radar system in an orbiting spacecraft could (with adequate tie-in to ground measurements) define many of the parameters needed for such a study.

Consider the difficulties of tackling such a problem without spacecraft, using earth-bound and aerial techniques. The minimum requirement is near-synchronous accurate profiling of the surface to at least several meters, accurate positioning of the edges of the sheet to say 200 feet with repeated monitoring of iceberg calving, and at least a first guess at ablation loss. If at all feasible, this should be coupled with continuous ice-thickness measurements. In a recent article on aerial triangulation in the Antarctic, Brandenberger[29] discusses at length the multitude of difficulties in cartographic work there. Some of these difficulties are:

1) A dynamic, ever-shifting surface, in which an annual movement of 600 meters is not unknown. This makes for great difficulty in establishing "fixed points" for triangulation.
2) Many astronomic positioning methods are weak in the Antarctic.
3) Vertical displacements of ice also take place.

Brandenberger concludes that "this crucial problem of the cartographic exploration of the Antarctic continues to exist and at present it is difficult to say how this problem should be solved. The solution to this problem requires additional research and investigation...." A radar spacecraft is worthy of serious consideration as a means of tackling the problem. Since the position of a spacecraft in its orbit is known to within approximately 10 feet and radar-determined range with a side-looking system may be obtained from the spacecraft with at least comparable accuracy, many positioning problems could be met with acceptable accuracy for a mass of the dimensions of the Antarctic.

Crary,[30] writing of U.S. traverses in East Antarctica, 1958-61, has stated that "the present traverse operations in Antarctica, though providing an overall description of the elevations, ice thicknesses, and snow character, are not adequate to treat the dynamics of the ice. The details of the strain values, flow pattern, particle paths, and densification require concentrated work in limited areas for long periods of time, and particularly along flow lines where phenomena that are observable at the surface, or determined at depth with drilling operations, can be correlated with the ice flow parameters." The God's eye view from spacecraft could substantially alter Dr. Crary's estimate of "long periods of time," at least for part of our answer. Studies are urgently needed to determine whether corner reflectors dropped as suggested by Simonett[31] over sample areas of Greenland or Antarctica could be tracked by polychromatic radar in spacecraft, day or night, winter or summer, covered in snow (if cold enough) and even to some degree embedded deep in snow. If this is feasible, it would aid the analysis of stress-strain rates and other parameters required in glaciological studies (Kamb[32]) which could be defined with an accuracy adequate enough for Antarctic-continent analysis (probably to 3rd order planimetric level) (Adler[33]). Truly detailed work accurate to a foot or less will still require conventional methods and radar cannot serve such ends. A radar mapping project coupled with detailed study on the ground could be the answer to Dr. Brandenberger's question.

During the period from June to August 1964, joint studies on radio echo sounding of the Greenland ice sheet were carried out by the Scott Polar Research Institute (Cambridge, England), the U.S. Army Electronics Research and Development Laboratories, and the U.S. Army Cold Regions Research and Engineering Laboratories, as reported by Bailey, Evans and Robin.[34] These studies obtained continuous profiling of the bottom surface of the ice over 97 percent of the route travelled, using a 35 mc frequency and energy pass band of 14 mc. Thicknesses of ice of 1400 meters were measured and it was found that depth of penetration was markedly temperature dependent -- "the echo strength was then up to 30 db (when measuring 1400 meters of ice) above receiver noise level and the mean temperature of the upper part of the ice sheet was -24° C. However, difficulty was experienced in following a bottom echo through an ice thickness of 500 m when the ice temperature was close to 0° C." These ground traverses, with an antenna supported at least 3 m above the snow surface, have in effect confirmed the reports by Waite and Schmidt[35] that radio altimeters operating at a frequency of 440 mc could be used to obtain echoes through polar ice sheets up to 300 m. thick. In January, 1965, members of the University of Wisconsin Antarctic study group used a 30 mc system developed by Waite[36] to measure ice thicknesses at the South Pole of some 9,300 feet.

Bailey, Evans and Robin[34] note further that "the ability to obtain a continuous record will be of great help towards our understanding of the factors governing the surface form and flow of the ice sheet, since our knowledge has been limited hitherto by the difficulty of obtaining a general picture of bottom relief from the spot soundings from seismic shooting or from the areal figure presented by gravity measurements."

Sea and lake ice thickness measurements with a 200-700 short pulse radar system, representing a modification of the system proposed by J.C. Cook,[37] are underway by Adcole Corporation of Massachusetts under contract to the U.S. Army Cold Regions Research and Engineering Laboratory (James McLerran, personal communication) and results obtained from helicopters indicate capability of measuring ice thicknesses from 11 cms to 60 meters.

