NASA Technical Memorandum 103945

Estimation of Photosynthetic Capacity Using MODIS Polarization: 1988 Proposal to NASA Headquarters

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Summary

The remote sensing community has clearly identified the utility of NDVI (normalized difference vegetation index) and SR (simple ratio) and other vegetation indices for estimating such metrics of landscape ecology as green foliar biomass, photosynthetic capacity, and net primary production. Both theoretical and empirical investigations have established cause and effect relationships between the photosynthetic process in plant canopies and these combinations of remotely sensed data. Yet it has also been established that the relationships exhibit considerable variability that appears to be ecosystem-dependent and may represent a source of ecologically important information.

The overall hypothesis of this proposal is that the ecosystem-dependent variability in the various vegetation indices is in part attributable to the effects of specular reflection. The polarization channels on MODIS provide the potential to estimate this specularly reflected light and allow the modification of the vegetation indices to better measure the photosynthetic process in plant canopies. In addition these polarization channels potentially provide additional ecologically important information about the plant canopy.

I. Introduction and Background

The remote sensing community has clearly identified the utility of NDVI, the normalized difference vegetation index, and other vegetation indices for estimating such metrics of landscape ecology as green foliar biomass (Tucker, 1980), photosynthetic capacity (Sellers, 1985 and 1987), and net primary production (Running and Nemani, 1988). These transformations have found application at both the continental and global scales for analyzing processes such as desertification in Africa (Tucker et al., 1985) and the seasonal exchange of CO_2 between the atmosphere and the biosphere (Fung et al.,1987).

Both NDVI and a second commonly used transformation, the simple ratio, SR, are combinations of the radiances measured in the visible and near-infrared.

$$SR = \frac{IR}{VIS}; \quad NDVI = \frac{IR - VIS}{IR + VIS}$$

Both theoretical (Stellers, 1985 and 1987) and empirical (for example, (Goward et al., 1985) and (Asrar et al., 1984)) investigations have established cause and effect relationships between the photosynthetic process in plant canopies and these combinations of remotely sensed data. Yet it has also been established that the relationships exhibit considerable variability that appears to be ecosystem-dependent and may represent a source of ecologically important information.

For example, the variability in one transformation of remotely sensed data of a forest stand has been used to estimate tree crown size and stem density (Jupp et al., 1988a, 1988b), both key parameters for estimating the successional stage of the forest. Forest successional stage information is an important parameter for modeling the carbon flux of an ecosystem (Shugart, 1984).

That such ecosystem-dependent variability can be important to understanding its photosynthetic apparatus is illustrated by the ecosystem-dependent relationship between green leaf area index and these spectral transformations; it may saturate at LAI values of approximately three or four for a cultivated agricultural stand—but at values above 16 for a canopy of western hemlock in Oregon (Peterson et al., 1987). These examples point to the critical need to better understand the sources of variability in the relationships between the photosynthetic process and the various combinations of spectral variables potentially available for describing that process.

Modeling of Canopy

To gain increased understanding of the potential information and sources of variability in transformations of spectral data, mathematical models have been developed to describe the light scattering and photosynthesis processes in plant canopies (Smith, 1983), (Sellers, 1985, 1987). Input data to such models include the spectral light scattering and architecture properties of the various canopy components. Only a few models account for the non-Lambertian character of leaf reflectance. Most models do not distinguish between the light scattered by the leaf surface as distinct from that scattered from its interior or volume. Sellers (1987) notes that such complexity may be unneeded.

Yet there is a growing body of evidence to indicate that for some species the light scattered by the leaf surfaces of the plant canopy may play a significant role—and in the chlorophyll absorption wavelengths sometimes a dominating role—in determining the overall canopy radiance. Remote sensing field measurements have demonstrated that the magnitude of this surface reflected and polarized light, represented by a Stokes matrix, may be estimated for species having specularly reflecting, as compared to diffusely reflecting, leaf surfaces (Vanderbilt et al., 1985a and 1985b), (Vanderbilt and Grant, 1985), (Grant, 1985), (Vanderbilt et al., 1988).

