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Remote Sensing in Polarized Light

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SUMMARY

It is well-known that sunlight reflected by various types of surfaces carries information about the surfaces themselves. This is the usual experience in everyday life. The eye, responding to light intensity, color, spatial configurations, etc., is very effective in distinguishing among water, grass, forests, mineral outcrops, roadways, and other types of natural and artificial surfaces. Similarly, remote sensing by means of cameras or other light-sensitive devices carried aboard aircraft or spacecraft has enabled successful characterization of agricultural, oceanographic, and geologic features of the Earth's surface, and such devices continue in widespread use for remote sensing.

With few exceptions, however, the cameras and other tools of remote sensing have used only the intensity of the radiation field and, thereby, have neglected the additional information carried by the state of polarization of the light received at the remote location. There is strong and convincing evidence to show that the polarization field, with its spectral, spatial, and temporal variations, may be interpreted to obtain information unavailable when only the light intensity is observed. Of course, the information yield, in a remote-sensing context, is maximized by combining both intensity and state of polarization in the measurements of the remote location. The primary purpose of the workshop described herein was to explore the potential and the means of using both intensity and state of polarization for practical application in remote sensing of the Earth's surface from the Space Shuttle or other spacecraft.

In order to apply the ideas of several scientists working in the fields of radiative transfer and remote sensing to these difficult problems, a 3-day workshop was convened under NASA sponsorship at the Lyndon B. Johnson Space Center on November 3 to 5, 1987. The names of the 26 attendees are listed in appendix A of this report. The format of the workshop included a number of presentations, with extensive group discussion of each presentation. The detailed program of the workshop is included as appendix B. In addition to the general sessions in which all delegates participated, individual sessions were held by four working groups for more thorough examination of the various problems. The members of the four groups are listed in appendix C. Each working group was assigned the task of discussing a particular aspect of polarized-light remote sensing in greater depth than was possible in the general sessions, and of developing a section of this report dealing with its assigned topic. The most significant findings of this report, including the recommendations, are a result of deliberations by the four groups on the following topics: group 1 - problems of surface reflection and radiative transfer; group 2 - instrumentation for remote sensing in polarized light; group 3 - needs for remote sensing in agricultural, geologic, hydrologic, oceanic, and land use applications; and, group 4 - remote sensing of polarization from planets, stars, and other extraterrestrial objects.

The most important recommendations developed at the workshop are the following.

1. An experimental and theoretical program of research on reflecting properties of geologic formations and plant canopies should be performed in conjunction with rigorous radiative transfer studies of the atmosphere to show explicitly how the polarized-light signal received at a spacecraft can be best interpreted in a remote-sensing context. Very important components of this investigation are the extent to which the modeling computations give unique solutions on the information content of measured polarization, and the supply of ground-truth data for selected

regions of the Earth's surface and atmosphere in which remote-sensing measurements are concentrated.

2. A three-phase program of the development of polarization instrumentation for use on the Space Shuttle should be initiated and performed as expeditiously as feasible. Phase I should consist of a simple upgrade of the camera system already used on four missions of the Space Shuttle. One additional camera should be added to the existing camera pair, the three cameras being fitted with polarizing filters oriented at angles of 0°, 45°, and 90°; each roll of film should have a density test wedge impressed at the beginning and end of the film; and film development should be carefully controlled. Phase II should consist of the development of a new, three-channel, high-resolution video camera system fitted with polarizing filters and mounted on a remotely controlled, gimballed platform in the cargo bay of the Space Shuttle. Phase III should incorporate an all-solid-state polarization imaging system with multispectral capability mounted in the cargo bay of the Space Shuttle. Phase I is sufficiently simple that it could be implemented in 1988. Phases II and III would need longer periods for development but are well within the capability of existing technology.

INTRODUCTION

A 3-day workshop was convened under NASA sponsorship at the Lyndon B. Johnson Space Center on November 3 to 5, 1987. Twenty-six scientists participated in and contributed to the workshop deliberations. The format of the workshop included a number of presentations on various aspects of the remote-sensing problem, each presentation being followed by extensive discussion by the delegates. The reports from those working groups constitute the primary content of this report. The method of approach in the following discussions is to present three different aspects of the problems: (1) the basic physics of surface reflection and atmospheric effects in radiative transfer inherent in remote sensing from space, (2) the primary needs and possibilities of remote sensing of the surface of the Earth and of other planets, stars, asteroids, and comets in polarized light, and (3) the development of specific instruments and instrument systems appropriate for polarized-light remote sensing from space.

It is pertinent to mention as a background to the workshop that the Space Shuttle Program has already yielded about 400 pairs of photographs of the Earth taken in polarized light by astronauts aboard the Space Shuttle. As far as is known, these photographs are the first polarized images of the Earth ever taken from space. Although the camera system used lacked proper calibration to give quantitative data and had to be pointed through cabin windows (which have their own polarization effects), analysis of the photograph has enabled the obtaining of interesting and significant polarization signatures of several different types of surfaces as seen from space. The preliminary results from these polarized images have been given by Coulson, Whitehead, and Campbell (1986).

RADIATIVE TRANSFER IN Tı ˬ EARTH - ATMOSPHERE SYSTEM

BASIC PROBLEMS

The intensity and the polarization of radiation emerging from the top of the Earth-atmosphere system are governed by scattering and absorption of radiation by the gaseous and particulate (aerosol) constituents of the atmosphere and of clouds, and by the generally wavelength-dependent reflectional and polarizing properties of the natural and artificial formations making up the surface of the Earth. Therefore, any measurement of the upwelling radiation from space would consist of a mixture of signals originating from within and at the surface of the atmosphere. The contribution of either of these two signals to the measurements made from space can be minimized by a proper choice of the spectral interval in which measurements are made, provided experimental constraints allow such a choice to be made. Thus, if one is interested in the surface signal, the contribution of the radiation scattered by the atmosphere (the atmospheric signal) can be minimized by making measurements in the near-infrared (IR) region of the spectrum, at wavelengths as great as 2 micrometers, where scattering and thermal emission by the atmosphere are minimal. On the other hand, if the intent is to study the atmosphere with measurements of the upwelling radiation, the atmospheric signal can be maximized by making measurements in the visible region of the spectrum. Although the surface signal is not negligible, even at visible wavelengths, the separation of atmospheric and surface effects can be accomplished if the bidirectional reflectional properties, including polarization, of the underlying surface are known and if the surface is relatively homogeneous over the area of measurement.

Thus, the central problem encountered in interpreting measurements of the upwelling radiation made from space is the separation of the atmospheric and surface effects. This complex problem should be addressed in its entirety to enable the obtaining of scientifically meaningful results from such measurements.

Against this background, and in view of the fact that the current emphasis is to delineate the usefulness of remote sensing in polarized light, the polarization of scattered light in the atmosphere and the polarizing properties of natural formations which make up the Earth's surface are discussed first. Then, the problems that are encountered in the interpretation of polarized-light measurements from space are enumerated. Finally, a set of recommendations as to how the aforementioned problem of separating the surface and atmospheric effects should be addressed is presented.

POLARIZATION OF RADIATION IN THE ATMOSPHERE

General

It has been observed that the radiation emerging at the top of the atmosphere in the visible and near-IR regions of the spectrum is polarized to an appreciable extent and that the degree of polarization exhibits strong wavelength dependence. Spatial and temporal variations in the intensity and polarization of the emergent radiation can be explained in terms of variations in the atmospheric aerosols and of the reflectional properties of the underlying surface.

