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LAND EVALUATION STUDIES WITH REMOTE SENSORS IN THE INFRARED AND RADAR REGIONS

by

David S. Simonett 1926-

TABLE OF CONTENTS

LAND EVALUATION STUDIES WITH REMOTE SENSORS IN THE INFRARED AND RADAR REGIONS*

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SUMMARY

This paper reviews the literature, especially of the last two years, dealing with remote sensor evaluation of surface and shallow sub-surface characteristics, employing remote sensors in the infrared ($1.5\mu - 14\mu$) and radar (0.5 cm - 100 cm) regions. Imaging and non-imaging sensors are examined to assess their current status and possible value in 1) assisting in the mapping of natural plant communities, 2) deriving hydrologic parameters, 3) discriminating among broad land use, crop type, and to a lesser degree, crop state, 4) delineating soil and geomorphic units, and 5) estimating soil moisture. Possible applications of these remote sensors in reconnaissance-scale evaluation of natural resources are considered. The paper leans heavily on unpublished and limited-circulation studies sponsored by the National Aeronautics and Space Administration, U.S.A.

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INTRODUCTION

During the last few years the tempo of research and publication in remote sensing has picked up rapidly as the National Aeronautics and Space Administration, U.S.A. has funded a great variety of sensor studies for earth resources evaluation. These studies are of course intended to support possible spacecraft sensing, but they have also had the immediate effect of defining more clearly than before both the potentials, and practical difficulties, as well as the research frontiers of remote sensing. In this paper two areas where NASA-sponsored research has been substantial--the infrared and radar regions--have been chosen for review.

In the sections which follow the infrared area is treated first and then the radar. For each area a brief sketch of energy-matter interactions is given. Imaging and non-imaging sensors are described, their advantages and disadvantages noted and the technical state of the art is discussed. Then follows an account of the present status of interpretation in studying natural plant communities, hydrology, land use, geomorphology, soil types and soil moisture.

In order to make the most effective use of space I have not used infrared and radar images in the report. At the Symposium a number of false color combination and black and white images will be discussed. Well illustrated articles to which the reader may refer are those by Colwell (1966, 1968), and Moore and Simonett (1967a).

REMOTE SENSING IN THE INFRARED

In the visible and near infrared-regions of the electromagnetic spectrum (respectively $0.4 - 0.7\mu$ and $0.7 - 1.3\mu$) conventional framing cameras and photographic techniques may be used if desired in land evaluation studies. However, in the middle infrared ($1.5 - 5.5\mu$) and the far infrared ($5.5 - 14.0\mu$), which are the areas considered here, such methods cannot be used for a number of reasons including the high level of background radiation which would arise from the camera and film itself at ambient temperatures. Consequently, other recording devices are used, of which the most usual is an aircraft-borne optical-mechanical scanner. In such a system the forward motion of the aircraft provides the along-track co-ordinates and across-track dimension is provided by a scanning rotating prism. The instantaneous field of view of the scanner is normally a few milliradians. Successive scans are swept out across-track through the rotation of the prism as the aircraft moves forward, and each scan in a properly functioning system is contiguous or slightly overlaps its neighbor. The energy incident on the prism mirror at various angles from the aircraft sub-point is focussed onto a sensitive detector element and the photon energy is transformed to an electric analog signal which in turn is recorded on magnetic tape, or, is used to modulate a glow-tube or cathode-ray tube for direct film recording. One, two, or three channel systems are relatively common and normally direct film record. Multi-channel scanners employing up to about 20 channels also have been developed to cover the region between .32μ to 14μ. The incoming energy is beam-split, filtered and directed onto detectors sensitive to each wavelength and the resulting electrical signal is recorded on magnetic tape for direct computer studies of the reflectances and emissions.

In land evaluation studies, aircraft-borne short wavelength (.4 - 2.5μ) and long wavelength (8 - 14μ) radiometer-spectrometers have been virtually unused and unavailable to date. They will, however, be used more extensively in future research in order that better quantitative data may be obtained on the radiometric and spectral quality of different elements of the landscapes, for it is infeasible in a single instrument to optimize spectral, spatial, and radiometric resolution. Imaging systems tend to optimize for spatial and to a lesser degree radiometric resolution and sacrifice spectral resolution. Non-imaging line trace spectrometers and radiometers sacrifice spatial resolution to obtain the spectral and radiometric resolution.

Both reflection and emission are important in the infrared region. Solar reflection on the skirts of the solar radiation curve is important in daylight to about 3.5μ, and is negligible beyond. Between 3.5 - 5.5μ earth glow also is modest, hence this is a useful region for forest fire detection. The peak of the earth-glow emission lies near 10μ. Atmospheric, water vapor absorption blanks out the region between 14μ and 1 mm for terrestrial remote sensing.

Many fundamental vibrational resonances occur in the infrared region such as those for water vapor (2.66, 2.74, and 6.3μ) and the SI-O bond of the silicate minerals near 10μ. Information related to the composition of some substances is thus potentially available in the infrared region through emission spectroscopy. The most active worker in this region is R. J.P. Lyon, (Lyon 1967, Vickers and Lyon 1967), who has studied the emission spectra of a wide variety of rocks. Further research is needed in the practical application of this technique to land evaluation.

Since there are substantial differences in the thermal inertia of substances, this property also lends itself to remote sensing use in the infrared. The daily cycle of termal response provides information which is related to composition (such as bulk density and contained moisture content) and several flights through the course of a day may enable these qualities to be estimated.