The step to spacecraft will pose many difficulties in evaluating the radar return signal with penetration of ice together with problems of Faraday rotation of the polarized signal, and other difficulties with auroral interference. Consequently, at this point it seems as if radio profiling of the bottom of the Antarctic and Greenland ice sheets will need to be carried out by low-flying aircraft and ground traverses. Neither will be easy. However, the attractiveness of being able to do this from spacecraft will certainly stimulate thinking among radar theorists. The key problem is to clearly separate slant range echoes at the surface from equivalent range bottom echoes beneath the ice. With a fan-beam altimeter this poses a very difficult problem. At present, it appears that a very narrow beam, highly directive altimeter is required and this would necessitate a very large antenna of the order of a hundred meters. The auroral problems, of course, would still remain, though some shots through the Polar low-auroral intensity area should be possible, and during the course of a year or more some passes would be at times of auroral minima. It is an intriguing problem.

The reverse problem -- that of accurately profiling the Antarctic surface -- can be met with much greater ease by the use of a spacecraft-mounted 8 gc radar fan-beam altimeter. The resolution patch would be large (15 km), but the average elevation could be determined accurately to $\pm$ about 2 meters, if the surface is reasonably smooth and repeated passes would enable more accurate elevation determinations in rough areas than might at first sight seem feasible. A more sophisticated system employing interferometry for profiling is currently under study for spacecraft. If such a system proves feasible in conjunction with coherent side-looking radar, detailed contour maps of the glacier chutes of Antarctica could be made from spacecraft[9, 38]. Stereo radar, also under study in both the classified and unclassified literature as reported by Laprade[39] and Levine,[6] could aid contouring in Antarctica. Finally, a chirping altimeter system could reduce the resolution patch to about 1/10 that of a simple altimeter, but at a cost of more power and complexity.

Temperate glaciers, though notably warmer than the Antarctic ice sheet and hence less amenable to studies involving radio propagation through the ice, are much shallower and many of the above techniques could be integrated with ground measurements such as those by Meier[40] and Konecny[41] in western Canada. Polypolarization, multifrequency radar offers a change to define crevassing patterns over large areas, since even small crevasses are detectable with radar, and should aid in answering questions about the mechanisms of crevassing.[30,42]

Ice cover surveys in the Gulf of St. Lawrence based upon low-resolution PPI imagery have been made by Cameron[43] and rates of movement of ice currents obtained by false parallax measurements between successive flights. Fig. 11 shows sea ice of various types in Alaskan waters.

Studies of patterned ground with air photos are now well-documented.[44,45] The capacity to penetrate frozen, very cold ground under winter conditions during the long polar night suggests that multi-frequency, polypolarization radar will add a significant fool for studying ice-patterned ground in Arctic Canada.

These examples will serve to indicate some of the grounds for optimism regarding the use of radar in Arctic and Antarctic studies. Geomorphologists and glaciologists will be able to think of many additional areas where radar could be useful in high latitude studies.

Geology

Geologic studies using radar images have been made by Fischer and Scheps,[46] Cameron,[47] Simons,[48] Simons and Beccasio,[11] and Feder[49,50,51,52,53] in the open literature. Additional classified contributions have also been made.

These studies have clearly shown that panchromatic aerial photographs and radar imagery usefully complement one another. In every case information was obtained from radar imagery which was not available in the photography, even with stereoscopic viewing, and of course the reverse was equally true.

The prime advantages the K-band (mostly 35 gc) side-looking radar commonly used in these studies brings to geologic analysis are those of the following:

1) A Generalizing Tool

Side-looking radar generalizes over very large areas, frequently many hundreds of miles long and over 40 miles wide. Using present commercial film packing densities, a 40-mile wide strip may be presented in excellent planimetric geometry in film 5 inches wide. This film then as a scale of circa 1:500,000 and can tolerate 10 to 20-fold enlargement as required. By using various enlargements for a working base, light table magnification and binocular viewing of the transparency enables one literally to have one's cake and eat it too. Grand generalizations are readily apparent without magnification. Major structural and lithological provinces are sharply defined by gray scale, stream-pattern and fracture pattern differences; and the continuity of beds in eroded complex fold regions is displayed with unusual clarity. The imagery of Burke's Garden Dome, West Virginia (Fig. 12) illustrates these points. At the same time details may be seen by enlargement, by magnification with binocular viewing of the transparency, or by zoom-optical projection equipment.

2) Angle of Illumination

The side-looking character of radar is itself an advantage for most studies, though dense shadowing does constitute a problem in some mountainous regions. Conventional aerial photography taken at low sun angles of modest relief not infrequently reveals elements of structure not detectable in photography taken with the sun at higher angles. Side-looking radars can easily cover a swath of such width that the inner edge of the imaged region is illuminated at an angle of 65° from the horizontal and the outer edge at about 10° from the horizontal. The side-looking mode thus confers on radar a valuable detection capability for geologic studies comparable to that of low angle solar illumination in conventional photography.