Specular Reflected Light

The amount of sunlight specularly reflected by such diverse plants as sunflower, wheat, Sudan grass, ponderosa pine, oak, and maple is often so large that canopies of these plants appear *white instead of green* when viewed obliquely toward the sun (Vanderbilt et al., 1985a). This means that to model realistically the process of the light-canopy interactions in such plant canopies, leaves can not be assumed to be diffuse reflectors with matte surfaces; the effect of the sunlight specularly reflected from the air-leaf interface must be included in the model (Vanderbilt and Grant, 1985).

Specular reflections from the shiny leaves of plants originate at the interface between the air and the cuticular wax layer. Unlike the diffuse portion of the light reflected by a leaf, the specular portion of the scattered light is reflected at the first surface it encounters, never entering the leaf (Vanderbilt et al., 1985b), (Vanderbilt and Grant, 1986), (Grant et al., 1987a). The Fresnel equations of optics predict that the light reflected by such a specular surface is polarized. The magnitude of the polarized reflection depends on the angle of the incident light ray on the leaf, on the optical index of refraction of the wax, and on the surface roughness characteristics of the wax. The information content in the polarized portion of the reflectance may be species-dependent (Grant, 1985), (Vanderbilt and Grant, 1986) (Grant et al., 1988) and is potentially related to the physiological status and development stage of the canopy—to such botanical variables as leaf age and plant water status and temperature regime (Vanderbilt et al., 1985a), (Grant et al., 1987b).

Polarization Separates Surface and Interior Light

All of this suggests that remotely sensed polarization measurements of a plant canopy will contain information about the *leaf surfaces* (Vanderbilt et al., 1985b), (Vanderbilt, 1988), (Guyot, personal communication, 1988)—information independent of that in the light reflected from the *interior* of the leaves. The information in the flux polarized by the leaf surface is independent of the information in the nonpolarized flux because the polarized portion of the reflected light does not enter the leaf to interact with cell pigments, walls or water (Grant, 1985), (Grant et al., 1987a), (Grant et al., 1988). Polarization measurements will also contain information due to a third phenomenon—*canopy structure* (Vanderbilt and Grant, 1985). This includes information on green leaf area index (Vanderbilt and Grant, 1985) and the probabilities that a leaf surface is illuminated, observed, (the probability of gap) and specularly directed—meaning the probability that the leaf surface is directed such that any flux from the source will be specularly redirected toward the sensor (Vanderbilt, 1987).

Polarized images of the Earth observed from space provide qualitative indication that information is potentially obtainable from a satellite polarization sensor (Coulson et al., 1986). The data, approximately 400 film transparencies, were acquired by the NASA space shuttle astronauts using two bore-sighted cameras with crossed polarizers. The apparatus was hand-held and aimed through a shuttle viewing port generally in the principle plane of the sun. The results reveal that polarization differences between ecosystems are not large, which suggests that a higher quality, more carefully calibrated imaging system may be needed and that atmospheric effects in the data must be corrected.

Polarization data have never been acquired routinely by satellite-borne imaging sensors as part of Earth observation research. The reason is that hard evidence in the form of physically based theories supported by actual data has only recently demonstrated the actual—not merely potential—information in such data thereby providing the justification for a satellite polarization sensor. MODIS represents a unique opportunity to apply these insights at the global scale.

Vegetation, Polarization, and the Atmosphere

Atmospheric path radiance potentially contributes to both the polarized and non-polarized fluxes measured by a satellite-borne sensor. Results from modeling (Coulson et al., 1965) of these polarized and non-polarized radiances suggests that for a significant range of view and illumination directions and even under benign atmospheric conditions this atmospheric noise would be a non-neglectable fraction of the signal due to the polarized flux scattered by the Earth's surface. This reaffirms that it will be necessary to correct the raw polarization data from MODIS for the effects of the atmosphere before extraction of useful information about vegetation on the Earth's surface. Such deterministic procedures have not been reported. Yet the atmospheric polarization models which are necessary for developing such algorithms are available (Coulson and Fraser, personal communication, 1988).