The relatively high energy levels, the spatial, spectral, and radiometric (thermal) resolutions available, and the vibrational, rotational and thermal interactions available in the infrared region give reason for believing this will be a most attractive area for remote sensing applications. It is, however, at present a complex area for unambiguous quantitative answers are few--being restricted to the simplest cases such as forest fire surveillance in the 4.5 - 5.5μ band, which is now operational (Wilson, 1966)--and much research lies ahead before operational infrared systems can be used in tackling earth resource problems. As Buettner, Kern and Cronin (1964) note, the effects of actual temperature differences, of variations in emissivity, and of atmospheric interferences are of about equal orders of magnitude in influencing the energies recorded in the infrared. They could well have added that the natural variances of plants, soils and water both in space and time through different days, weeks, seasons and years are at least equal in order of magnitude to the other variables. The extremely variable state of the atmosphere both vertically and horizontally makes infrared imagery difficult to use for quantitative purposes. Pertinent observations may be found in Menon and Ragotzkie (1967) and Blythe and Kurath (1967).

Far-infrared imaging systems currently available and declassified in the United States have resolutions of about 3 milliradians. When used at the normal photographic mapping altitudes of 10, 20 and 30 thousand feet a 3 milliradian system would have respective spatial resolutions or 30, 60 and 90 feet. These resolutions are notably inferior to those obtained with 6 in. focal length cameras at the same altitudes and many objects of both natural and cultural interest simply cannot be effectively resolved. While there is no theoretical reason why these resolutions cannot be improved probably one milliradian resolution is about all that we ought to look forward to for some time. Unlike framing camera systems from which all data can be brought to equivalent planimetry, infrared line-scan imagery has geometric distortions which make multiple images taken at different time and in different directions exceedingly difficult to bring to a compatible planimetric format (Derenyi and Konecny, 1964), yet diurnal imagery is needed for full use of infrared.

To the degree that multiple wavelengths obtained at the same time can substitute for the temporal information available from a single wavelength used several times in the course of a day or a season a multiple-wavelength scanning system such as that developed at the University of Michigan (Donald Lowe, personal communication) and which records all channels on tape in compatible geometry may overcome in part this geometric problem. The University of Michigan 18 channel scanner is interesting in a number of respects: 13 of the channels lie in the visible, near ultraviolet, and near infrared regions, while the remaining 5 lie in the infrared regions in the wavelength bands 1.5 - 1.7μ, 2 - 2.6μ, 3 - 4.1μ, 4.5 - 5.5μ, and 8.2 - 14μ. In addition, unlike most infrared imagery, there are provisions for some calibration of the radiometric quantities involved in the analog signal.

Practical resolutions from spacecraft are likely to lie in the range of several hundred feet at least for the next decade. Consequently infrared imagery from spacecraft will properly be addressed to problems of large spatial dimensions and it is not appropriate to look to it for a solution of problems requiring detailed resolution. The key technical reference for this area is Wolfe (1965).

Studies of Natural Plant Communities and Their State

Surprisingly little work has been done with infrared in studies of natural vegetation. Part of this arises from the fact that a good deal of infrared imagery has been flown at night and as Blythe and Kurath (1967) note, since leaf temperatures at night tend to be close to local air temperature trees in leaf look brighter than shorter plants irrespective of whether the tree is a conifer or deciduous or of the type of lower plants. They do however note that in "summertime images of adjacent stands of conifers and deciduous trees during the daytime, conifers appear to be brighter than adjacent deciduous trees." They also note that while boundaries between plant communities are commonly visible in midday thermal IR imagery, differences between tree types within these communities, is not easily detectable on the IR images. This was true despite the fact that considerable ground information was available for the images they studied. It is fair to say that tree species cannot be differentiated at present with the thermal infrared line scanner because of inadequate spatial resolution and inadequate reflectance and emittance data.

Most spectral reflectance measurements in the literature are laboratory data with single leaves. While such data may accurately predict the response by several species when imaged there is no guarantee that this will be the case for as Myers et al. (1966b) have demonstrated this could lead to misleading interpretations, especially in the longer wavelengths, where layers of leaves have a very different response to a single leaf. C.E. Olson (personal communication) has also found that there are substantial differences between species in this regard, leathery leaves such as some oaks or rhododendroms giving a much higher percent reflectance from a single leaf than say a cotton leaf. There is a pressing need for spectral measurements obtained from aircraft using short and long wavelength radiometer-spectrometer of the type developed by R.J.P.Lyon of Stanford University (Lyon, 1967).

Spectral reflectance studies by Olson (1964) in late August, 1963, showed that in the near IR region and portions of the middle IR region the leaves of white ash (Fraxinus americana), black oak (Quercus velutina), black cherry (Prunus seratina), shag bark hickory (Carya ovata), Norway spruce (Picea excelsa), and Austrian pine (Pinus nigra) all show the same pattern of reflectance and only Norway spruce of this group is sufficiently less reflective to have a chance of being discriminated from the other species. The results of aircraft flights at the same time agreed with the laboratory studies.

Colwell and Shay (1965) report an analysis of multispectral tone signatures given of 10 vegetation trafficability types, in and near Mud Lake Bog, Michigan at 11 a.m. June 26, 1963. A six-channel scanner with 3 channels in the 2 - 2.6, 4.5 - 5.5, and 8 - 14 μ bands was used. They found much the same results were obtained in the 4.5 - 5.5 as in the 8 - 14μ band, and that there was a tendency for different vegetation types to group their response in pairs or triplets. However, in the 2 - 2.6μ band there was a wide spread in tone signatures between various swamp types.