3) Suppression of Minor Cultural Detail

For many geologic ends, conventional aerial photography is replete with redundant information, especially minor cultural detail which serves to distract the photo-geological interpreter. This arises from resolutions, in many cases too fine for geologic purposes. The relatively gross resolution of radar much more nearly meets an optimum resolution for generalized data. Minor cultural detail is suppressed and the radar geologist is able to work faster and cleaner in interpretation. Of course for very detailed study the advantages shift to photography.

4) Detection of Faint Lineaments

Side-looking radar, because of its large areal coverage, enables the eye to integrate faint differences over long distances. Partly for this reason, and partly for presently unknown reasons, it is acutely sensitive to macro and meso and some micro lineaments, including those not emphasized in the topography by weathering, stream dissection and vegetation alignements. It is this feature especially which is immediately attractive to structural geologists, even on casual inspection. Tear faults, grabens and fracture sets previously undetected on aerial photographs have been revealed by radar as noted by Feder,[51] Simons[48] and Badgley and Lyon.[54] Cameron[47] has inferred the presence of two previously unknown thrust faults in the Gaspe Peninsula with radar imagery.

5) Some Gray Scale Differentiation of Contrasting Lithologies

Fischer and Scheps[46] studied micro-densitometer measurements of various lithologies in a radar image of an area some 100 miles southeast of Albuquerque, New Mexico. They found that the rocks in this area could be grouped into three categories, depending upon the level of brightness of their radar image. In order of decreasing brightness these were 1) igneous rocks, 2) ferruginous sandstones and 3) limestone, siltstone; gypsum and soils. These different groups displayed no overlap in micro-densitometer values despite varying aspect angles of illumination and topography, strongly suggesting, at least in semi-arid and arid environments, that some lithologies may be separated with radar. These differences may well relate to variations in the geometric properties of the surface as well as some variations in dielectric properties. In arid environments, identical lithologies (particularly eruptives) may be separable by radar by variations in geometric and conductivity-related, time-dependent contrasting weathering states. Qualitative separation of lithologies similar to those made by Fischer and Scheps, have also been documented by Simons and Beccacio,[11] and Cameron.[47]

The studies reported on above have been almost entirely non-quantitative in terms of gray-scale evaluation (except for that by Fischer and Scheps[46]), and have been of a general geological reconnaissance type, using equipment (35 gc, one polarization transmitted and received) capable only of limited penetration through vegetation or into bare soil. Multi-frequency, polypolarization studies presented in congruent geometry which are beginning at the University of Kansas and GIMRADA under NASA support are directed to defining wider radar capabilities for geology under quantitatively controlled, or evaluated, conditions. As many as five frequencies in four polarizations will be tested.

The thinking behind this radar multi-band approach, especially as it applies to geologic studies, may be viewed against some of the current active areas in structural geology.

Short wave length radars (35 gc) have limited penetration and most surfaces appear rough at this wave length. At the other extreme, in the .3 gc band, with a meter wavelength, penetration of dry (or even wet) soil is considerable, attenuation of the signal by vegetation is sharply reduced, and relatively fewer surfaces are rough to that frequency. Consequently, the return signal does not originate on the surface only, nor is the roughness component necessarily the dominant element in the signal. It is anticipated that a multi-frequency system will give a substantial information gain on lithologic differences compared with use of a single frequency only. In the same manner, polypolarization hopefully will be sensitive to differences between rocks in their dielectric field, crystal orientation, bedding and foliation and so on; and will increase our discrimination between lithologies and fracture systems. If our hopes are realized this approach will be of great value to the geologic community in regional stress and tectonic analysis, by defining more lineations and by helping distinguish between more different types of lineations than is currently feasible with aerial photography.

Mapping of air photo linears during the last decade, as used by Badgley,[55] Lattman,[56] Lattman and Nickelson,[57] Boyer and McQueen,[58] and others, has proven the worth of aerial photographs in regional and local stress analysis. Radar already has added to this capability. It may well add appreciably more. There is a pressing need for completely defining fracture sets in key areas, and in particular separating ancient sets propagated upwards into an overmantle from later mechanisms. This is especially significant at this time when laboratory experiments such as those by Badgley,[55] Donath,[59] Belousov,[60] and M. King Hubbert,[61] designed to generate fracture sets of widely varying type under tension, shear and compression are being compared with field-determined systems and while new, commonly mathematical, models of fault, fracture and joint system evaluation are increasingly being studied.[62,63] Remote sensing from spacecraft in general and radar in particular may well provide some of the needed information.

Coverage of areas of the world known only in the most general terms by spacecraft radar would greatly aid reconnaissance-scale geologic mapping and help to define anomolous and problem areas for detailed study. The production of radar-based geologic surveys of underdeveloped countries would be a useful and welcome form of foreign aid. The basic requirement to meet this multiplicity of potentials for geologic mapping would be complete coverage of the earth. One of the principal long-span advantages of such data collected on a world-wide basis in a relatively short span of years would be a datum against which future changes of the more dynamic components of geology could be measured.