Atmospheric Aerosols

Atmospheric aerosols are critical for cloud formation and, consequently, for the planetary albedo for sunlight. They are a significant factor in the chemistry of atmospheric trace constituents. The properties of principal interest are their mass and area distribution with respect to their size and their chemical composition. Current satellite measurements of spectral radiances give information about the particles within the range of diameters 0.1 to 1 micrometer. The particle mass and optical thickness, a crude measurement of particle size, and the albedo of single scattering are derived. No estimates of the chemical properties can be made. The question to be answered is whether or not polarization measurements can improve accuracies of the previously described parameters and add some chemical data.

Both theoretical and experimental data show that the intensity and the polarization of light scattered by aerosols depend significantly on their size, chemical composition, and amount. No published data show, however, what the optimum method of measuring aerosol properties is: whether by spectral radiances alone or by a mixture of radiance and polarization observations.

Therefore, the initial step should be to show theoretically the advantages of measuring polarization. If the results are encouraging, the first Space Shuttle experiments should be restricted to the oceans, for which the weak surface reflectional properties are known rather well. A significant experiment would be to investigate the effect of air-pollution aerosols on cloud albedo. The properties of both aerosols and the adjacent clouds would be measured in the presence of air pollution. The spectral bands should be at the limits of possible wavelengths, 0.4 and 1.0 micrometer, in band-widths of 0.02 micrometer, or less. Spatial resolution of 1 kilometer would suffice.

POLARIZING PROPERTIES OF NATURAL FORMATIONS

Soils and Sands

Naturally occurring soils are complex composites of dissimilar materials in all three states of matter. Their interaction with electromagnetic radiation is governed to a great extent by their index properties such as texture, composition (chemical and mineralogical), moisture content, and consistency. It is, therefore, reasonable to expect that the polarization of radiation reflected by such natural formations should be dependent on at least some of the aforementioned index properties.

Laboratory and field studies in the main, and some airborne investigations, have indicated that

1. Light reflected by sands and soils, when illuminated with natural (unpolarized) light, is partially linearly polarized. The degree of polarization shows a strong dependence on the angles of illumination, observation, and relative azimuth. Maximum polarization is observed about

90° to 110° away from the antisource direction in the principal plane; neutral points are also generally observed in this plane. When the illumination is completely linearly polarized, the reflected radiation exhibits only partial polarization.

2. The texture of the reflecting surface, as determined by the particle size, shape, and gradation, influences the polarization of reflected light. The smaller the particle size, the brighter (generally) the surface and the lower the polarization, and vice versa.

3. The near-surface moisture content of the surface affects the polarization of the reflected light in a very pronounced manner. Thus, wetter, darker surfaces polarize reflected light to a greater extent than do the drier, brighter surfaces.

4. Polarization of reflected light is strongly wavelength-dependent, with greater polarization being observed at the shorter wavelengths.

Plant Canopies

Field investigations have indicated that the polarization of light directionally reflected by plant canopies may be useful for remote sensing of agronometric properties. It has been observed that the polarization of reflected light can be used to identify the presence of vegetation. It is found that as leaves get drier, the polarization of reflected light increases. Both measurements and modeling studies have indicated that the primary mechanism for polarization is specular reflection from leaf cuticle wax on the uppermost leaves of the plant canopy.

The positive polarization from the uppermost leaves of the plant canopy can be modeled as arising from specular reflections of leaves with different orientations. Measurements show that two varieties of wheat with different leaf angle density functions produce significantly different polarizations in reflected light. Such sensitivity of polarization to plant canopy geometry may allow the detection of the onset of heading for crops with spherical leaf density functions, such as Compton wheat. In practice, the yield of important crops such as wheat can be estimated from the date of heading onset and concurrent meteorological data. Such estimates cannot be made with the currently available spectral radiance signatures alone. However, any such application of polarization directed toward the detection of the onset of heading and of weather-induced (e.g., hail and wind) damage to crops should properly account for short-term changes in polarization of reflected light. Such changes may be caused by wind-induced crop surface motion, drying of leaves, and changes in the ratio of leaf surface area to bare soil in the observed scene.

Experimental data show that the degree of polarization of light reflected by a plant canopy is larger in the blue and red chlorophyll absorption bands than in the green and near-IR regions of the spectrum. Future investigations should be directed toward determining the dependence of reflected-light polarization on changes in measurable crop properties such as leaf area index, leaf orientation, etc., along with developing appropriate plant canopy models. It is felt that the wavelength interval 0.65 to 0.70 micrometer might be the most suitable for these investigations. However, for reasons mentioned earlier, appropriate corrections must be made for atmospheric effects if this spectral region is chosen.

Clouds

Rigorous radiative transfer computations in realistic models of terrestrial clouds have shown that the polarization of the reflected radiation is more sensitive to changes in cloud microstructure than is the intensity. The reason is that multiple scattering does not obscure features of polarization, which arises mainly from primary and low-order scattering of radiation, as it does features of intensity. It is thus possible that polarization measurements, especially in the near IR could be utilized for the identification of clouds and in studies of their microphysical properties.

Water Surfaces

Laboratory studies, of a very limited extent, have indicated that the intensity and the polarization of light reflected by apparently smooth surfaces of water are in broad agreement with predictions according to the Fresnel theory of specular reflection. However, complete polarization has not been observed at the Brewster angle, and perceptible reflection in the lateral directions has been noticed. This result could be due to the departure of the surface from absolute smoothness. Very-broad-band polarization measurements made from the Space Shuttle have indicated that the interference patterns observed on the sea surface in the region of Sun glint carry a significant polarization signature.

In conclusion, it should be stated that the available experimental data indicate that the polarization of light reflected by the artificial and natural formations that make up the surface of the Earth exhibits the Umow effect – the darker the surface, the greater the degree of polarization, and vice versa.

The following example illustrates the coupling between atmospheric and surface effects. Suppose 90 percent of the upwelling radiation originates at the surface, with a polarization of 10 percent, and the remainder is made up of the atmospheric contribution, with a polarization of 50 percent. The resultant polarization of the upwelling radiation is 14 percent: $[100 \cdot (0.9 \cdot 0.1 + 0.1 \cdot 0.5)]$.

A large error will be made if this measured polarization is attributed to the surface alone. Similarly, if the surface contribution is 50 percent with a polarization of 50 percent, and the remaining atmospheric contribution has a polarization of 10 percent, the resultant polarization of the upwelling radiation will be 30 percent. A large error is once again made if all of this polarization is attributed to the atmosphere.

UTILITY OF POLARIZED LIGHT IN REMOTE SENSING OF THE EARTH

REMOTE SENSING OF VEGETATION

Leaves

Light incident on a leaf interacts first with the epicuticular wax and then with the cuticle. Together, these form a nonabsorbing (in the visible wavelengths), multilayered protective covering displayed by the leaves of all species. The indexes of refraction of these various layers appear to be similar and in the range of 1.4 to 1.5. Inside the cuticle, cells contain pigments which absorb light in the visible wavelengths.

