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MULTIANGLE DIRECTIONAL MEASUREMENTS IN SUPPORT OF THE MODIS-N LAND MISSION

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ABSTRACT

Systematic, multiangle measurements of VNIR radiance are essential for land studies for four reasons:

First, such measurements reveal the bidirectional reflectance distribution function (BRDF) of land surface covers, which in turn can be related directly to surface structural parameters such as size, shape, and density of plants, or the surface roughness of soils or ground cover;

Second, such measurements will provide surface albedos and surface radiant energy fluxes with much better accuracy than can be derived from radiances measured by nadir-pointed instruments;

Third, a global data set of land surface BRDFs and albedos derived from multiangle measurements enables MODIS-N data to be properly corrected for directional effects. This is essential to provide accurate global estimates of key land parameters such as NDVI, LAI, NPP, land surface temperature and land cover type; and

Fourth, because multiangle observations enable simultaneous retrieval of surface BRDFs and atmospheric optical parameters, such data will be integral to development and validation of atmospheric correction methodologies for MODIS-N, as well as for other instruments on the same platform.

Both MODIS-T and MISR are capable of making multiangle measurements that address these objectives. As instruments of very different designs, however, they have different strengths and weaknesses. MISR will provide frequent, consistent global coverage of multiangle measurements in four spectral bands; MODIS-T will provide less frequent coverage in more bands and at a finer angular resolution. MODIS-T should provide the more accurate BRDF estimates, while MISR will produce a more desirable albedo product. Either may be used for validation of the MODIS-N atmospheric correction algorithm.

INTRODUCTION

Most land surfaces are strongly anisotropic reflectors at optical wavelengths. This fact has three important implications. First, the nature of the anisotropy can reveal information about the physical structure of land surfaces. This arises ~~arises~~ because the anisotropy is primarily determined by the three-dimensional character of the surface. That is, the size, shape, and spacing of surface objects or projections, such as trees in a forest, crops in a field, or stones on a playa, produces a distinctive pattern of shadows that varies with viewing position and induces large changes in surface radiance throughout the viewing hemisphere. Since the shadow pattern is related to the size, shape, and spacing of the objects/projections, the bidirectional reflectance distribution function (BRDF) of the surface can reveal structural information about the surface that cannot be obtained in any other way. The practical implication is that multiangle directional measurements can provide critical information for (1) climate models and simulations that utilize surface roughness and surface energy exchange parameters; and (2) ecosystem studies that require knowledge of vegetation structure.

Second, because radiances observed from a surface vary strongly as a function of both the sensor view angle and the sun's position in the hemisphere, radiances from different parts of a scan for wide field-of-view imagers, such as MODIS-N, are not directly comparable without correction of angular viewing effects. This means that the BRDF of the surface must be known to some degree a priori or obtainable from contemporaneous multiangle directional measurements if the information content of MODIS-N data is to be fully exploited.

Third, multiangle directional measurements are required for accurate estimates of surface albedo -- a key parameter for understanding, modeling, and monitoring climatic change and its impact on human systems. If the BRDF of a land surface cover or the structural information that controls it is extracted from multiangle measurements, then the albedo may be derived directly from the nested integral of the incoming irradiance from all directions in the hemisphere as scattered in all outgoing directions, described by the BRDF. Even if the full BRDF is not known with certainty, a series of multiangle directional measurements can be correlated directly with albedo with high accuracy, whereas a single near-nadir measurement will prove highly inaccurate due to the anisotropy of surface radiance.

MULTIANGLE MEASUREMENTS FOR MODIS-N LAND PRODUCTS

In the view of the MODIS Land Group, the correction of MODIS products for atmospheric and geometric effects represents a very significant advance by comparison with the products of previous instruments, such as AVHRR. For example, AVHRR's Normalized Difference Vegetation Index (NDVI) is known to be influenced by atmospheric turbidity, both through differential attenuation and effects on the spectral distribution of diffuse irradiance; it is also sensitive to viewing geometry due to shadowing effects in which red and infrared shadows behave differently due to leaf scattering properties and differential diffuse illumination. Compositing procedures reduce these problems, but introduce difficulties by concealing important multitemporal variations due to isolated rainfall events, plant phenology, etc. Similar problems can be anticipated with other MODIS land products that are also derived in some way from radiances, such as soil color and soil brightness, leaf area index (LAI), land surface temperature, net primary productivity (NPP), vegetation stress, snow cover, land cover, and land-c
over change.

To alleviate these problems, the MODIS Land Group believes the best approach is to define or redefine these products in terms of data that are corrected for atmospheric effects and view geometry. The approach is to provide four basic products from MODIS land channels: land-leaving radiance (in the view direction); BRF (bidirectional reflectance factor); albedo; and BRDF. Land-leaving radiance is the radiance in the view direction that would be measured by a radiometer close to the surface; the BRF is the land-leaving radiance normalized by the radiance of a Lambertian panel illuminated and viewed under the same conditions as the surface; the albedo is the ratio of all outgoing radiation to all incoming radiation in the selected waveband; and the BRDF is described by 2-4 key physical surface characteristics that summarize and model the behavior of the entire BRDF.

As an example of product definition/redefinition, the NDVI will be defined in terms of red and infrared albedos, instead of red and infrared brightnesses or radiances, thus making it independent of view angle and atmosphere. Further, the LAI product will use the redefined NDVI and the surface roughness parameter derived as controlling the BRDF to provide LAIs that are independent of view angle and are adjusted for clumping. Other products use similar strategies.