Geomorphology

Very little work has been carried out to document the value of radar as a tool in aiding geomorphological studies, and as is true of geologic work, almost all has been based on short wave length (1 cm), non-penetrating systems.

The promise for geomorphology of multi-polarization, multi-frequency systems, offering greater penetration and object-signal differentiation, remains only a promise at this time. However, on the basis of unclassified, K-band imagery, taken with the AN/APQ-56 and AN/APQ-86 systems we may reasonably make the following generalizations:

1. Generalization over large areas enables some major landscape facets, including relict surfaces to be differentiated. Multi-cyclic surfaces in stream headwaters appear in some cases to be identifiable, as discrete topographic units.

2. Large areal coverage also is a distinct advantage in investigating gross relations between structural elements including jointing and stream patterns, detection of water gaps in unsurveyed country, interpretation of meander entrenchment and the like.

3. With appropriate angle of illumination to avoid shadowing, streams at least as small as so-called first order streams taken from topographic sheets at 1:62,500 (and even 1:24,000 in some areas) are distinguishable and mapable on unclassified radar imagery. Studies are currently underway at the University of Kansas to determine the degree of coincidence between map-derived parameters of stream statistics (basin circularity, indices of drainage density, frequency relations between stream orders, etc.) and the comparable values obtained from radar image analysis. Tests of operator error, population coherence, etc. are to be made, using the procedures followed during the last decade by Strahler,[64,65] Melton,[66,67] and others.

4. Flood plains and some terraces are clearly distinguishable.

5. On major flood plains, meander scrolls and point bar accretions are easily distinguished if the alluvials are cultivated. It is much less easy under trees. Tests are also to be carried out comparing conventional panchromatic aerial photographs and radar in their selectivity in defining such features. Resolution becomes an important limitation on radar if all such features are required, at least with the unclassified imagery discussed here.

6. As noted in the section on geology, surfaces composed of strong scatterers (unweathered igneous rock, bare sand, sandstone) tend to give brighter radar returns than soils, or soft sedimentary rocks. This opens up the possibility of demarking with some clarity, bare rock surfaces, serirs in desert areas, wind-swept dreikante fields in periglacial environments and the like.

7. In semi-arid areas of very gentle relief gray scale differences arising from minor sedimentary differences in shallow stream dissection or deposition are observed.

8. In arid regions, the relations between major structural systems, joints, etc. and the evolution of tent-shaped hills may readily be documented with radar and clues obtained for areas suitable for detailed field work.

9. Alluvial fans of different composition, size of gravel and degree of weathering are distinguishable at least tentatively with K-band. Here is a case where a multi-frequency system has real potential in aiding the mapping of pediment and bajada complexes, such as those delineated on aerial photography by Davis and Neal.[68]

10. Lakes are very clearly distinguishable from land and ice surfaces nearby (Fig. 11). Geomorphologists interested in arctic areas will be able to use radar to detect the various ratios of frozen and unfrozen lakes in high latitude by size of lake and date.

11. The extent of major floods in Arctic areas during the spring and the extent of savannah-area floods in the tropics are important geomorphological facts easily obtainable from orbiting imaging radars.

12. The extent to which buried structures may influence surficial alignments and traces in overlying unlithified, unjointed sediments is being studied at GIMRADA.

These illustrations are given to bring to the fore the types of features sensed by short wave length radars. This is not exhaustive. In a recent conference on the use of orbiting spacecraft for geographic research (Houston, January 1965) the panel on geomorphology listed several dozen possible monitoring experiments of value to geomorphologists and suitable for spacecraft sensing, ranging the whole field of any text-book of geomorphology. Many of these experiments were of a type requiring radar capabilities, or in a general sense <u>suitable</u> for radar imaging systems. There were, of course, some experiments most readily satisfied with either multi-spectral photography or IR or passive microwave systems, and for which radar was not appropriate. A similar panel on Coastal Geography at the earlier Woods Hole meeting on Oceanography (August, 1964) also defined topics suitable for spacecraft study.

Among those experiments contemplated, most suitable for radar are the following:

1. The Antarctic mass budget problem already discussed under the heading Glaciology.

2. Sea-state sensing near coastlines throughout the year to define gross or potential energy levels of coastlines. The actual energy is of course a lesser figure depending on the nature of submarine contours, bars, breaking zone and so on. However, the potential energy value would serve to define highly anomalous areas in which coastal forms and potential energy are widely divergent, suitable for detailed ground study. When coupled with other sensors capable of inferring submarine topographic information to 5 fathoms or so, the energy level value would be most valuable.