All of this suggests that use of polarization data from a satellite sensor such as MODIS potentially will improve our understanding of global ecosystems. Thus, for example, it potentially will permit improved discrimination of vegetative ecosystems in synoptic remote sensing data (Curran, 1983). When employed in conjunction with vegetative indices such as SR and NDVI, it will potentially permit improved estimates of green leaf area and biomass, photosynthetic capacity, and net primary production. Because polarization data are quite sensitive to canopy structure and thus roughness, MODIS polarization data potentially will contain the information needed for estimating the aerodynamic roughness (the coefficient of drag) of vegetative ecosystems, which is a key parameter in global circulation models (GCM) describing the atmosphere.

Overall Hypothesis of this Proposal.

The ecosystem-dependent variability in the various vegetation indices is in part attributable to the effects of specular reflection. The polarization channels on MODIS provide the potential to estimate this specularly reflected light and allow the modification of the vegetation indices to better measure the photosynthetic process in plant canopies. In addition these polarization channels potentially provide additional ecologically important information about the plant canopy.

II. Relevance to NASA

The understanding of the polarized light scattering process in plant canopies measured at scales from one pixel to the globe and the search for ecologically, physiologically, morphologically, and phenologically significant information in spectra of this scattered light represent important aspects of the NASA remote sensing EOS science program. The insight gained into these scattering processes is essential to understanding the potential information in remotely sensed data acquired at all scales.

III. Background of Present Proposal

In 1982, NASA funded a task to measure and model the polarized light scattering properties of both leaves and plant canopies with the applicant as the principal investigator at Purdue University, West Lafayette, Indiana. Following transfer to Ames Research Center, the applicant received funding for a second task continuing and building upon the previous research.

Twelve papers describing the results of the research conducted under these tasks have appeared in peer reviewed journals. One paper was a review article and another was an invited review article. Three papers have been recently submitted for publication in peer reviewed journals. In addition six written papers or abstracts have been presented at conferences.

The present proposal will continue and expand this earlier research.

IV. Proposed Research

IV.A. General Conditions

As outlined in a previous section (I), we have made significant progress in our understanding of the light scattering and polarizing processes of importance for remote sensing of vegetation.

- Our results support the theory that for purposes of remotely sensing plant canopies in the visible wavelength region no significant amount of the reflected flux, polarized during the scattering process, originates in the interior of the leaf. For purposes of remote sensing, the polarization of the reflected light is due to the polarization of the incident light and to the properties of the cuticle of the leaf, the roughness of its surface and the composition of its epicuticular wax.
- Our measurements of the leaves of 18 species/varieties show that their light polarizing properties are species-dependent and related to the physiological status and development stage of the plant and to such botanical variables as leaf age and plant water status.
- Our measurements of plant canopies show that their light polarizing properties are due not only to the properties of leaves but also to the geometric characteristics of the plant canopy—to such parameters as the density of stems per unit ground area, the probability of canopy gaps, and the probability density function of leaf area as a function of direction.
- From these results, we have developed a mathematical model which predicts both the polarized and specularly scattered portions of the reflectance of a plant canopy. This model is based on the importance of specular reflection as a scattering process in canopies. The model is supported by polarized bidirectional reflectance measurements of leaves and canopies and by visual observations.

The proposed research will build upon these lines of investigation. While the results obtained to date are extremely encouraging, the research is in many ways constrained. The research will expand present lines of investigation and, at the same time, it will focus on several polarized vegetation indices. It will expand the measurement and modeling activities related both to polarized vegetation indices and to the atmosphere, and it will extend these capabilities to research at the regional, continental, and global scales. The advantages and limitations of these models will be explored during their development.

The proposed research is designed to provide better insight into the following two broad questions: What is the nature of the polarized light scattering processes at the canopy, atmospheric, and spacecraft levels? Then, if we understand these processes and their interactions, can we deduce from remotely sensed polarized data, information of ecological importance at regional, continental, and global scales.