Electron micrographs show that leaf surfaces are never flat but, instead, have significant surface roughness. The interactions of a beam of light with a leaf surface include scattering by surface particles of structures (both large and small, relative to the wavelength of light), specular reflection from the epicuticular wax surface, and further scattering of the upwelling specular beam.

Studies have shown (Grant, 1985) that light reflected from leaves may be divided into two components, each component having its own history of reflection from the leaf surface or of scattering from within the main structure of the leaf. The primary polarizing process is surface reflection, particularly specular reflection from properly oriented areas of the leaf. Fresnel's laws of reflection show that light reflected from the surface covering of wax should be highly polarized at some angles, in accordance with observations. A convincing argument that the strongly polarized component is due to surface reflection is provided by the fact that the strength of this component has no significant spectral dependence and, thus, that the polarized portion has not been subject to absorption by plant pigments below the surface. The spectral dependence of the unpolarized portion, however, is such as it would have if it were transmitted through the surface to the layers of plant pigments, where some wavelengths were absorbed more than others by the pigments. This portion then emerges from the body of the leaf in a spectrally dependent and largely unpolarized state because of multiple scattering by cells, cell walls, vacuoles, and other structures inside the leaf.

Plant Canopies

For a plant canopy (an ensemble of leaves, stems, fruit, flowers, and soil), the polarization of the scattered light depends on four factors: the polarized, spectral scattering properties of its components (just examined for leaves); the canopy architecture; the directions of illumination and view; and the polarization properties of the sources, skylight and sunlight. The light-scattering properties of components other than leaves are often neglected, as they appear to be most often of secondary importance in understanding the polarization properties of the light scattered by plant canopies covering the soil.

Values of the Stokes vector contain information describing the physiological and morphological status of a plant canopy. For example, the magnitude of the specularly reflected light provided by one unidirectional source - the Sun, scattered by a canopy containing plants of one species, should be a function of the number of these plants per unit of ground area. The rationale is that each leaf will specularly reflect an average of one unit of flux. The total specularly reflected sunlight will be proportional, therefore, to the number of leaves - which is related to the density of plants per unit ground area of the canopy.

The magnitude of the specular flux contains other information concerning such structural properties of the canopy as the probability density function of leaf area as a function of angle, and the probabilities that a facet of foliage is illuminated and observed, all key input data to radiation-transfer models of plant canopies.

The canopy architecture is a rich source of information for discriminating species and varieties and for assessing the condition of plants. This information is often not discernible in radiance data; yet, polarization data, because they are particularly sensitive to the canopy architecture, do manifest changes. For example, the ability to discriminate varieties of wheat having different leaf angle probability density functions has been demonstrated on the basis of polarization data. The ability to detect phenological changes associated with canopy architecture has been demonstrated for heading wheat.

Remotely sensed data of the phenological phases (stages of growth) of a plant canopy, when coupled with the corresponding sequence of weather conditions, could provide important input data to phenologically based models for the production by the plants of photosynthetic products - both the accumulation of phytomass and the ultimate grain yield. Currently, to estimate production for a geographical area, average phenological phases and weather conditions for the area must be used in the models because estimates for the plant canopy in each field are unavailable. Use of the actual phenological phase of the plants coupled to the actual weather conditions to which they are exposed rather than coupled averages, potentially enables the obtaining of more accurate production estimates using these models. The reason is that certain species-specific weather conditions (such as elevated temperatures in wheat canopies at the heading stage), if they occur even briefly at key phenological phases, will affect significantly and adversely the photosynthetic process in such canopies. Not all canopies are at the average phenological phase at any one time over a region. Canopies at different growth stages may be affected differently by the weather conditions.

In the case of wheat, analysis of a synoptic, remotely sensed, temporal sequence of polarization images can provide for each field the desired coupling between the two temporal sequences - weather conditions and phenological phases of the plant canopy. This possibility is based on the fact that field measurements of the light-polarizing properties of several plant canopies have been shown to change with the advent of the heading stage.

Polarization data of a plant canopy, even if measured with a calibrated sensor and perfectly corrected for the effects of the atmosphere, will display variation typical of natural targets. Wind is potentially a large source of this variation. In fact, the effects of wind may preclude interpretation of polarization data in an absolute sense because, depending upon its direction and strength, the wind is capable of redirecting the leaves of a canopy and thereby changing the probability density function of leaf area with angle.

Canopy polarization data, when obtained from satellite sensors, probably will be used in conjunction with other remotely sensed data. The information contained probably will be extracted by analysis of frequent, synoptic data sets, by using the temporal and spatial information to make relative comparisons between ground areas measured on one date and between dates for one area. One polarization data set representing one ground area measured on one date will have little value unless it is compared to polarization data of that area and other areas for that date and other dates. Again, such comparison approaches will probably be necessary because it is unrealistic to expect that canopy polarization data will be uniquely related in an absolute sense to the discrimination of a particular plant stand or to a particular botanical variable.

REMOTE SENSING FOR GEOLOGY AND HYDROLOGY

Current Status

Studies such as those of Lyot (1929), Zellner (1977), Egan (1985), and others have shown that natural Earth materials exhibit a polarization signature in reflected light. The phenomenon is largely independent of the photometric character of the materials and may, therefore, offer an additional remote-sensing tool for lithologic discrimination and field mapping. Light reflected from samples of barren rock and soil appears to be plane polarized to one degree or another as a function of grain size (surface microtexture), grain morphology and grain orientation, porosity (degree of particle sorting, compaction, and/or cementation), surface albedo, grain refractive index, and surface moisture. Perhaps related to these parameters, or perhaps due to other whole-rock characteristics, polarimetric anomalies are expected to be associated with metallic mineralization and hydrocarbon contamination.

Lithologic units can often be discriminated and even identified using but a few of the previously described parameters. Consequently, if variation in these characteristics could be reliably predicted, modeled, and observed remotely in the field using polarized-light photography, the concept of a new and powerful remote-sensing tool would be established. Polarization phenomena have been observed in Earth observation photography taken from the Space Shuttle. Unfortunately, there may be significant atmospheric transmission factors that so complicate the problem as to render this or other remotely sensed light polarization product difficult to interpret in the analyses of Earth surface materials. The presence of aerosols or of invisible ice or water droplets may induce polarization effects that are more significant than those expected from the Earth material and, thus, mask the Earth surface polarization effects.

Potential Applications

On the assumption that the masking effects of the atmosphere can somehow be overcome and the exact nature of the polarimetric phenomena of rock and soils understood, the powerful capability of polarization photography could be useful in discriminating, mapping, and potentially identifying lithologic units. Once rock units can be recognized and mapped, geologic structure can be interpreted and hydrocarbon or mineral deposits predicted or even directly located and evaluated. Previously unrecognized fault lines or regions of Earth surface instability could be mapped and, thereby, construction in hazardous locations could be avoided.

Because snow particles undergo a process of granulation as they age, the difference between new snow and old snow can possibly be recognized by the change in polarimetry. On this basis, new snow accumulations could be calculated and seasonal snowmelt/runoff predictions refined.

REMOTE SENSING OF OCEAN SURFACES

Potential applications of polarized-light remote sensing may be useful in addressing several significant problems and questions with regard to oceanic surfaces. These surfaces extend to shallow water depths that include particles and processes of importance to issues of marine geology, chemistry, biology, and physics. Most of the potential applications are ones which are under study with existing methodologies. Nevertheless, the development of a polarized-light-based technology may provide a degree of enhancement that could be of value.