Carneggie, Poulton and Roberts (1967) found considerable redundancy between the 18 channels of the University of Michigan scanner when used to detect soil and natural vegetation boundaries. The most useful information lay in the following bands: .32-.38, .62 - .68, .8 - 1.0, 1.5 - 1.8, and 8 - 14μ. More soil-vegetation boundaries were distinguished in the .62 - .68μ band than in any other; moist meadow sites were best distinguished in the .8 - 1.0μ band; and wet soils, marsh, and narrow streams obscured by vegetation were best determined in the 8 - 14μ band. Many areas of wet soils observed in the latter could not be seen on any other band. Finally, they found that occasional vegetation and soil boundaries were seen in the .32 - .38 and 1.5 - 1.8μ band.

Early work by C.E. Olson (personal communication) in the 8 - 14μ band suggested that imagery of trees taken during the maximum thermal and transpiration load in the early afternoon should produce different responses from healthy trees with an abundance of water for transpiration, and those which are under moisture stress caused by insect attack, plant pathogens, or drought.

Continued tests of this possibility are being made by Heller et al. (1967) and Weber and Olson (1967). Working with poisoned red pine Weber (1965) found that elevation of leaf temperatures from 3 to 5° C occured under the high radiation load in the middle of the afternoon. The practical application of this information is at present hindered because of poor scanner spatial resolution and Heller et al. (1967) found that tree crowns within a forest canopy could not be distinguished on thermal imagery as to whether they were healthy or dying. They found that (in mid-June) in South Dakota, "the foliage temperatures of dying trees were 6° to 8° C higher than healthy trees at 1000/hours; the difference was slightly less at 1400 hours (4° to 6° C)." Detectors in optical-mechanical scanners are capable of discriminating temperature differences this small; however, the resolution cell at safe aircraft operating altitudes in hilly regions is usually larger in area than the dying tree crowns which are surrounded by cooler healthy trees. They also found in this study of Black Hills Beetle (Dendroctonus ponderosae hopk) infestation of Pinus ponderosa that radiometer readings showed consistently higher temperature readings from those infested trees which subsequently died than from those which did not.

Thus, while it is still not possible to predict the location of low vigor trees from previsual thermal symptoms with airborne imagery, there seems to be good grounds for believing that it may be feasible with IR scanners with better spatial resolution.

Myers et al. (1967) found that when plant leaves slowly dry in plants under severe moisture stress reflectances increased at all wavelengths, probably as a response to shrinking and increased density of the leaf and to changes in refractive index discontinuities. However, leaves dried in the laboratory or on a forest floor may respond differently (V.I. Myers, personal communication; Olson 1967a). In his study of fine forest fuels Olson found that not all bands respond equally. At 1.55μ and at 2.05μ he recorded a slight but steady increase in reflectance with drying in the moisture range 330% - 20% (oven-dry basis). At 2.5μ the reflectance curve is flat from 330 to 250% contained moisture and then increases rapidly. Since the 2.5μ band lies near the fundamental vibration frequency for water vapor (2.66μ), this is probably a response to reduced absorption.

In a study of sycamore and yellow poplar seedlings Weber and Olson (1967) discovered that "in all cases the level of water stress at the time of leaf formation and development appeared to exert a greater influence on foliar reflectance (in the near and mid IR region) than did the level of water stress at the time the reflectance measurements were made." The implications of this research are many for remote sensing and this study must be extended and repeated with other species, situations, and ages of plants.

Land Use, Crop Discrimination and Crop State Studies

Important remote sensing studies are being made at the Laboratory for Agricultural Remote Sensing at Purdue University, and at the U.S.D.A. Weslaco Agricultural Experiment Station, Texas. Those by Myers and his colleagues at Weslaco on plants under stress will be discussed first. Myers et al. (1967) note that reflectance from plants affected by drought, salinity, disease, and other factors is complex. This arises because not all parts of the plant react in the same manner. Russian studies quoted by Myers and his co-workers indicate that the upper leaves of the plant, which are the ones detected by aerial sensors, keep in good shape the longest by drawing water fromleaves positioned lower, as a result of which, the latter are the first to wilt or dry up during a drought. In orchard crops the upper leaves also draw water from the fruit rudiment as well as from the lower leaves. Thus, drought may cause failure of the fruit crop while the upper leaves are perhaps still not registering stress in thermal imagery.

Myers et al. (1966a,b) measured plant leaf temperatures as a method for studying the energy budgets of agricultural areas, for estimating soil moisture, and for detecting the occurrence and extent of soil salinity. They found that leaves from cotton plants affected and unaffected by salinity have contrasting reflectances in the range from .5 - 2.5μ. These contrasts may provide the means for remote prediction and differentiation of moisture and salinity stress.

C. L. Wiegand and L. N. Nanken presented data at the American Society of Agronomy meetings in Columbus, Ohio, in 1965 on the range of temperatures in cotton leaves under moisture stress. These were evaluated through variations in relative turgidity between 1430 and 1500 CST, the time of maximum daily plant moisture stress. Under the conditions of the experiment they found that cotton leaves exhibited symptoms of wilt at 70 - 72% relative turgidity. With a relative turgidity of 82% a leaf temperature of 36.5° centigrade was obtained and with a relative turgidity of 58% a leaf temperature of 40° centigrade was obtained. The slope of the best fit regression line was -0.15° centigrade per percent relative turgidity.