A key part of the proposed research will involve modification of vegetative indices to include information derived from polarization data from MODIS. Use of polarization data potentially may allow correction of the Simple Ratio (SR) and Normalized Difference Vegetation Index (NDVI), as well as other vegetation indices, for the ecosystem dependent effects of specularly reflected light scattered by a plant canopy. The figure below illustrates what we have found from both our theoretical modeling and our field measurements. That is, that the specular radiance, S, of a plant canopy is a constant with wavelength, containing no evidence of pigment absorption. This suggests that the equations defining SR and NDVI may be modified to provide better correspondence to the photosynthetic capacity of a plant canopy:

$$IR = S+DIR, \quad VIS = S+DVIS$$

$$SR = \frac{DIR}{DVIS} = \frac{IR-S}{VIS-S}$$

$$NDVI = \frac{DIR-DVIS}{DIR+DVIS} = \frac{IR-VIS}{IR+VIS-2S}$$

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radiance                    .......
  +                        .
  +                       .
  +         . .          .
  +        .    .    .    DIR
  +    .            . .
  +   .........DVIS.............
  +          specular=S
  + + + + + + + + + + + + + + +
              wavelength
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where the radiance of the canopy in the visible (VIS) and infrared (IR) is the sum of its diffuse (DVIS and DIR) and specular (S) components. Unlike the polarized specular radiance, the non-polarized diffuse radiance of the canopy varies according to the concentration of pigments such as foliar chlorophyll, which suggests definitions of SR and NDVI aimed at describing the photosynthetic process in plant canopies should better involve the variables DVIS and DIR, rather than VIS and IR. This is possible potentially through the use of polarization data provided by MODIS.

IV.B. Objectives

The overall objective is to investigate the morphological, physiological, and phenological information in the light scattering properties of plant canopies observed through a disturbing atmosphere at the regional, continental, and global scales. We will selectively measure, analyze, and/or mathematically model the light scattering properties, described by the Stokes matrix, of plant canopies and the atmosphere. The potential advantages and limitations associated such an analysis approach—involving polarization data acquired over large areas—will be explored. The ten year effort will involve a wide variety of plant species from primarily forests but potentially also including species from wetlands, grassland, and arid lands. To properly characterize the phenomena at the various scales and to investigate the effect of the atmosphere, measurements will be made in the laboratory, in the field, from C-130 and ER-2 aircraft, and finally from MODIS. Also analyzed will be photographs, acquired during four recent shuttle missions, showing the polarization of the light scattered from Earth.

Specific objectives at each scale are:

<u>Aerospace</u>:

- Determine the effect of various disturbing atmospheres on the polarization of the flux scattered from several plant canopies measured as a functi of sun-view directions. Develop algorithms for correcting for these atmospheric effects in polarization data acquired by aerospace sensors.
- Determine the potential of polarized vegetation indices for describing the various states or conditions—specifically green foliar biomass, photosynthetic capacity, net primary productivity, and carbon flux - of plant canopies, measured through and corrected for a disturbing atmosphere, at the pixel, regional, continental, and global scales.
- Determine the potential of the Stokes vector for discriminating ground covers, measured through and corrected for a disturbing atmosphere.

<u>Field</u>:

- Determine (measure and model using (Vanderbilt and Grant, 1985)) the Stokes matrix description of the multispectral light scattering properties of a few plant canopies and their skys. Some of these measurements will be performed concurrently with acquisition of polarization data during aircraft overflights.

- Determine the potential of the polarized vegetation indices to aid in quantifying the various states or conditions—specifically green foliar biomass, photosynthetic capacity, net primary productivity, and carbon flux—of plant canopies.
- Determine, as appropriate, the natural, statistical variability of the Stokes vector of individual leaves as a function of such variables as plant species, plant development stage, leaf age, and leaf relative water content.