The sea surface (including the waters to approximately one optical depth; i.e., on the order of 10 meters) may be characterized as containing particles (organic and inorganic) and dissolved matter. In two dimensions, the near surface (order of 0 to 5 meters) may also be defined by small-scale structures of roughness (such as wind waves and capillary waves) and by large-scale structures characteristic of subsurface topography or hydrodynamics. In three dimensions, this surface is variable and may be driven by global-scale geostrophy and weather patterns. At the smallest depth scales (order centimeters or micrometers) the surface is often a complex skin of chemical microlayers.

The nature of polarized light has been shown to be somewhat effective in characterizing near-shore, suspended particle loads. Additional specific issues for which polarized-light remote sensing may be of value include sea surface wave directional spectra, sea surface dynamic heights (as inferred from large-scale eddies), description of sea surface manifestations of subsurface features (including internal waves in deep water and bathymetry near shore), suspended particle concentrations and variability, biological productivity (or organic/inorganic ratios of suspended material), particle-size distributions, and characterization of oceanic zones of convergence and divergence. In addition, the application of polarized-light sensing to detection and characterization of surface microlayers or slicks may be of very high value. Unpolarized images within and around the Sun-glitter ball are provocative and suggest that polarized images may be even more revealing in regions characterized by these slicks.

Although techniques for remotely measuring these processes exist or are under study now, that should not preclude an effort to determine the potential for using polarized light to enhance the understanding. Existing images may, in fact, be shown in a qualitative way to demonstrate that polarization techniques are very revealing of some of these processes.

REMOTE SENSING IN CLIMATOLOGY

Currently, the climatic effects of the buildup of carbon dioxide in the atmosphere is the subject of considerable controversy. Some predictions are that the level of the sea will rise 50 feet by the year 2030, but not all climatologists agree with this estimate. Some data (Egan, 1987) indicate that the climate in the Adirondack Mountains of New York State has been stable over the last century. Some of the information needed to unravel the climate question are definitive data on the effect of aerosols and clouds in the atmosphere in relation to climate.

Polarization has the unique capability to remotely characterize cloud particle size that is not possible with photometry. In addition, polarization alone has the capability to distinguish ice crystals from water droplets in clouds.

Changing cloud patterns have not been included in global climate models. Cloud patterns have a dominating effect on climate. Polarization alone has the capability to characterize cloud particle sizes and cloud optical depths by means of the scattering phase function. This capability can elucidate the physics and microphysics of clouds.

Further, absorption line shapes (of carbon dioxide and methane), which vary with altitude and temperature in the atmosphere, may be characterized with moderate- to high-resolution spectroscopy. The absorption line shapes are affected by scattering, which enhances the absorption continuum level because scattering is equivalent to additional absorption in the viewing direction. Although the line shape is unchanged, as well as the central wavelength, the equivalent width is less and the elemental abundance will be overestimated. Polarization will permit a delineation of scattering as it affects individual line profiles as well as band structure.

Another point to be made is that an analysis of the Garp Atlantic Tropical Experiment data showed that polarization observations of Sahara duststorm areas from space yield a unique characterization of the optical thickness of the dust cloud as compared to corresponding ambiguous results with photometry alone.

REMOTE SENSING OF POLARIZATION FROM ASTRONOMICAL AND EXTRATERRESTRIAL OBJECTS

GENERAL

Although photographic polarimetry from the Space Shuttle cannot be adapted to the most important needs of current astronomy, most investigators in this field welcome and support the idea. At the same time, astronomers have contributed numerous ideas and suggestions in order to obtain observations from outside the atmosphere that are important and will complement the future work with the Space Telescope and the Astro mission.

The following recommendations are focused on observations of very extended objects. In this regard, it is convenient to keep in mind that the angular size of the Moon, about 30 arc minutes, will register an image of about 1.8 millimeters in diameter when observing with a 250 millimeter-focal-length objective lens. All the planets have angular diameters of less than 1 arc minute. Some special observations of unresolved objects are also recommended, but the information is obtained from the temporal variations of polarization rather than from the image.

Astronomers also favor observations in the ultraviolet (UV) region of the spectrum over observations in the optical region. Ultraviolet observations may be easy to implement if one considers that UV optics is available for most types of cameras; that normal photographic emulsions are sensitive to wavelengths beyond 200 nanometers; and that the Space Shuttle has a quartz window built for the same purpose.

For astronomical observations, it will be convenient to use emulsions with the largest dynamic range, even if they are only black and white. Based on experience, astronomers prefer to select the spectral band with filters, and thereby to avoid leaks of contiguous spectral regions.

The different objects which have been recommended for observation have been divided between targets of opportunity and scheduled targets. For obvious reasons, the most important observations are those of the targets of opportunity. In order of their probability of occurrence, the targets of opportunity include comets, novae, and asteroids.

TARGETS OF OPPORTUNITY

Comets

On the average, about five comets brighter than 11 integrated magnitude are visible per year. Angular size of these bright comets ranges between several minutes of arc to a few degrees for the coma. At their brightest appearance, the tail covers at least 10° with clear differences of length for the ion and dust tails. Measurements in the optical region indicate that the polarization due to scattering of the solar light amounts to about 10 percent. Larger polarization is observed in fluorescence emission of some molecules, especially in the cyanide band at 388.9 nanometers. Since the intensity of this band dominates the rest of the spectrum by about two orders of magnitude, observations in the near UV will provide polarization of larger signal to noise ratios than in other wavelengths. This type of observation is very important because imaging polarimetry of comets in the CN band is very difficult from the ground and very seldom attempted. Although apparition of bright comets cannot be predicted, it is possible to program the observations on short notice; that is, a few days before the start of a mission.

Novae

Imaging and polarimetry of novae in the UV at any stage of evolution remain the most compelling observations for this type of objects because the results could help to test conflicting theories on the type of explosion. The high degree of interest in such observations was recently illustrated by the precipitate flight of the Quantum module in the Mir space station in April 1987. The Quantum module is a contingent of X-ray and UV telescopes from Switzerland, Great Britain, West Germany, and the European Space Agency that was rushed into orbit to observe the Large Magellanic Cloud, supernova discovered in February 1987. Supernovae are infrequent, but several novae are discovered every year. Some of them are conspicuously bright in the optical region, and observations in the UV are practically nonexistent. Studies in the optical region indicate that the polarization of novae is negligible in the early phases of the explosion. However, in many cases, the effects of Rayleigh scattering, presumably due to the formation of dust grains, start to appear after 4 or 5 months. It remains to be confirmed whether the wavelength dependence of Rayleigh scattering reveals polarization in the UV at an earlier age of the nova.

Asteroids

It is estimated that about 1300 asteroids periodically cross the orbit of the Earth. These asteroids have sizes between 1 and 10 kilometers and their orbits are frequently scrambled by close planetary encounters. In some cases, a close approach to the Earth is possible. If such an opportunity occurs, it will be important to photograph the asteroid and to measure its polarization. Even if the image of the asteroid is unresolved, variations of the reflected light and the polarization can provide important information on the orientation of the rotation poles. In the optical region, the polarization of asteroids is about 1 to 2 percent, certainly too small for photographic polarimetry; however, there have been no attempts to measure the polarization in the UV.

SCHEDULED TARGETS

It is difficult to attach priorities to the scheduled targets; for this reason, they are described here in an arbitrary order.