3. Mapping the major interior and coastal dune fields of the world, especially in view of the fact that many ancient dune fields preserve paleo-climatic wind fields, now different. These are suitable for conventional photography in conjunction with radar in densely vegetated coastal fields, and in interior dune fields at least 20 feet in height. Studies of changing Pleistocene wind directions as preserved in "fossil" dunes, are of value to Pleistocene geology, glaciology, geomorphology and climatology as indicated in Smith,[69,70] and Simonett.[71]

4. The mapping of relict laterite surfaces in tropical savannah regions would be feasible with imaging radar. Polygenetic surfaces, multiple laterites, kopjes, mesas, and exposed ortstein as discussed by Stephens,[72] Simonett,[73] de Swardt,[74] Prescott and Pendleton,[75] and many others, would be sharply defined. This capability would at one stroke serve to document thoroughly the inter-relations between dissected laterite remnants, geomorphology and soil types.[72]

Radar imagery obtained from spacecraft to meet the needs of the geological community will also serve geomorphologists as well by providing a datum against which to gauge all future change, and opportunities to monitor remote areas where the dynamics of geomorphic processes may be unravelled by time-lapse radar imagery.

Plant Geography, Forestry and Agriculture

Examine the radar imagery (Fig. 13) of farmland in Michigan and one sees clear differences between plow land, crops and forest. Trees 100 feet apart in grassland are individually detectable, while those lining watercourse, roads or field borders cast radar shadows. Gray scale values for crops range widely depending on type, height and maturity.

A knowledge of such differences enables us to infer that vegetation maps may be made with spacecraft radar of remote, difficult-of-access, and cloud-covered regions in the rainforest, savannah and desert belts, in mountain tracts and arctic latitudes. Many existing vegetation maps of such regions are based on the sketchiest of information, and mapping even on the grossest basis would be valuable. It should be easy to separate rainforest from alang-alang, caa-tinga from palm savannah, caingin clearings from high forest, galeria from acacia savannah, Triodia desert from Atriplex steppe, taiga from ericaceous heath and alpine tussock from coniferous forest.

Beyond such macro-distinctions, there are also grounds for believing that meso and micro densitometry studies with radar imagery, plus analysis of signal characteristics as recorded on signal film or magnetic tape will lead to a marked improvement in the level of detail extractable from imaging radar. The key to such possibilities lies in evaluating radar data of carefully documented plant communities. Feasibility studies of this type will begin at the University of Kansas in the fall of 1965.

Identification of field crops on aerial photographs is aided by inferences on field size, plowing and stook patterns, row and tree spacing and so on. However, the relatively modest resolution likely with spacecraft radar will largely, though not entirely, confine the identification possibilities to gray-scale variations on a whole-field basis. Studies to evaluate radar gray scale differences and signal characteristics in relation to crop type, height, stage and state are commencing under cooperative programs at the University of Kansas, Kansas State University, GIMRADA, and Purdue University.

Pedology

Short wavelength imaging radar has value in delimiting breaks of slope, and some lithologic changes, and to the degree that soil boundaries are coincident with these, will supplement to a degree our existing photo-interpretation abilities in soil series mapping at the county level and at the reconnaissance level for studies in undeveloped areas such as those by Eden[76] in the Rupununi savannahs of British Guiana or by Perry,[77] and Mabbutt and Stewart [78] in tropical Australia.

Polychromatic radar is not without its interest in regard to soil exploration. The capacity of some bands to penetrate vegetation and give a return from the surface and sub-surface layers of soil may be of great value in the preparation of soil maps in highly developed, let alone remote, areas. On basalts throughout part of the wet-dry tropics, for example, latosolic and pedocalcic soils lie cheek by jowl. With an open savannah grass and tree cover it is very frequently not possible to distinguish between these soils. Catenary differences and differences in the age of flows account for soil variations. Since the latosols are normally high in sesquioxidic compounds and 1:1 lattice minerals; and the pedocals, on the other hand, are dominated by montmorillonoids, and if at all moist are very highly conductive soils since they contain dissolved salts, and since, further, the structure and granulation of these soils are markedly different, we may anticipate that some differences of these types may be detectable by radar of various polarizations. Strongly structured, strongly layered, and buried soils might be detectable by multiple frequencies and polarizations. Studies to evaluate these aspects will commence at the University of Kansas during the summer of 1965.

Seismology

Polychromatic imaging radars will give a view from space of massive earthquakes occurring in regions very nearly always cloud covered, or during the long polar night. The recent Alaskan tragedy comes to mind. Depending on the nature of the displacements it may be possible to make estimates of horizontal fault movements by offsets, and this would not require previous imagery, for many natural and man-made lineations cross fault lines. Vertical movements could be detected readily along coastlines by comparison with maps or previous imagery. Since so much of the highly seismic areas of the world lie in the Pacific rim, subsidence and elevation involving the coastal strip are common.

Evaluation of such parameters as landslide occurrence, stream derangement, seismic-lakes and extent of coastal inundation would be possible within several days in the 50-90^{o} latitude band using spacecraft photographic reconnaissance (polar orbit) if lighting conditions were suitable (summer hemisphere) and clouds were absent. In the winter (and summer) hemisphere the time needed for radar coverage ultimately will depend on spacecraft power limitations and state-of-the-art. As far as we may reasonably judge at this time, the time required will be in the range of 4 to 16 days for the same latitude.