Laboratory:

- Determine the relationships necessary to support the field measurement and modeling activity; specifically, for those few canopies measured in the field, determine as necessary the relationships between (a) the bidirectional Stokes vector light scattering properties of leaves and (b) their morphological and physiological properties. These may include optical properties of the cuticle (complex index of refraction at various wavelengths and microscale surface roughness and topography) and biological properties of the leaf/plant.
- Determine the potential of the polarized vegetation indices to describe various states or conditions—specifically green foliar biomass, photosynthetic capacity, net primary productivity, and carbon flux—of a leaf of a plant.

IV.C. Aerospace Plans

Atmospheric modeling– These activities, involving both the design of experiments and computer-based atmospheric modeling, are being and will be conducted in collaboration with Dr. Bob Fraser, Goddard Space Flight Center, who is a participating principal investigator in the NASA program of research in Remote Sensing Science.

The objective is to acquire those data necessary to numerically model the effect of the atmosphere on remotely sensed polarization data and to develop the algorithms capable of removing the atmospheric effects from polarization data. This data set will include acquisition of data of the polarized bidirectional light scattering characteristics of several plant canopies measured at ground level and measured from the NASA C-130 at intermediate altitudes and/or from the NASA ER-2 at high altitudes. The data set will also include solar atmospheric transmission data acquired from the C-130; analysis of these data will allow the atmospheric affects of both Rayleigh-sized particles and aerosol particles on remotely sensed polarization data to be numerically modelled and better understood.

Development of this knowledge, gained from the quantitative analysis of these data, is essential if the full utility of an imaging, satellite-borne, remote sensing polarization sensor measuring vegetative canopies is to be realized. Thus, the results of this portion of the proposed research will be critically important to meet the overall scientific objective of this project.

To support the objectives of this portion of the research, we will develop the necessary instrumentation, acquire data, and coordinate data collection activities. The data—both "ground-truth" and aircraft data—will support efforts by both Dr. Fraser and ourselves to investigate, numerically model, and better understand how a polarized signal from the Earth's surface is affected by the disturbing atmosphere. The aircraft data will be acquired in collaboration with Bob Wrigley, NASA/Ames Research Center, who is the principal investigator of a project to model atmospheric effects in remote sensing data. Bob Wrigley's atmospheric project will involve measurement of solar irradiances at various altitudes using the NASA/Ames C-130 as a platform.

Synoptic polarized imagery from aircraft– A CCD push broom scanner of the High Altitude Missions Branch at Ames will be modified to develop the MODIS Instrument Polarization Simulator (MIPS), and used to simulate the instrument characteristics of the MODIS polarization sensor. MIPS will be flown in the NASA Ames ER-2 high altitude aircraft to obtain synoptic, polarized, relatively low cost imagery representing the following ground areas: the Oregon transect (Peterson et al., 1988); the Duke Forest, North Carolina; Bonanza Creek Experimental Forest, Alaska; the Biological Station of the University of Michigan; La Selva Forest, Costa Rica. These test sites were selected because they exhibit significant variability in biome, species, and biomass. Except for the Oregon transect, the areas are also test sites in an Interdisciplinary EOS Proposal with Norm Christensen, PI, and this applicant and several others as Co-Is. All test sites support significant on-going ecological research and the physiology and morphology of each is well documented. The Bonanza Creek Test Site is the location of an NSF-sponsored Long-Term Ecological Research (LTER) program. A proposal to establish a LTER program at La Selva is pending at NSF. Polarization data acquired with the sensor at an altitude of 65,000 feet in the ER-2 will include all significant atmosphere effects.

These synoptic, polarization images of the test areas will be analyzed together with ground and atmospheric data and with the algorithms developed in collaboration with Dr. Robert Fraser, GSFC, and Dr. Kin Coulson, prof. emeritus, UC Davis, for removing the effects of the disturbing atmosphere to (1) estimate the proportion of specular flux in the radiances of the ground areas, (2) estimate polarized vegetation indices for the ground areas, (3) assess the validity of the polarization and specular reflection model (Vanderbilt and Grant, 1985) and its invertibility for estimating canopy properties from polarization data, and (4) assess the validity of the Sellers model (1985, 1987) for estimating canopy properties from polarized vegetation indices.