Moon

The polarization of the Moon increases toward shorter wavelengths. There are variations during the waxing and waning phases because of the different distributions of maria and highlands involved, but observations of the whole disk reveal that the maximum polarization is about 15 percent at 360 nanometers and about 8 percent at 550 nanometers. There is considerable interest in knowing the amount of polarization in the UV to investigate the dominant type of surface scattering on the Moon.

Zodiacal Light

There is a lingering controversy about the degree of variability of the intensity and polarization of the zodiacal light. Early indications of variable polarization appear to have been refuted by observations obtained from the Helios 1 and 2 space probe (Leinert and Plank, 1982). The data were collected in several runs between 1974 and 1979 in the visual band at an effective wavelength of 529 nanometers. These results fail to confirm early reports of variations in the polarized intensity, the position angle, and the asymmetry of the zodiacal light polarization. On the other hand, observations obtained from the D2B satellite between 1975 and 1976 (Mancherat, Llebaria, and Gonin, 1986) in a spectral band centered at 440 nanometers, show variations of intensity and morphology of the zodiacal light near the antisolar direction. These variations may be caused by the injection of dust clouds resulting from a comet or from disintegration of an asteroid. Further observations of the zodiacal light are required to establish firm limits to the degree of variability. These observations can be made in the optical or the UV spectral regions.

Solar Corona

Observations with an improvised coronograph, consisting of the mechanical arm of the Space Shuttle, can provide highly rewarding information on the solar corona. Estimates of the brightness at 10 solar radii give about one magnitude per square second of arc in the visual band and about 4 magnitudes per square second of arc at 260 nanometers. In other words, the solar corona is sufficiently bright to provide accurate polarization and a map of the projected structure independent of the spectral band used.

Terminator of the Earth

Considerable interest in the polarization characteristics of the Earth terminator and in the scattered light exists among geophysicists. Here, we can suggest that such observations will provide important information on the different layers of the atmosphere, the photochemistry involved, the weather, and the effects of volcanic dust. We are not aware of any planned investigation of the terminator in any spectral region.

Space Debris

More and more astronomical observations are being contaminated by reflected light from space debris. Since some astronomical objects display light flashes which resemble the glints of space debris, it has become important to find a way to discriminate between the two. Imaging polarimetry is a promising way. Furthermore, identification and determination of the size distribution of space debris are of special importance to the Space Telescope because very bright pieces of debris could saturate and damage sensitive detectors of narrow dynamic range (Shara and Johnston, 1986). A program to obtain imaging polarimetry of debris in the UV or the optical region will certainly find wide support from astronomers.

INSTRUMENTATION FOR REMOTE SENSING IN POLARIZED LIGHT FROM THE SPACE SHUTTLE

CONSTRAINTS IMPOSED BY THE SPACE SHUTTLE

The major constraints imposed by the Space Shuttle are those due to the available orbits; i.e., 28.5° inclination, with a 57° inclination orbit being available occasionally. The lack of control of the launch time and probably of the specific altitude will make selection of test sites equipped with surface and atmospheric "truth" measurement systems difficult.

A possible viewing approach to get bidirectional reflectance and polarization measurements from the Space Shuttle is shown in figure 1. This scheme was developed for the multispectral linear array (MLA)/STS experiment, but it is equally applicable to polarization measurements from the Space Shuttle. Applicable also are the orbit parameters of table I and the orbit configurations for a 3-day repetition of the 28.5° inclination shown in figure 2.

Observations from within the Space Shuttle cabin are constrained by the field of view (FOV) of the windows and the problem in locating test sites. When the Space Shuttle flies with the cargo bay facing the Earth and with nose forward, it is reasonable for the astronaut to see the target through the front windows, locate it, then photograph the scene through the overhead windows which face the Earth in this flight orientation.

Only when the launch time is such that the plane of the orbit contains the Sun (approximately) will it be relatively easy to make observations of the same scene at multiple-phase angles in the principal plane.

A possible carrier for polarization instruments mounted in the cargo bay is the Hitchhiker-G and Shuttle Payload of Opportunity Carrier (SPOC) or the getaway special cannister. The SPOC can provide all of the services required with the possible exception of a high-data-rate link for the digitized polarization data.

REQUIREMENTS FOR POLARIZATION SENSORS FOR IMAGE ACQUISITION

Very few firm requirements for polarization sensors have been defined. However, the following considerations are pertinent.

1. Natural materials do not generate any significant amount of circular or elliptically polarized light. Therefore, it is probably adequate to measure only linear polarization.

2. It may be acceptable to measure only two components of linearly polarized light if they are parallel and perpendicular to the principal plane.

3. It is preferred to measure the signal from a common instantaneous field of view (IFOV) through three polarization analyzers at 0°, 45°, and 90°.

TABLE I. - SPACE SHUTTLE MLA CONCEPT ORBIT/STUDY SITES

Orbit parameters	Rationale
Inclination: 28.5°	– Standard Space Shuttle
Altitude: 278 km	– 3-day repeat - allows multiple chances for cloud-cover avoidance – Near standard Space Shuttle
Node: Such that a 26.3° S ascending, descending crossing point occurs at 20° E	– Prime study site coverage
Launch/orbital insertion time: Such that 26.3° S crossings occur at ~9:00 local standard time site, descending and ~12:13 local standard time ascending on day 1	– Low-, high-Sun-angle coverage of prime test with minimum cloud cover
Time of year: Southern Hemisphere summer summer (mid-November to mid-April)	– Nominally March 1

Limitations induced by 28.5° inclination, near-standard-altitude orbit (278 km)

– Coverage limited to ±28.5° latitude

– The ascending/descending-node crossing points within one daylight period occur in distinct latitude belts approximately as follows:

Latitude	Time Difference
27.9° N/S	1:35
26.3° N/S	3:10
23.5° N/S	4:45
19.6° N/S	6:22
14.7° N/S	8:00
8° N/S	9:30
2.5° N/S	11:12

– In order to get significantly different solar zenith angles on the two passes, the 3:10 and 4:45 (26.3° N/S, 23.5° N/S) time difference points are required, allowing midmorning, near-noon or near-noon, midafternoon coverage.

– Fixing either the Northern Hemisphere passes or the Southern Hemisphere passes as daylight makes the other pairs both night.