Photographic and radar coverage would be invaluable in field studies such as those by Wright and Mella[79] in Chile, or air photo studies of landslides in relation to epicenters such as that by Simonett[80] in New Guinea.

OCEANOGRAPHIC EXPERIMENTS WITH RADAR ALTIMETERS AND IMAGING RADAR

The oceans cover 71% of the surface of our globe. To probe the oceans from a manned space vehicle at first sight seems incongruous because much that we need to know about the oceans can be learned only by making measurements below their surface. The difficulties inherent in studying the oceans from so high up are more than counterbalanced by the advantages to be gained. A polar orbiting vehicle provides a way to cover the world's oceans in twelve hours. Other orbits provide the opportunity to study large swaths of an ocean every 80 minutes or so. Thorough coverage and efficient data collection procedures provide for the first time the possibility of nearly synoptic measurements of many features of the oceans given the sensing devices to measure the phenomena of interest.

Many possible sensing devices were discussed at a recent WHOI-NASA conference on the use of manned space vehicles in studying the oceans. Much can be done to improve our knowledge of the oceans by the approaches described in this report.

Radar is one remote sensing device suitable for study of the oceans. Since it is an active device, signal to noise can be controlled, and its design can be optimized to provide the kinds of data needed. Radar altimeters seem ideally suited for measurements of the form of the surface of the ocean as a function of space and time, $\eta(x,y,t)$ (or $\eta(\phi, \lambda, t)$). For this application, rather long electromagnetic waves will have to be used to penetrate clouds and rain so as to be sure to reach the surface and to eliminate echoes from clouds and rain.

Types of disturbances on the ocean

The surface of the ocean departs from a level surface as determined by the geoid for many reasons. Geostrophic currents are related to one component of $\eta(x, y, t)$ that can be thought of as time independent. These currents are the result of both a density stratification in the water as a function of the space variables and of a departure from the geoid of the ocean surface with slopes of the order of 1 meter in 2500 km.

The various periods in the tidal forces each produce a complex system of amphidromic points, cotidal lines and co-height lines in the various oceans. Important tidal periods are clustered in groups near values of two weeks, one lunar day, one solar day, one half lunar day, and one half solar day.[81] The tides are highest at the edges of the ocean with extreme ranges as in the Bay of Fundy of 15 meters.

Transient cyclones in the atmosphere produce storm surges. These surges have horizontal scales of the order of 600 km along a coast and elevations and depressions of 1 to 4 meters.

Seismic sea waves radiate from their epicenter source at speeds of 200 meters/sec. These waves are about 400 km long and have periods near 20 minutes and amplitudes in the deep ocean of 0.5 meters.

Finally, the winds over the ocean generate storm seas in which individual waves as high as 30 meters from crest to trough with an apparent wavelength of 500 to 800 meters can occur. Smaller waves superposed on these larger waves have lengths through the whole spectrum down to fractions of a centimeter.

The use of radar

Radar altimeters provide a possible tool for the study of sea surface tilt, tides, storm surges and tsunamis, and a usually undesirable feature of radar--sea clutter--may be used for the study of wind waves and indirectly of the winds over the ocean. The two techniques are different and can be discussed separately.

Geodesy and sea surface slope

One of the greatest advances in geophysics has been the determination of the shape of the geoid from satellite data. Newton has shown the contours[82] of the geoid as computed from eight spherical harmonics with undulations in oceanic areas of the order of plus 20 meters to minus 19 meters. It is not too much to hope that the continuing efforts in geodesy will provide the shape of the geoid along a particular space vehicle trajectory to an accuracy of a fraction of a meter as continuing effort along these lines is made. A particular space vehicle can presently be located with an elevation accuracy of about 3 meters and even this can probably be improved. The path of the vehicle in space tends to follow the local geoid.

The radar altimetry capability is based on averaging many return pulses. The pulses averaged over 70 km of flight path should have an rms error of about 1/3 meter, but proper analysis of sequences of return pulses could on a time series and filtering basis provide even closer space resolution. Techniques for detecting signals in noise are well developed.

Since the vehicle will tend to follow the geoid, there are four parts to the problem of detecting sea surface slopes with reference to the geoid. They are (1) to find the departure of the path of the vehicle from the geoid contours immediately below the vehicle, (2) to measure by radar a quantity equal to the sum of the departure of the path of the vehicle from the geoid contours and the variation of the elevation of the ocean, (3) to remove the time varying component in the ocean elevation, and finally (4) to subtract the first result from the third to get the variation of the elevation of the ocean with reference to a level surface.