Polarized space photographs– In collaboration with Vic Whitehead, NASA/Johnson Space Center, images of the polarization of the light scattered by the Earth photographed by astronauts on four flights of the space shuttle will be analyzed to investigate the potential information contained in such data—especially of vegetative canopies.

The importance of this portion of the proposed research is due to the synoptic view of polarization phenomena afforded by the approximately 400 shuttle images covering land and water surfaces from many areas of the Earth. As film products, the images are somewhat radiometrically imprecise. Yet their careful analysis potentially will provide direction and qualitatively identify those research areas deserving further attention.

After launch of MODIS– Map products at the regional to global scales will be produced for displaying the various polarized vegetative indices. Techniques and algorithms developed during the prelaunch period will be validated and modified as appropriate to obtain better estimates of photosynthetic capacity.

IV.D. Field Plans

Angular reflectance measurements– In collaboration with Susan Ustin, Dept. of Botany, U.C. Davis, we will acquire data of the visible, near-infrared, and middle-infrared light scattering properties of the several canopies, located at the test sites described above under Aerospace Plans, measured in a variety of view and illumination directions. A Barnes model no. 12-1000 will be modified to permit collection of polarization data from the three spectral regions, visible, near-IR, and middle-IR. In addition to the canopy measurements, the sky will be measured at the multiple view and illumination directions. All canopy characteristics necessary to support modeling activities (described above) will be determined during data collection periods. These physiological and morphological characteristics of the scene include leaf area index, canopy profiles, leaf angle distribution, and development stage. These data will support our efforts to validate and expand our model for the light specularly reflected by a plant canopy. The polarized bidirectional scattering data of the plant canopies will provide an estimate of the lower boundary condition needed for the atmospheric modeling research.

IV.E. Laboratory Plans

Laboratory leaf polarization measurement– As necessary for support of the field and aerospace plans, the Stokes matrix light scattering properties of individual healthy intact leaves will be investigated by employing an apparatus similar to those described by Breece and Holmes (1971) and Vanderbilt et. al., (1985a). The index of refraction of the epicuticular wax of specularly reflecting leaves of forest species from the test sites will be measured with an automatic ellipsometer located at Ames Research Center.

V. Data Plan

Modis polarization data will be handled taking advantage of the techniques and procedures developed by C. J. Tucker at GSFC to estimate NDVI spatially and temporally at the continental scale (Tucker et al., 1985). Data rates and volumes will be within the handling capabilities of the computer facilities at the Ames Research Center. The final digital map products will involve comparatively small amounts of data.

Data products to be produced and archived for access by the scientific community include computer coded maps displaying at the various spatial and temporal scales (1) the polarized vegetation indices, and (2) the atmospherically corrected polarized and specular radiances of the scene. For archiving purposes, digital map products will be formatted according to specifications to be determined during the definition phase of the project. The volume of data archived each year will approximate that of Tucker et al., (1985).

The deliverables will also include published papers describing both methods and the set of algorithms used (1) to correct for atmospheric effects, (2) to compute the specular portion of the vegetative scene radiance, and (3) to estimate the polarized vegetation indices SR and NDVI at the pixel, regional, and continental scales.

VI. Management Plan

Responsibilities

The research is to be carried out within the NASA Ames Research Center. In addition to the principal investigator, Vern C. Vanderbilt, the research team will include two postdoctoral fellows and two graduate students. Following the launch of MODIS, a full time data analyst. Vanderbilt will be responsible for overall project coordination, technical direction, and management of project monies. One post-doctoral fellow will be responsible for the research in the area of atmospheric corrections to polarization data and the second fellow, for the research in the area of polarized vegetation indices. The data analyst will be responsible for processing of the MODIS polarization data. Development of the atmospheric correction algorithms will be undertaken in collaboration with Dr. Bob Fraser, GSFC, at his option.