In a valuable recent study of crops on the Purdue University Agricultural Experiment fields Hoffer (1967) discusses the variations in multispectral response patterns of different crops and soils at various times during the growing season. Numerous examples are given of different responses in each wavelength for the various crops, including striking differences in response between, for example, corn and soybeans in the 1.5 - 1.7, 2.0 - 2.6, and 3.0 - 4.1μ bands at a time of the year -- July 29, 1964 -- when the photographic and thermal infrared portions of the spectrum showed little, if any, differentiation.

Other significant observations by Hoffer include the following:

1) There is not necessarily a direct correspondence between ground measured temperatures of crops and thermal infrared scanner response.
2) "Analysis of many pieces of multispectral imagery in many wavelength bands indicates that a capability exists to

differentiate and perhaps identify various crops species or crop categories by remote sensing. The key is to obtain multispectral data at the proper period of crop development and at intervals throughout the growing season."

3) A major variable in response patterns is the proportion of soil covered by the crop canopy -- that is, the relationship between crop cover and bare soil as observed from above. "From a limited number of situations studied, it would appear that very early in the growing season radar and thermal infrared imagery may be more useful than visible or infrared photography in differentiatiating between field crops in early developing stages, and fields of bare soil."
4) Stage of maturity causes considerable variation in reflectance within a crop species.
5) During the period of active growth of crops it is difficult to discriminate between crops because the reflectance curves -- from .32μ to 2.6μ -- for green leaves "had about the same shape and differences among the species were small."
6) A number of researchers have found the photographic infrared portion of the spectrum very useful in detecting certain crop diseases, because of the common reduction in reflectance in the near infrared regions as a result of plant stress. The Purdue studies, however, have shown virtually no difference in reflectance between diseased and non-diseased crops. Rather, the difference in response arises because the diseased plants were severely dwarfed and allowed more soil to be exposed causing a lower response in the diseased plots.
7) Moiré patterns in row crops obtained with a line scan infrared image flown at modest altitudes above the crop can be used to obtain information on row direction, row width, and general crop category. However, Moiré patterns severely affect the spectral response determination of an area.
8) "Multispectral reflectances may not be the same on a given date from year to year, even for the same geographic

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8) "Multispectral reflectances may not be the same on a given date from year to year, even for the same geographic

region." This was the case for corn and soybean imagery near the end of August, 1964 and 1965.

The key comment in Hoffer's paper is the variation on a year-to-year basis in the multispectral response pattern for various crops. This clearly implies a need to build up an empirical catalogue of seasonal response patterns so that these annual and seasonal variations may be taken into account in a probability model for crop identification.

Another useful report by the Purdue group is that by Shay et al. (1967). Detailed work with the University of Michigan 18 channel scanner is reported, including quantitative analysis of the 1964 multispectral imagery using statistical pattern recognition techniques. They report a range of correct recognitions of oats, wheat, alfalfa, various soil types, soybeans, corn, wheat stubble, etc. For various groups of crops, identifications ranged between 99% correct recognition to a low of 87% correct recognition. These exceedingly encouraging results for multispectral identification of crops required the use of the wavelength bands in the middle and far infrared as well as those in the visible and photographic near infrared regions to ensure discrimination.

Another useful part of this report is a series of cross tabulation plots of responses from crops for one wavelength against another. As might be expected adjacent wavelengths in the visible region had very high correlation with one another. For example, that between $.53 - .57\mu$ and $.62$ and $.68\mu$ are very closely correlated, as are those between $1.4 - 1.9\mu$ and $1.6 - 1.8\mu$. However, the cross tabulation plot of the wavelengths $.53 - .57\mu$ versus $1.2 - 1.25\mu$ showed very little correlation indicating that with sufficient wavelength separation truly orthogonal parameters are being evaluated.

Lyon (1967) has obtained detailed field spectra of a number of crops at the Davis test farm of the University of California, employing a short wavelength spectrometer in the region $.75 - 2.1\mu$. Stepwise discriminant analysis of this data indicated that one single wavelength (1.05μ) was all that was necessary with 99 spectra to make a 97% decision out of 5 crop possibilities including wheat.

Broader land use evaluations with $4.5 - 5.5\mu$ imagery of a type of interest in reconnaissance surveys may be found in Olson (1967b).

Hydrology and Soil Moisture

Studies in California by Draegger (1967), in Indiana by Hoffer (1967), and by Myers and Heilman (in press) in Texas have demonstrated conclusively that variations in the moisture content of bare soils notably affects the daily cycle of their response in the 8 - 14μ band.

In the Weslaco, Texas studies, even though soils were equally dry on the immediate surface, variations in water content (Myers and Heilman, in press) in the shallow sub-surface and to depths as much as 50 cm. were detectable with diurnal imagery. As would be expected, moist soils having a large thermal inertia show a damped response throughout the day.

Myers and Heilman believe that the daily temperature oscillations can be a good indicator of gross soil moisture conditions of significance to farm management in irrigated and dry farming regions. They found that soils at Weslaco, which were relatively dry, had an oscillation between 45 and 51° C and adjacent moister fields had oscillations between 40 and 42°C. They also suggested that negative heat exchange during the cooling phase of the daily cycle and in the fall months would be helpful not only in giving information on subsurface moisture content, but on the variations in physical properties of the soils at depth.

While much additional work will be needed to bring infrared sensing of bare soils to the stage of semi-quantitative estimation of soil moisture, the results obtained to date are sufficiently encouraging that we may reasonably hope that operational systems for this purpose will eventually be developed.

Estes (1967) and others have reported detection of buried stream channels on infrared imagery. Wallace and Moxham (1966) found that infrared imagery of the San Andreas Fault showed moisture held back along the fault zone in a semi-arid to arid environment. Flights at several times a day over potential irrigation areas may aid in the detection of water bearing channels and thereby improve irrigation prospects substantially. However, much experimentation will be needed before such a water divining tool is perfected.