The chance of success in measuring variations in elevation of the ocean surface by radar from a satellite seems small at present in terms of the above considerations. However, continued improvement in technology, or presently classified achievements, may put this goal within the realm of the possible. There is perhaps one saving factor in the situation in that this variation in elevation of the ocean surface may be of a different space scale than the variation of the geoid. The radar altimeter signals over the oceans will be of considerable value in themselves as a first indication of the presence or absence of smaller scale fluctuations in the geoid. If these smaller scale fluctuations are absent over most of the ocean, and present where sea surface slopes are believed to be present, then this could be considered to be a good indication that the sea surface departure from the geoid was being sensed.

The oceanographers' knowledge of the density stratification of the ocean would then make it possible to compute the currents along a section with no _a priori_ assumption of the level of no motion . The only other way to avoid this assumption has been given by Swallow and Worthington.[83] The radar technique has the advantage of covering vast areas of the ocean.

Certain theories about the slope of the sea surface with reference to the geoid are shown in Figs.14 and 15 for the Gulf Stream near Cape Hatteras and for a north-south section across the equator in the Atlantic. The "Meteor" data suggest a slope of 25 cm in 300 to 400 km in one part of this section which would be barely detectable at the present state of the art. Other areas of greater slope would be over the Kuroshio and the Somali current. Altimeter sections over such areas could perhaps verify these theories and provide exceptionally valuable data to oceanographers. Such data could provide a basic input to the theories of the ocean circulation.

Tides

Two other large scale motions, tides and storm surges, are time varying. They are large on the border of the oceans. For these reasons it is quite likely that the present precision of radar altimetry will be enough to provide the needed kinds of information. A space vehicle in orbit long enough will begin to repeat its previous trajectories over the earth. Each time it passes from land to water or water to land that part of the altimetry signal over the land will be nearly the same as one for a previous pass. (Interpolation and extrapolation are of course quite possible.) The difference in the over water part of the signal would be due to tides and storm surges.

A series of traces across the Bay of Fundy would surely detect the tidal changes at the present state of the art, but no new knowledge would be gained as this portion of the globe is already well documented.

There are, however, many portions of the globe where the tides are not well documented. In particular the Arctic Ocean and the Antarctic Ocean are not thoroughly covered. Also the location of the amphidromic points and cotidal lines for the various frequencies involved is poor for any ocean.[84] Data along the edges of the continents can help locate the cotidal lines, and with the help of islands, the co-height lines over various oceanic regions could be sketched.

For the tides, a long flight time is needed, and the data reduction and analysis would be extensive because a number of passes near many given points on the land-sea boundary would be needed. A minimum would be two weeks of data from a vehicle in a near polar orbit, and two months of data would probably be better.

Storm surges

The heights of storm surges, which occur when hurricanes, typhoons, or willy willies (depending on the ocean) and intense extra-tropical cyclones travel, or develop near, a coast line are well documented in the United States, Europe, and Japan.[85,86,87] For other parts of the world, measurements are lacking, and even when measured, the data is obtained from tide gages installed close to the coast and give only a time history at a point.

The variation in elevation away from the coast and the spatial appearance of the surface are not measured. Space vehicle precision altimetry could provide such measurements which in turn could be used to improve the various numerical computer based models that have been developed to try to understand these surges.[88] Improvement in these models would in turn result in improved forecasts of the surges whenever they threaten to inundate a coastal area.

As a storm moves along a coast the departure from normal of the sea surface elevation might be sketched as in Fig. . A pass by a space vehicle would for the first time verify the form of the postulated contours, by providing a cross section through a portion of the surge.

Tsunamis

Fortunately, tsunamis (seismic sea waves) are infrequent events. The historical record of tsunamis is well documented and a useful recent review has been given by Wiegel.[87] The Chilean tsunami of May 23, 1960 took only 15 hours to reach Hawaii and 22 hours to reach Japan. For water of constant depth the form of such a disturbance has been predicted by Kranzer and Keller[89]. There is the possibility that the waves will not be radially symmetrical as they propagate from their source. Were this lack of symmetry to be observed in deep water, it would help to explain the vagaries in the destructiveness of these waves from point to point and from one tsunami to another. For example, why was Crescent City in California the only community on our Pacific coast severely damaged by a tsunami that originated from the recent Alaskan earthquake? If the space vehicle is traveling in the direction of tsunami propagation, there is a good chance that such a disturbance would be detected by an altimeter radar because the space scale of the tsunami would be characteristic and because there is evidence[90] that background fluctuations at these scales are small over the ocean.

For tsunamis, however, the major problem is that of frequency of occurrence. Unless continuous monitoring is undertaken, the presently projected durations of such radar experiments have only a slight chance of ever measuring the waves in a tsunami.

Wind generated waves

Winds blowing over the oceans generate waves. These waves have been measured as a function of time at a fixed point, as a combination of signals representing elevation, slopes and curvatures at a fixed point, and as a surface at an instant of time by stereophotogrammetric methods. About five hundred power spectra estimated from time histories are available to describe waves without regard to their direction. About fifteen experiments have been completed that provide spectra spread out over both frequency and direction of wave propagation, notably those by Cote et al,[91] Cartwright and Smith[92], and unpublished work in Great Britain.