In addition to the administrative and investigative personnel named above, Ames Research Center will provide equipment, facilities, and data as necessary. This includes field radiometers, an automatic ellipsometer, a Cary 14 spectrophotometer, U-2/ER-2 and C-130 aircraft and related support facilities for these aircraft, a CCD linear array push broom polarization scanner and data acquisition system which is under development and is scheduled to be available in time for the definitional phase of this project, and facilities necessary for construction of special purpose optical, electrical, and mechanical apparatus required for the successful completion of the proposed research. The data set of polarized imagery acquired from the space shuttle and the necessary image analysis facilities are available to investigators at NASA/Johnson Space Center and will be collaboratively used in the course of this project.

Schedule of Activities

The proposed research encompasses two phases, a definition phase and an execution/operations phase, lasting a total of 10 years beginning in FY89. Table 1 lists the schedule of activities.

Table 1. Time schedule for definition and execution phases

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Definition Phase Tasks                                1989 /    1990
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                                                    JJASOND.JFMAMJJASOND
1. Review science requirements                      <->
2. Support instrument definition                    <------------------>
3. Prepare execution phase statement of work        <->
4. Update excution phase proposal                            <->
5. Modify and code canopy specular model            <--->
6. Select, modify and code atmospheric model             <-------->
7. Adapt MODIS Polarization simulator to ER-2       <------------------>
8. Analyze Polarization Space Shuttle photos        <-------->
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Execution Phase Tasks                          91 92 93 94 95 96 97 98 99
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1. Duke Forest exp./data analysis              <------> .  .  .  .  .  .  .
2. Bonanza Creek exp./data analysis             .  .<-----> .  .  .  .  .  .
3. Michigan Biological station exp./            .  .<-----> .  .  .  .  .  .
   data analysis
4. La Selva exp./data analysis                  .  .  .  . <-------> .  .  .  .
5. Development of atmosphere                   <-------------->.  .  .  .  .
   polarization correction algorithms
6. Development/validation algorithms to<---------------> .  .  .  .
   estimate specular from polarization
7. Development/modification of code to <-------------------->
   estimate polarized vegetation index
8. MODIS validation trials                      .  .  .  .  .  . <------------>
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Key Participants

Principal Investigator, Vern C. Vanderbilt, research scientist, has 22 years experience in remote sensing, including 15 years in optical measurement and modeling of plant canopies. He is a principle investigator (PI) in the remote sensing science program of the Land Processes Branch of NASA Headquarters and is conducting research measuring and modeling the optical reflectance of plant canopies to gain better understanding of the physiological and architectural information extractable from such data. He has collaborated with members of the International Forest Investigation Team (IFIT) for two years and is a collaborator in the Eos Synergism Study, both projects involving research funded by NASA.

Dr. Robert Fraser	NASA GSFC	atmospheric radiative transfer
Dr. Kin Coulson	prof. emeritus UC Davis	atmospheric radiative transfer
Dr. Susan Ustin	Dept. Botany UC Davis	botany, plant sciences, and ecosystems
Dr. Vic Whitehead	NASA JSC	engineering sciences
Robert Wrigley	NASA ARC	physics
post-doc (TBD)	NASA ARC	atmospheric radiative transfer
post-doc (TBD)	NASA ARC	botany, plant sciences
data analyst (TBD)	NASA ARC	computer science/ remote sensing

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The remote sensing community has clearly identified the utility of NDVI (normalized difference vegetation index) and SR (simple ratio) and other vegetation indices for estimating such metrics of landscape ecology as green foliar biomass, photosynthetic capacity, and net primary production. Both theoretical and empirical investigations have established cause and effect relationships between the photosynthetic process in plant canopies and these combinations of remotely sensed data. Yet it has also been established that the relationships exhibit considerable variability that appears to be ecosystem-dependent and may represent a source of ecologically important information.

The overall hypothesis of this proposal is that the ecosystem-dependent variability in the various vegetation indices is in part attributable to the effects of specular reflection. The polarization channels on MODIS provide the potential to estimate this specularly reflected light and allow the modification of the vegetation indices to better measure the photosynthetic process in plant canopies. In addition these polarization channels potentially provide additional ecologically important information about the plant canopy.

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