A potentially important application of spacecraft in semi-arid areas is monitoring the path of heavy rain storms during the break of the monsoon season. To some degree almost any sensor, be it photography, infrared, microwave, or radar, will sense major storm boundaries after the fact. The well known Gemini photograph of the high plains of Texas analyzed by Hope (1966), for example, shows the path of heavy rainfall photographed from space. A Nimbus high-resolution infrared scanning system should be able to do equally as well scanning in the 8 - 14μ band. At the same time preliminary studies by Catoe et al. (1967) and Moore and Simonett (1967a) suggest that spacecraft-borne passive microwave and radar systems may perhaps detect rain falling over land.

The ultimate possibility also arises of using a number (perhaps three) of sun synchronous Nimbus infrared or passive microwave satellites of modest resolution following one another in orbit, but separated by eight hours (2 p.m., 10 p.m., 6 a.m.). Such space vehicles following the same path could well be used to monitor the state of moisture changes in semi-arid irrigated or pasture lands. While quantitative detection and identification using thermal infrared is fraught with many difficulties, the ability to detect change and to derive valuable qualitative and semi-quantitative data from short-term changes is both feasible and reasonable.

Additional hydrologic roles which infrared imagery may fulfill include, 1) seeking sites of ground water discharge into marine coastal waters as documented in Hawaii by Fischer et al. (1965), and Fischer, Davis and Sousa (1966) who mapped 219 springs along the shoreline with infrared images, 2) in studying effluence both natural and artificial (Moxham 1967), and 3) in studying flood, tide and salt damage along inundated coastlines.

REMOTE SENSING IN THE RADAR REGION

Imaging radars with characteristics suitable for land evaluation surveys have been developed in the past two decades. Because most of the images produced in the past by these radars have not been available to the scientific community, their potential in resource surveys is not recognized widely.

The kind of radar which has the greater application in such surveys is side-looking airborne radar. Such radar produces a continuous-strip image that looks much like a continuous strip photograph taken from a very high altitude. Unlike a photograph or an infrared scan image, however, the area imaged is not below the aircraft, but rather extends from a short distance out to the side to a considerably larger distance away from the aircraft.

Figure 1 and the following description after Moore and Simonett (1967a) shows the operation of a side-looking airborne radar. The antenna directs its energy at right angles to the flight path. A short pulse is transmitted. The signal first returns from a region at the inner edge of the illuminated area. The strength of the signal determines the brightness of a dot on a cathode ray tube. As time goes on, the return signals come from further and further away. During this time, the position of the spot on the cathode ray tube is changed in synchronism with the time delay or with the ground range until, at the time the signal is returning from the farthest point illuminated, the spot on the cathode ray tube has moved from the bottom to the top of the tube. Since the spot brightness is determined by the strength of the signal received from the different portions of the ground, the density of film exposed to this spot is also proportional to the signal intensity. Hence, a line on the film has been exposed whose density is proportional to the "brightness" of the radar signal from the different points to the side of the aircraft. By the time the next pulse is transmitted the film has advanced slightly and so has the aircraft. Hence, a new line on the film is exposed and the film density is proportional to the "brightness" of the area to the side of the new position of the aircraft.

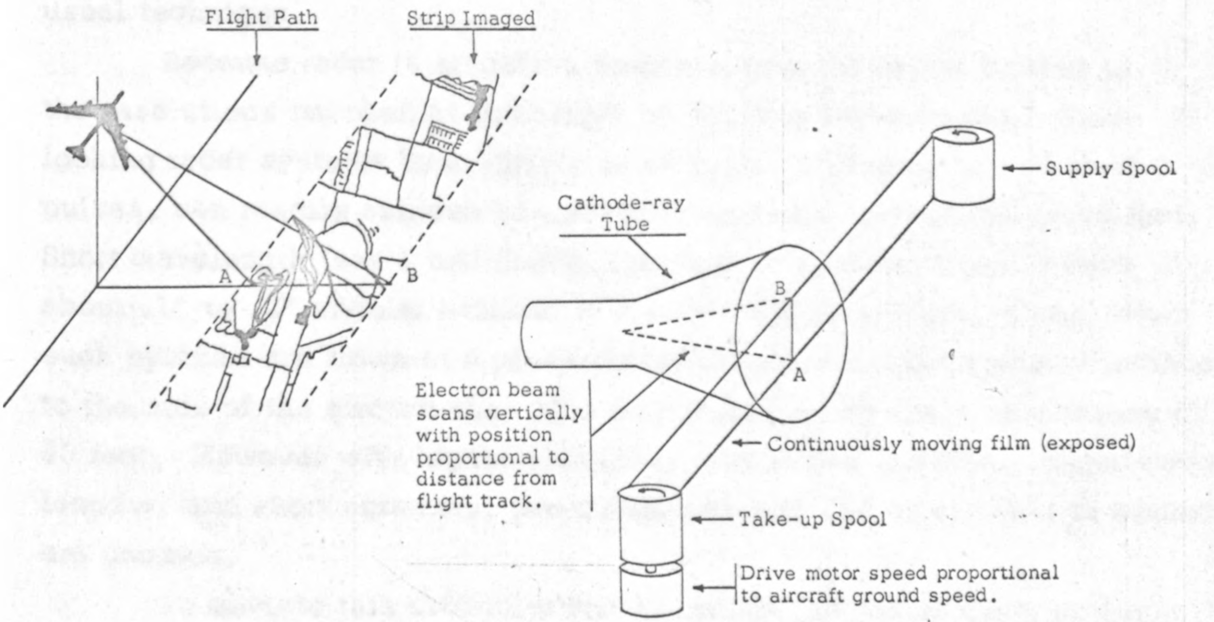

Figure 1. Side-looking Airborne Radar and Recording Technique

Thus, as the aircraft advances the film advances and a continuous picture is produced. As is true in the infrared region this information could be recorded on tape, though film recording is much the most usual technique.