The patch of sea surface illuminated by radar is covered by many waves, and the signal returned is based on some averaged property of the waves. Time histories recorded at a point when spectrally analyzed show that the contribution to the total variance of the signal is spread over all frequencies as the wind increases as in Fig. 16 which shows the way the wave spectrum changes as a function of wind speed. Since for gravity waves $k = \omega^2/g$ in deep water the choppiness at short wavelengths also probable increases a parameter such as scattering cross section will vary in proportion to sea state.

From a study of wave spectra computed from wave records obtained by a British weather ship at one point using equipment developed at the National Institute of Oceanography, and at Argus Island by the U. S. Naval Oceanographic Office, a computer based wave hindcasting and forecasting procedure has been developed for the North Atlantic Ocean. The initial work on this problem is described by Moskowitz, Pierson and Mehr[93] Moskowitz[95], Pierson and Moskowitz[96] and Pierson[97]. The study is not completed. The input is the wind field over the Atlantic every six hours referred to an elevation of 19.5 meters above the surface.

The hindcasts, which are computations that describe the wave spectra given the wind field as actually reported by ships, as opposed to forecasts, which require a prediction of what the winds will be in the future, usually yielded good results when verified against the spectra obtained from observations.

A number of results of the study provided new understanding of the problems connected with describing the state of the sea over the oceans. Even for the relatively small North Atlantic, the sea, in a sense, remembers the past for as much as a week in determining the wave spectrum at a point at a given time. The sea responds quickly to the winds, and the response takes place over small distances. Unless the wind field is completely and accurately described, the waves will not be hindcasted properly.

The North Atlantic is the most densely trafficked ocean in the world. To describe the waves, more than 300,000 ship reports of the winds were available for a fifteen month period. Yet due in part to redundancy (many ships in the same area) only 40,000 were used. Nevertheless, whole storms were missed, and some of the hindcasts were wrong.

Evenly spaced observations are essential to describe a phenomenon. They must be close enough to describe the actual variation from point to point and far enough apart to be economical. At present, the winds are poorly observed on a non-uniform pattern over the ocean. Waves are so poorly observed--with the commendable exception of the British weather ships and the U.S. Naval Oceanographic Office installation at Argus Island--that their reports are, in the opinion of many oceanographers, marginal in their usefulness. They are better than nothing, but not much.

The coverage is so poor that even in the North Atlantic, the details of the winds in many cyclonic developments are missed with a consequent degradation in our ability to describe the waves. The North Pacific has poorer coverage, and the southern hemisphere has the poorest.

Weather satellites detect cyclones from cloud patterns, but meteorologists must guess the surface wind and pressure fields that accompany them in the absence of ship reports. A radar that could detect as simple a thing as the significant height of the waves would help to correct the chart representing the current state of the sea, and, in making the wave correction, the wind fields and pressure patterns could also be corrected to the same degree. In short, iteration of TIROS or NIMBUS cloud imagery against radar altimeter-derived sea-state data has the potential for giving a definite improvement of our knowledge of sea-air interaction, an area most difficult to instrument, and of great significance to both oceanographers and meteorologists. This knowledge will help improve our estimates of energy flux over the oceans, oceanic climatology, and computer-oriented numerical forecasting procedures for both waves and pressure fields.

Radar can measure waves by a number of techniques ranging from quite simple procedures to very sophisticated ones. The simplest technique involves the variation of scattering cross-section with radar beam angle. Such curves have been correlated with wave height. One observation every eighty nautical miles whenever the vehicle was over the ocean would provide a detailed picture of the heights of the waves over the oceans.

Other techniques, with the ultimate being a side-looking imaging radar can provide information on wave direction, the spectrum of the waves, and finally, the full directional spectrum of the waves.

CONCLUDING REMARKS

We wish to re-emphasize two aspects of the presentation made in the course of this paper. The first is that many areas suitable for experiments or mapping with radar from orbiting spacecraft have been omitted from this presentation because of space considerations (this applies particularly to aspects of urban, transportation and other areas of cultural geography); or because the existing literature is extremely controversial; and to give an adequate account would also take too much space. The utility of radar for meteorological purposes in orbiting spacecraft is an example of the latter and we propose to give a fuller analysis of the problems and potentials of spacecraft-borne radar systems for meteorology and climatology in another publication.

The final point for emphasis is that while we have directed our attention to certain experiments or information-gathering from spacecraft which at this time seem most suitable for radar, there are many processes, notably those of air-sea interaction in which several sensors operating together will be required fully to unpack the dynamics is of the energy exchanges, and the vectors involved. We are wedded to the notion of the multi-sensor, multi-frequency approach in grappling with the dynamics of terrestrial, oceanic and atmospheric phenomena, and our presentation here should not be taken to indicate an unawareness of the supportive role all sensors have with one another. For mapping in all forms, cartographic photography and multispectral photography in particular when allied with radar imagery, will be of great value.

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