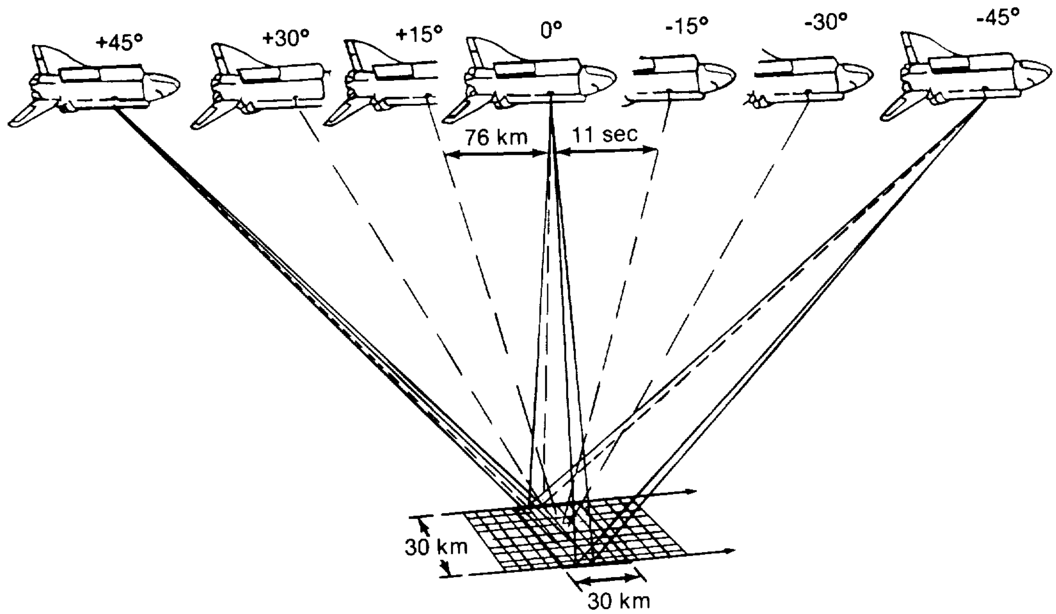

Figure 1.- Off-nadir pointing for bidirectional reflectance measurements of terrestrial land cover.

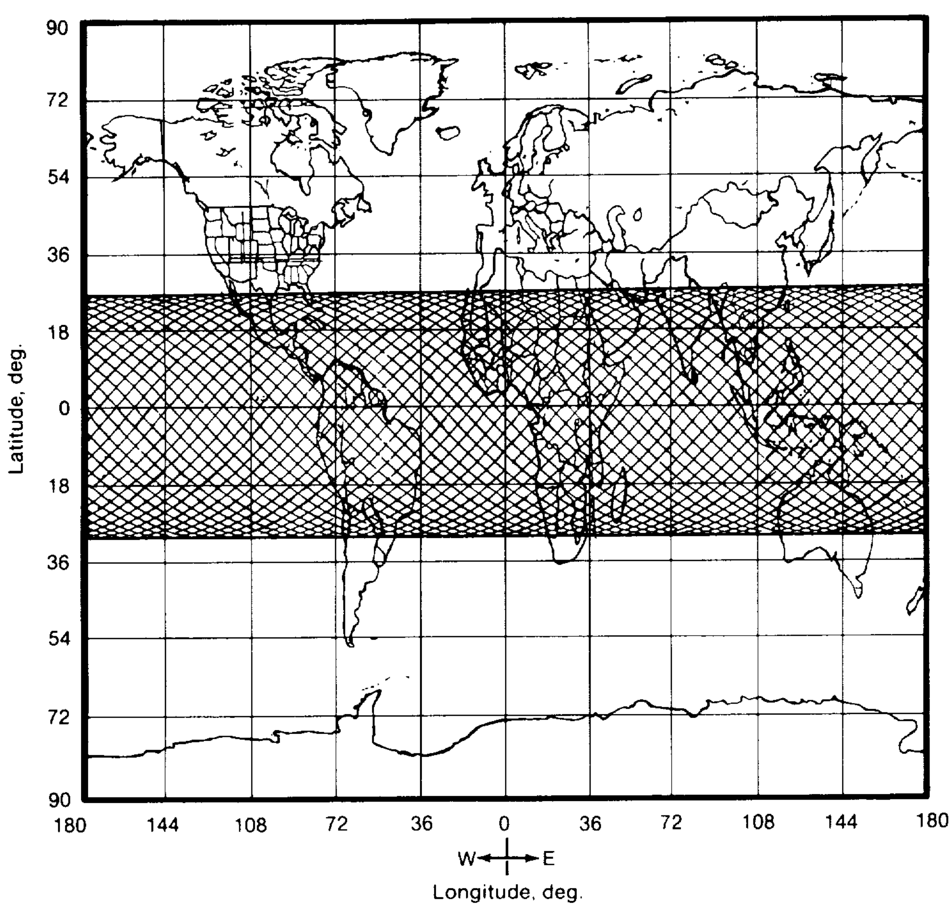

Figure 2.- Preferred Space Shuttle orbit (28.5° inclination, 278 km, 3-day repeating).

4. The IFOV's of the various polarization channels in a given spectral band must be very precisely registered if accurate polarization measurements are to be made.

5. For most applications, only a few spectral bands are required.

6. Atmospheric users of polarization information would like to have spectral bands as long as 3.1 micrometers in conjunction with bands in the green, the red and the near IR. They could use an IFOV of 1 kilometer or larger and desire an FOV of a few hundred kilometers.

7. Vegetation observers would like an IFOV of 30 meters to no more than 100 meters, and a narrow FOV of perhaps as little as 30 kilometers could be used for selected experiments. The preferred spectral band is 650 nanometers; 850 nanometers may provide additional information.

8. Ocean observers seem to prefer wavelengths of 550 and 800 nanometers. An IFOV of a few hundred meters would be generally adequate, but many uses will require an FOV of several hundred kilometers.

9. Geology observations are not well defined but probably will require characteristics similar to high-resolution imaging spectrometer (HIRIS); i.e., 30-meter IFOV and 30- to 40-kilometer FOV. No spectral bands have been identified.

OPTICAL SYSTEMS FOR IMAGE ACQUISITION

There are no "standard" configurations for a polarization sensor used to observe the Earth from orbit. The cameras with polarizing filters that have been flown on the Space Shuttle are the only Earth observing polarization sensors that have been flown. Polarization sensors have been used to observe Venus and Mercury, and many ground-based astronomical observations have been made using polarized measurements of electromagnetic signals. An instrument concept for use in polarization measurements from the Space Shuttle has been suggested by Egan (1986), but it is applicable only to measurements in the principal plane. Chen (1985) has produced a polarimeter design for use on a geostationary satellite.

The unique requirements for a polarization sensor are the need for:

1. Precise coregistration of polarized IFOV's (< 1 percent)

2. Ultralow induced polarization in the instrument

3. Precise calibration of the detectors

4. Simultaneous observation in the polarized IFOV's

These unique requirements, when combined with the spectral band needed and with the IFOV and FOV desired, create the challenge in designing a polarization-sensing instrument. Given a reasonable set of requirements for an early mission, however, it will be possible to develop a viable instrument concept.

CALIBRATION CONSIDERATIONS

Polarization sensing requires differencing large values of radiance to measure a small polarization component. Therefore, for most applications, the calibration required of a polarization sensor must be better than that of a conventional multispectral imaging radiometer.

The required calibration accuracy will depend on the required accuracy in measuring polarization and radiance and the scene characteristics. It may be more appropriate to calibrate a polarization sensor as a reflectometer rather than as an instrument for making absolute, or relative, power measurements in the various spectral bands, since reflectance and the polarization properties of the reflected light are the primary data to be acquired. On a large spacecraft, such as the Space Station, it may be feasible to locate a diffuse reflector so that it will be illuminated by the Sun and observable by the instrument. The problems with this calibration technique are many. The diffuser changes with time, but on the Space Station, it would be feasible to bring it into the manned modules and verify the calibration, or to exchange it for a new reflector on a routine basis. Assuring that no other illumination, such as light reflected from the Earth or by the Space Station intrudes would require careful design. Periodic observations of the Moon may provide reflectance calibration, since the lunar reflectance is very stable. The roughness of the Moon means that its reflectance changes with solar illumination angles, and this variation will require careful control in the data acquisition. It is also essential to carefully match the gain applied in calibrating the data from different detectors in a given spectral band.