Because radar is an active remote sensor, it is not limited to the resolutions imposed at first sight by its long wavelengths. Side-looking radar systems by a variety of methods, including use of short pulses, can readily achieve across-track or range resolutions of 50 feet. Short wavelength (say 1 cm) diffraction-limited systems usually have about .1° to .2° angular azimuth or along-track resolution. Thus, when such systems are flown at modest altitudes and look only a short distance to the side of the aircraft they also may obtain along-track resolutions of 50 feet. However with higher altitudes, longer path lengths, longer wavelengths, and short antennas, resolutions of from 300 to 600 feet in azimuth are common.

To obviate this difficulty and to enable the use of much longer wavelengths, and also to reduce the size of antennas so as not to affect the stability of aircraft, synthetic aperture radar systems have been developed. In synthetic aperture systems the phase as well as the amplitude of the returning pulse are stored and are later put together in a computer as if they were produced by an antenna a great deal larger than the aircraft. By this means finer resolution is achieved along-track than can be obtained with a "brute force" or "real aperture" diffraction-limited system.

The radar echo intensity that determines the brightness of an image is proportional to four basic factors: the geometry of the material imaged; its dielectric properties; the radar wavelength employed; and the polarization of the transmitted and received energy. Materials having large flat surfaces cause strong signals when the radar beam is perpendicular to the surface and weak signals at other angles. Very rough surfaces -- roughness say equal to or greater than the wavelength employed--give signals more nearly independent of the angle at which radiation strikes them.

The dielectric properties determine both the strength of the signal produced by a given material and the amount of absorption experienced by this signal in passing through the material. The absorption is primarily influenced by the conductivity, and the signal returned by the permittivity. The latter is most influenced by water which has the highest permittivity commonly found in nature. Thus the moisture content of plants and soils can be an important factor in the strength of the signal and hence the brightness of the image, although the roughness of the vegetation mantle is normally much the most important single factor with short wavelength radar.

The wavelengths used range from .5 cm to 60 cm or longer. Those shorter than 3 cm may be used for real aperture systems, while synthetic apertures may cover the whole range. In this wavelength range radar signals penetrate slightly moist to dry substances a distance of perhaps the order of the wavelength employed. Consequently the information in the return signal is not exclusively surficial as is the case in the visible region. Thus different information is to be expected from different radar wavelengths both from this penetration effect and the differential effect of various roughnesses.

Polarization of radar waves has turned out to be a useful discriminent in crop and land use studies. The radar wave is said to be polarized in the direction of its electric field vector. An object permitting current to flow in the direction of the electric field vector will give a stronger return than one for which such current flow is difficult. Thus vertical polarization may be expected to emphasize trees with straight trunks and few secondary limbs better than horizontal polarization and so on. Most surfaces also tend to depolarize the wave to some extent but not all to the same extent; that is an incident horizontally polarized wave is returned with both horizontal and vertical components, of varying intensity. Thus there is merit in employing radar systems with the capacity to transmit alternate horizontal or vertical polarization pulses and to receive both polarizations. In this article the convention is followed that the transmitted polarization and received polarization are given as abbreviations in that order, i.e. HV is horizontal transmit, vertical receive.

There are several major advantages to be noted with radar systems. First, they are unaffected by clouds and by all except the heaviest of storms, but, even more importantly, the atmosphere makes virtually no contributions to the radar return signals. Since, in addition, the quantity of energy transmitted is known, radar has a unique opportunity for quantitatively handling terrain reflectances which is not available in any other portion of the spectrum or in passive systems. The radar back scattered return from terrain targets which are areally extensive and which do not contain point high reflectors such as metal objects, corners of buildings and so on, unambiguously represent the back scattering properties unaffected by the atmosphere.

The necessity for retaining accurate phase as well as amplitude information with synthetic aperture radar systems has led to the development of very accurate inertial control devices so that it is possible to construct almost planimetric quality synthetic aperture radar imagery over areas of slight relief. Finally, the side-looking illumination mode emphasizes relatively minor terrain features and has therefore proven useful in certain geologic and geomorphic studies.

The disadvantages of imaging radar systems are several. First, the side-looking nature of these systems means that the data cannot be obtained at the same instant or in the same geometric format as that of either optical-mechanical scanners or framing cameras. The point-by-point pattern recognition approach that becomes feasible with the Michigan multi-band scanning system between .32μ and 14μ cannot be made compatible with the point-by-point output of imaging radar systems. Second, relief displacements are opposite to those in the optical region. There is, consequently, an inevitable tendency to regard radar systems as being set apart from the other systems. Multiple-frequency and multiple-polarization radars are, however, as a group capable of being made mutually compatible and multi-spectral pattern recognition is quite feasible with multiple radar systems carried on the same aircraft. Finally, since the long wavelengths make for much specular reflection, cultural objects tend to show severe scintillation, target breakup and a general graininess to the image not found with broad band, i.e. panchromatic, images in which there is much frequency averaging. Studies are underway at the University of Kansas employing broad band, non-imaging, and imaging systems to help overcome this problem.