The spectral defining filters over the various polarization channels in the sensor must be very nearly identical; otherwise, the convolution of the scene spectral signature with the spectral defining filter and the detector spectral response will lead to scene-dependent errors that cannot be removed from the system by calibration. It would be best if the same spectral filter could be used for all polarization channels. Variations in the reflectivity of the scene will also cause errors in scene polarization estimates if the detector IFOV's are not accurately coregistered.

POTENTIAL INSTRUMENTATION FOR POLARIZATION MEASUREMENTS FROM THE SPACE SHUTTLE

As mentioned previously, polarized images have been obtained on four Space Shuttle missions. They were obtained by using a system of two Hasselblad cameras fitted with orthogonally oriented polarizers in front of the lenses. Although some significant results were obtained, the project was primarily exploratory, and the resulting data are not sufficiently precise for quantitative investigations. By building on this experience, however, it will be possible in a three-phase development to improve precision of the data within reasonable time and budgetary constraints. The phases anticipated for the development are the following.

Phase I: Minimum upgrade of present system (could be flown by January 1, 1989) - Major improvements would be in the adding of a third camera system to completely measure linear polarization and to improve the calibration of the system. Three 35-millimeter cameras with a nominal 50-millimeter lens would be used as the basic system, with polarizing filters at 0°, 45° and 90°. The analysis system to be used will generally provide 1000 or 2000 samples in each direction, which is compatible with good 35 millimeter film.

Calibration of cameras, lenses, filters, film, and Space Shuttle windows will be required if precise measures of the polarization signatures are to be achieved. The major variability in the cameras may be in the reproducibility of the f-stop transmission as it is set by the astronaut. In many systems, there is a significant difference if the final stop is reached by closing down rather than by opening up to the desired value. This effect, if it is significant, must be minimized. Calibration of the shutters for temperature changes may also be required.

Density test wedges must be recorded on the film at the start and end of each roll. It may be desirable to photograph a step density wedge during the mission to validate the effects of latent image fading between the time the prerecorded density wedges were placed on the film and the time the images were taken.

Calibration of the Space Shuttle windows is an especially challenging problem. Preflight and post-flight calibration must be checked against at least one in-flight test. Using neutral density filters, images of the Sun could be recorded on linear portions of the film density range through various portions of the window and by this means the necessary calibration information could be provided. A nadir view of a uniform cloud region might be an alternate source of nonpolarized radiation if the Sun were in the right position. A sheet polarizer could be placed over the window to provide calibration with a fully polarized scene.

The choice of the film to be used may be dominated by the calibration requirements. Color film tends to have spectral crosstalk since the internal filters are designed to provide pleasing images, not precision multispectral radiometry. If appropriate multiple narrow-band-pass filters could be used in conjunction with color film, it may be feasible to get two or perhaps three bands of information with well defined spectral response and acceptable crosstalk. Black and white film with spectral filters could provide better spectral and radiometric calibration, but manual changing of filters on three cameras does not seem reasonable. It may be feasible to develop a camera holder in which the camera lenses are at the apex of a triangle so that a set of filters on a wheel could be used to simultaneously place the selected spectral filter over all three cameras.

The time of image acquisition must be recorded on the film, along with the f-stop, the shutter speed, and the filters used. Perhaps the addition of a microcassette recorder on the camera system would allow the astronaut operator to easily identify the conditions as well as to comment about the scene. If a filter wheel is used, the position could perhaps be encoded along with the time.

If Sun glint or a landmark is included in the image, it will be possible to determine the orientation of the cameras at the time of requisition. Any future improvements should include every reasonable effort to establish the camera attitude at the time of image acquisition. A technique for automatically measuring the length of extended spring-loaded strings to fixed locations could provide this information. Another alternative would be to use "digital Sun sensors" with IR sources at fixed locations near the windows. Three sources, each operating at a different frequency and two or three pairs of angle sensors could provide the pointing information to an accuracy of 1°.

Phase II: Imaging system in cargo bay - The second level of improvements to provide the required polarization information may be to locate the imaging system in the cargo bay of the Space Shuttle using a pointing system that could be controlled by either the astronaut or a ground operator. The imaging system would require a pointing system to hold the polarization-sensing instruments and an imaging video system to provide pointing information for the astronaut or the ground operator via the Tracking and Data Relay Satellite System (TDRSS). The major advantage of this mode of operation is that the errors introduced by the Space Shuttle windows are eliminated. A set of 3 high-resolution video cameras with 1000-line resolution, electronic shutters, and remote selection of filters would be the preferred instruments for acquisition of the polarization information. With this system, data could also be acquired during the crew sleep periods. An alternative would be to use film cameras, but such use would significantly reduce the range of data that could be acquired on a given flight.

Calibration of this system using techniques similar to those described before is necessary. The attitude of the pointing system will be telemetered so that the attitude of the cameras can be established. If the pointing platform has only one degree of freedom, it will be desirable to control the Space Shuttle yaw to a specified attitude for one to two passes during the mission so as to acquire data with the required illumination and scan angles.

Phase III: Final imaging polarimeter for Space Shuttle operation - The third phase of a polarization-sensing system for flight on the Space Shuttle would consist of an all-solid-state sensing system on a two-degree-of-freedom pointing system in the cargo bay. The sensor would measure three polarization components in three or four spectral bands with the data digitized, temporarily stored on an onboard tape recorder, and telemetered to the ground via TDRSS. Data acquisition would be controlled primarily from the ground, but the astronauts could control data acquisition for special scenes using a video camera on the pointing system with a display in the cabin. The precise specification of the instrumentation will be determined as a result of further definition of the program objectives and the analysis of the data acquired from laboratory, field, aircraft, and Space Shuttle flights. An instrument emphasizing polarization of the atmosphere (i.e., having an IFOV of between 300 meters and 1 kilometer and an FOV well within the state of the art) could be developed into flight instrumentation in a few years.

CONCLUDING REMARKS

We conclude by enumerating significant problems that must be addressed in any meaningful investigation of the potential of polarized-light remote- sensing and by recommending future action in this direction.

PROBLEMS IN USE OF POLARIZATION IN REMOTE SENSING

1. The type, the variety and the quantity of currently available data on atmospheric and surface polarization properties are not adequate to establish whether or not remote sensing in polarized light will add significantly to the information about the Earth-atmosphere system that can be obtained from remotely sensed spectral radiances alone.

2. Because of the nonuniqueness of the solutions given by existing algorithms that can be used to interpret polarization measurements made from airborne and spaceborne platforms, it cannot yet be established whether the measured polarization contains information that is unique to either the overlying atmosphere or the underlying surface.

3. The effects of the intervening atmosphere on the polarization signature associated with the underlying surface has not yet been properly understood.

4. The bidirectional reflection and polarization properties of natural formations have not yet been adequately measured or modeled in sufficient detail to permit their incorporation in rigorous radiative transfer models.

5. The lack of "truth" data on surface and atmosphere taken at the time and location of satellite overpasses makes assessment of remote-sensing results very difficult to properly interpret. This problem is particularly severe for remote sensing in polarized light.

RECOMMENDATIONS

A coordinated experimental and theoretical program of research, having the following main components, should be initiated.