Studies of Natural Plant Communities and their State

A number of studies on the effect of natural vegetation on radar returns have been made with two-polarization K-band imagery in various environments in the United States, and in all areas some influence of vegetation on radar returns was observed.

The methods which my colleagues and I are using in our vegetation studies include the familiar analysis of tone and texture together with more sophisticated analysis using a multiple Image Discrimination Enhancement Combination and Sampling System (IDECS) developed at the University of Kansas. Operations presently possible with the IDECS system include tri-color image combinations, gray-scale level selection, automatic texture discrimination, signature selection, generation of probability density functions, and various differentiation and other enhancement techniques. The IDECS system is naturally more applicable to area-extensive flat or gently sloping uniform targets such as the fields in an agricultural area and is difficult to employ in studies of natural vegetation.

Our studies to date indicate that multiple-polarization K-band radar is sufficiently crude both in resolution and discrimination between natural plant communities that it is suited best for gross-scale reconnaissance studies. This is not to say, however, that broadband radar, and additional frequencies and polarizations will not contain additional information. It is quite feasible, for example, that long wavelength radar systems may well contain information relating to the spatial periodicities and densities of trees in plant communities and might thus usefully supplement other methods for estimating timber volumes. I hasten to add that this is at the moment nothing more than a possibility and it needs much thorough analysis.

In summary form, radar appears to have a possible role in:

1. Preparation of small-scale regional or reconnaissance maps of vegetation type, especially when there are pronounced structural differences between plant communities,
2. Delimiting vegetation zones that vary with elevation,
3. Tracing burn patterns of previous forest fires,
4. Delimiting the altitudinal timber line,
5. Identification of species by inference in areas characterized by monospecific stands,
6. Possible discrimination of structural sub-types in cutover, burned and regrowth forests,
7. Deriving estimates of vegetation density in sparsely vegetated areas, and
8. Supplementing very high altitude low-resolution photography in which textural differences related to vegetation are weakly expressed.

Not all of these are equally likely a success, but all are worthy of further study. Details will be found in Simonett and Morain (1965), Morain and Simonett (1966), Morain (1967), and Morain and Simonett (1967).

A number of general comments should be made about the use of radar imagery in studying plant communities. Because the radar return is markedly influenced by major variations in topography, radar imagery is not suited for use in mountainous regions. R. N. Colwell and associates have found it of quite limited use, for example, in their studies at Buck's Lake in California. We have also found that logged and cutover areas on the Oregon coast simply cannot be distinguished from high forest because of the slope of the terrain and the radar look-angles involved. For this reason those environments where radar is likely to be most sensitive to vegetation differences are regions which have pronounced seasonal contrasts and are relatively flat, such as the great sweeps of the tropical Savannas or the Arctic Plain of North America, and in which notably disjunct lithology and ground moisture states are juxtaposed. However, to date no such imagery has been obtained or interpreted.

Land Use, Crop Discrimination and Crop State Studies

Because different crop types and varieties are planted at various times, are subjected to diverse life experiences and mature at different dates there is considerable natural variance in reflectance and emission in all parts of the electromagnetic spectrum. For these reasons it will be necessary to obtain remote sensor imagery at several times throughout the agricultural cycle in a given region. Given multiple-frequency, multiple-polarization radar imagery at several times throughout a growing season I am reasonably sanguine that radar will prove to be a useful tool in the mapping of broad land use categories, in statistical pattern recognition studies, in crop discrimination including semi-automation, and even to some degree ultimately in perhaps discriminating crop state. While in effect expressing my faith in long term potential of radar for such studies in the future it is necessary to emphasize that very little work has been done to date. The most detailed studies are those with a K-band multiple-polarization flown twice (1965 and 1966) in a single test area near Garden City, Kansas. Despite the paucity of available data the results of the Garden City studies (Simonett et al. 1967; D.E. Schwarz and F.C. Caspall, unpublished manuscript; and F. Caspall, R. Haralick, R.K. Moore and D.S. Simonett, unpublished manuscript) are very encouraging.

Seven types of agricultural information gathering ranging from simple to very complex are of potential interest for remote sensing application. These involve:

1) delineation of field boundaries,
2) detecting the presence of different crops,
3) determining the acreage of different crops,
4) determining which crops are actually present,
5) determining the vigor of crops,
6) determining the agent responsible for any loss of crop vigor, and
7) predicting yeilds.

Research to date with radar has dealt with items 1, 2 and 3 and a fair amount of success is indicated. In the Western Kansas test site, 85% of the fields were detected as being separate using flights in August and September of 1965. Quite possibly flights at a different time of year would have distinguished many more fields since in September (and even to some extent in August) many fields had been harvested and look much alike to radar or photography. The results of this study are:

Total Number of Fields in Test Area: 419	Number of Fields Identified	% of Fields Differentiated or Added	Total % Fields Separated on Imagery
September-HH imagery	267	64%	64%
Added by Sept. HV imagery	16	4%	68%
Added by Aug. HH imagery	38	9%	77%
Adjacent fields-same crop	34	8%	85%

No comparative study has been made to differentiate these fields on photographs.

The K-band radar used was able to distinguish sugar beets from corn with a 97% probability, and corn from all other crops with a probability of 87% during September. Bare or essentially bare ground could be distinguished with a probability of 93 percent. Hoffer (1967) also found bare ground appeared to be distinguishable at Purdue. Grain sorghum, wheat and alfalfa however are hard to distinguish at that time of year.