1. More extensive measurements and modeling of the bidirectional reflectional and polarizing properties of natural formations should be undertaken.

2. To delineate the effects of the overlying atmosphere on the measured polarization, rigorous radiative transfer studies, incorporating the characteristic reflection matrices developed in following recommendation 1, should be started.

3. The effects of the nonuniqueness generally associated with solutions obtained in following recommendation 2 on the information content of measured polarization should be studied.

4. Since experimental evidence exists to indicate that the polarization of reflected light is sensitive to certain agronometric properties, efforts should be made to monitor changes in such agronometric properties using airborne and spaceborne remote sensing in polarized light, supplemented to the extent practicable with ground-truth data.

5. The utility of remotely sensed polarized light in the detection of slicks and interference patterns on the sea surface should be explored fully.

6. The possible uses of the information on atmospheric aerosols derived in following recommendations 1 and 2 in climate- and weather-related studies should be considered.

7. The polarized images which are already available from four Space Shuttle missions should be analyzed to the fullest extent feasible to reveal polarization effects observable from a space platform.

8. The remote-sensing instrumentation for use on the Space Shuttle should be upgraded in three phases as follows:

   a. Phase I - One additional camera should be added to the existing camera pair, the three cameras being fitted with polarizing filters oriented at angles 0°, 45°, and 90°; each roll of film should have a density test wedge impressed at the beginning and end of the roll; andthe film should be developed under carefully controlled conditions.

   b. Phase II - A three-camera television system should be fitted with polarizing filters and mounted on a remotely controlled, gimballed platform in the Space Shuttle cargo bay.

   c. Phase III - The television cameras of phase II should be replaced with an all-solid-state imaging and polarizing system operating in three or four spectral bands with sufficient dynamic range to observe surfaces from dark soils or water to the brightest snowfields or clouds.

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APPENDIX B
DETAILED PROGRAM OF THE WORKSHOP ON
REMOTE SENSING IN POLARIZED LIGHT

Day 1 - Tuesday, November 3, 1987

0830 - 0835	Introduction
0835 - 0845	Welcoming remarks - Dr. W. H. Shumate
0845 - 0900	Objectives and protocol - V. Whitehead, K. Coulson
0900 - 0930	Presentation: The Physical Nature of Polarized Light - Dr. Ben Herman
0930 - 0945	Comments and discussion: Dr. Herman, leader
0945 - 1015	Presentation: Atmospheric Effects in Remote Sensing from Space - Dr. Robert Fraser
1015 - 1030	Comments and discussion: Dr. Fraser, leader
1030 - 1045	Coffee break
1045 - 1115	Presentation: Reflection Properties of Natural and Artificial Surfaces - Dr. Bruce Fitch
1115 - 1130	Comments and discussion - Dr. Fitch, leader
1130 - 1200	Presentation: Remote Sensing Requirements for Agriculture - Dr. Vern Vanderbilt
1200 - 1215	Comments and discussion - Dr. Vanderbilt, leader
1215 - 1330	Lunch break plus travel
1330 - 1400	Presentation: Possibilities of Remote Sensing from the Shuttle - Dr. David Amsbury
1400 - 1430	Presentation: Polarizing Properties of Clouds - Dr. Andrews Lacis
1430 - 1445	Comments and discussion - Dr. Lacis, leader
1445 - 1500	Coffee break
1500 - 1700	Division into four working groups (see app. C.)

Day 2 - Wednesday, November 4, 1987

0815 - 0845	Presentation: Remote Sensing Requirements for Land Use, Demography, and Other Social Problems - Dr. Walter Egan
0845 - 0900	Comments and discussion - Dr. Egan, leader
0900 - 0945	Presentations: Analysis of Images Acquired on Four Shuttle Missions - Dr. Victor Whitehead Training the Astronauts - Dr. D. C. Carico
0945 - 1000	Coffee break plus travel
1000 - 1130	Tour of Shuttle training facility
1030 - 1045	Coffee break
1130 - 1145	Travel
1145 - 1245	Lunch break
1245 - 1300	Travel
1300 - 1345	Presentation: Physical and Operational Aspects of Shuttle Observations - Astronaut J. F. Buchli
1345 - 1415	Presentation: Systems Engineering for Polarization Measurements from Space - Marvin Maxwell
1415 - 1430	Comments and discussion - Mr. Maxwell, leader
1430 - 1445	Coffee break
1445 - 1515	Presentation: Analysis of Near-IR Polarization from Balloon-Borne Instruments - Dr. Richard Santer
1515 - 1700	Preliminary report preparation by working groups

Day 3 - Thursday, November 5, 1987

0830 - 0915	Presentation: Military Requirements for Remote Sensing - R. S Spinrad, D. Mautner, G. Kratochvil
0915 - 0930	Comments and discussion - Dr. Spinrad, leader
0930 - 1000	Presentation: Polarizing Radiometers for Space Applications - Dr. Santiago Tapia
1000 - 1015	Comments and discussion - Dr. Tapia, leader
1015 - 1030	Coffee break
1030 - 1100	Presentation: Development of Instruments for Earth Observations from Space - Mr. Martin Ruzek
1100 - 1115	Comments and discussion - Mr. Ruzek, leader
1115 - 1145	Final comments, as desired
1145 - 1300	Lunch break
1300 - 1600	Report preparation by working groups
1600 - 1645	Summarization by working groups
1645 - 1700	Comments and close of workshop

APPENDIX C
MEMBERSHIP OF WORKING GROUPS

Group 1 - Problems of Surface Reflection and Radiative Transfer

Chairman: Bruce Fitch
Cochairman: C. R. N. Rao

Robert Fraser
Ben Herman
Andrew Lacis

Group 2 - Instrumentation for Remote Sensing in Polarized Light

Chairman: Hsi Chen
Cochairman: Marvin Maxwell

David Amsbury
Charles Campbell
Richard Santer
Victor Whitehead

Group 3 - Needs for Remote Sensing in Agricultural, Geologic, Hydrologic, Oceanic, and Land Use Applications

Chairman: Vern Vanderbilt
Cochairman: Walter Egan

William Johnson
Gary Kratochvil
Don Mautner
James Smith

Group 4 - Remote Sensing of Polarization from Planets, Stars, and other Extraterrestrial Objects

Chairman: Santiago Tapia
Cochairman: Martin Ruzek

Kinsell Coulson
Michael Duggin
John Martonchik

APPENDIX D
ACRONYMS AND ABBREVIATIONS

FOV	field of view
HIRIS	high-resolution imaging spectrometer
IFOV	instantaneous field of view
SPOC	Shuttle Payload of Opportunity Carrier
STS	Space Transportation System
UV	ultraviolet
MLA	multispectral linear array
TDRSS	Tracking and Data Relay Satellite System
N/S	north/south
IR	infrared

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15. Supplementary Notes

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16. Abstract

Preliminary analysis of polarized images of Earth collected by hand-held cameras on Shuttle Missions 51A, 51G, 51I, and 61A indicate that unique information of the Earth's surface and atmosphere exists in those data. To ensure that follow-on research in polarization is focused upon and that the experiments are properly designed to address specific questions, 26 scientists with past experience and interest in polarization observations met at the NASA Lyndon B. Johnson Space Center on November 3-5, 1987. This conference report summarizes the discussions and provides the recommendations of the group for follow-on research.

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