Further study of various parameters influencing the return showed the following results:

1) percent ground cover strongly influences the return,
2) crop height makes a substantial contribution to the return particularly after cover is nearly 100%
3) crop moisture may add to the variations in return, the difference being a function of crop type, and
4) soil moisture may also influence the radar return, although in general because soils moistened through irrigation tend to be smoother than dry-farmed fields, the relation is masked by the effects of differential surface roughness.

Statistical pattern recognition studies on radar images of crops are also underway at the University of Kansas. Electronic circuits have been built to perform a number of algorithms in adaptive signature recognition (Haralick 1967) and Bayesian decision theory techniques (Dalke 1966) for use with the IDECS system.

Drainage Nets

Little work has yet been done in application of radar images to hydrologic problems. Preliminary study by McCoy (1967) of radar as a tool for drainage basin analysis shows considerable promise. The large areal coverage and abundance of landform detail available on radar images make them especially suitable for such studies. Twenty-eight basins were analyzed by McCoy and the results of the radar analysis were compared with hydrologic data obtained from a 1:24,000 scale map. The same methods of stream ordering, counting, measuring and data handling were applied to map and radar drainage displays. The radar imagery shows a substantial number but not all first order streams. Correlation and regression analysis therefore was used to determine the actual relationship between the radar data and topographic map data. As a result it was found that drainage area, basin perimeter, bifurcation ratio, average length ratio and circularity ratio can be measured from radar and map-derived values. Correlation between lengths of streams or drainage basin areas as determined on 1:24,000 scale topographic maps and the radar imagery was very high ($r = .98$).

Though monoscopic radar images were used in McCoy's study observation of terrain slope angles was possible using two different radar views on the same slope. The regional slope was the same using map data or radar data on 35 sample slopes ($r = .99$, 1 S.E.E. = 2.9°). Automatic interpretation techniques were applied to the imagery by means of edge enhancement and line-scanner counter systems. The experiments show a promising correlation between the total enhanced line length of a drainage basin and the total stream length measured from a topographic map. These relationships may provide a useful means for rapid analysis of large drainage areas. The results are sufficiently promising that further testing is underway.

Reconnaissance Geology, Geomorphology and Soil Mapping with Radar Imagery

Fracture trace and lineament maps obtained from air photos have proven valuable in many phases of hydrogeologic and mining exploration. In some cases, in the identification of faults and lineaments, radar has proven to be superior to conventional aerial photography (Dellwig, Kirk and Walters 1966; MacDonald, Brennan and Dellwig 1967). Gross resolution, X-band, radar imagery of the southern Boston Mountains in Arkansas, for example, shows a series of pronounced, north-trending linear features which exert a marked control on the topography. These linear features were not detected on either air photos or in detailed geologic mapping. Kover (in press) reports on unpublished studies by the U.S. Geological Survey that major lineaments and other structures not previously known to exist even in well-mapped areas were found with radar imagery. Many unmapped lineaments have been located on radar images of the Ouachita Mountains in Arkansas and Oklahoma (J.N. Kirk, personal communication). These have been noted on images from five different radar systems, obtained at different times and with different flight paths. The reality of the lineaments thus appears well established. In areas of very low relief it has been noted by Rydstrom (1967) that minor topographic expression of deep-seated faults and other structures not normally detected on air photographs, may be observed on radar images when the illumination angle is near grazing. A close correlation has been found between lineaments detected on aerial photographs and radar near Lawrence, Kansas (H.C. MacDonald, personal communication). However, more lineaments were noted on the radar imagery than on the photographs and certain long lineaments seen on the radar appeared as small segments only in the photographs. The detection by radar of lineaments is not uniformly so successful, however, as observed in a study in Pennsylvania by Wise (1967).

Thin sand veneers have been detected with radar imagery which were not evident on air photographs, and this has been confirmed in an unpublished USGS study referenced by Kover (in press). Differences between alluvial drainages in a complex bajada at Pisgah Crater, California were better detected on radar than on photographs and cross polarization added significantly to the detection of some lava-alluvial contacts (Dellwig and Moore 1966). Radar imagery has also been shown to be very sensitive to micro and meso surface roughness in flat playa lakes as a function both of the wavelength of the radar and the penetrating capabilities of the radar system (Ellermeier, Simonett and Dellwig 1967). In Arizona radar and photographs each contained information the other lacked: a major fault and certain soil texture differences were better expressed on the radar image than on the photo (MacDonald, Brennan and Dellwig, 1967). Several geologists have noted a number of areas where cross-polarized radar images emphasize certain volcanic rocks. No single explanation appears to account for this feature and further studies are underway (Gillerman 1967).

Numerous additional references to geologic and other studies are to be found in a radar bibliography for geoscientists prepared by Walters (1967).

In regard to the use of radar in soil reconnaissance mapping, Simonett (in press) found in northern Oklahoma that "the information obtainable from... radar imagery for soil mapping is distinctly uneven in both distribution and quality, for while it is sometimes possible to make clear distinctions between adjacent soils even at the series level, and more usually at the association level, there are many instances when neither is feasible. Separation of soil groups at the association level is more likely in untilled and sub-humid to arid regions, than in cultivated or densely forested humid lands. To put these conclusions in another way, where extreme differences occur in adjoining plant structures, in soil or plant moisture content, in soil texture, in topography, and -- in areas of scanty vegetation -- small-scale surface roughness, then discrimination on the radar image of soil units closely tied to these differences will usually be possible. Lesser differences will not be so easily detected, especially in cultivated areas, and careful timing of aircraft flights to coincide with the greatest seasonal vegetation contrasts will be necessary."

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