The first two basic products, land-leaving radiance and BRF, require atmospheric correction; for these, the Atmosphere Group of the MODIS Team plans a robust method using dark targets within images and regional aerosol climatologies. For the latter two products, albedo and BRDF, a new algorithm for multiangle directional data has been devised (by Martonchik and Diner) that yields surface BRF's and atmospheric optical characteristics simultaneously. Further, the string of BRF measurements can be used to fit a BRDF model, thus providing both of these products, and atmospheric parameters as well. In addition, where multiangle data are collected simultaneously with MODIS-N data, the atmospheric parameters and BRF's are thus doubly derived and can be used for cross validation.

MULTIANGLE INSTRUMENTS

In the original selection of instruments for the EOS-A payload, two instruments were included that are capable of making multiangle directional measurements at spatial and temporal scales allowing their use with MODIS-N: MODIS-T and MISR._1/ MODIS-T is a tilting imaging spectrometer that can acquire as many as 59 multiple views of a target as it approaches the target, overflies it, and then moves away. MISR uses nine CCD array cameras to simultaneously image at four off-nadir angles forward and aft, and one at nadir.

_1/ Although ASTER will collect high-resolution VNIR data in both nadir and forward directions, the two looks are not sufficient for proper characterization of angular variation in radiance. Further, its fine spatial resolution precludes its use in a global mapping mode, which is a requirement for application to MODIS-N imaging.

Both design and operational characteristics influence the use of MODIS-T and MISR for land applications. Briefly comparing the two instruments, MODIS-T provides 32 spectral bands in the range 0.40-0.88 micrometers, while MISR provides only 4 in about the same range. Regarding coverage, MODIS-T's scan angle is 90 degrees, providing a swath width of 1500 km and a revisit cycle of 1-2 days; MISR's corresponding values are 28 degrees, 360 km and 2-9 days. Spatially, MODIS-T's resolution is 1.1 km at nadir, coarsening with tilt and scan. MISR's spatial resolution is switchable at either 240 m or 1.92 km, and by selection of appropriate focal lengths for each camera, it is independent of look angle, at least at the center of each swath.

Under new funding constraints faced by the EOS program, it seems likely that only one of these two instruments will fly concurrently with MODIS-N. Thus, it is appropriate to assess and compare the role of these of two instruments in in the preparation of land products as proposed and planned by the MODIS Team Land Group. Accordingly, we discuss below (1) the ability of each to determine BRDF's of land surfaces, both locally and globally; (2) the ability of each to produce global albedo at high temporal resolution; and (3) the utility of each in enhancing atmospheric correction procedures to be applied to MODIS-N data. Most of our discussion will center around the first issue, since it is the most complex.

BRDF Capability

For extraction of land BRDFs, MODIS-T has a distinct advantage over MISR. This arises because of MODIS-T's ability to collect data at or near the "hotspot" -- a peak in the BRDF at the location in the hemisphere at which illumination and viewing positions coincide. The hotspot is important because its shape (that is, the way in which radiance decreases with angle away from the hotspot position) contains information about the shapes and orientation of ground objects and surface facets. (Note that imaging the hotspot amounts to collecting angular data in the direction of the platform's shadow as the shadow moves along at the side of the ground track.) The ability to collected a dense sample of reflectance measurements around the hotspot has a direct impact on the potential ability to extract surface structural parameters and, to a slightly lesser extent, on the accuracy of retrieved estimates of albedo, depending on the angular anisotropy of the surface reflectance.

HOTSPOT OBSERVATIONS. For data collection near the hotspot, MODIS-T has two distinct advantages. First, MODIS-T can collect more observations near the hotspot because of its wide field of view. This is because at crossing times of 10:30 AM or 1:30 PM, the hotspot direction will lie far from the ground track for much of the orbit, and thus a capability to image well to the side is required. Since MISR acquires data only within 175 km of nadir, it cannot view the hotspot except near the solar equator._2/

_2/ This will be true for orbits with crossing times of 10:30 AM and 1:30 PM; however, if MISR flies on a noon crossing, it can sample the BRDF very near the principal plane over a large portion of the orbit.

NUMBER OF LOOKS. Second, MODIS-T can make many more multiangle observations of a given point on the ground than can MISR, which is fixed at nine. If MODIS-T is repointed between successive scans (which is within the cability of the mirror and scan cycle timing), as many as 59 angular observations can be made. However, a more modest number of measurements is likely to be sufficient, and in that case MODIS-T can make several scans between tilts, thus increasing the target area. The table below shows how pointing angles can be traded off for target areas.

Scans Between Tilts	Number Of Tilts	Area Covered, _3/ 10^3 km^2
1	59	46
2	29	92
4	15	184
6	11	276
8	7	368

_3/ Since the area scanned increases with look angle, we consider the area covered to consist only of the area of the nadir view associated with each tilt sequence.

Global BRDF Coverage

COVERAGE AREA. In assessing the capabilities of MODIS-T and MISR for global mapping of BRDF, several factors are important. The first of these is coverage area. Because MODIS-T tracks a target area by tilting, it cannot provide complete coverage along a single orbital path. That is, there is a gap between tilt targets where no coverage is obtained. Therefore, global coverage must be built up by successive tilting maneuvers on successive orbits, which requires time. In fact, in a scenario where a continent about the size of South America centered at 40 degrees latitude with a width of about 40 degrees longitude is covered by MODIS-T in the 7-angle mode (8 scans between tilts), 21 orbits out of 26 available within the 16-day orbital repeat are required for complete coverage, which takes 13 days.

In contrast to MODIS-T, MISR takes data continuously, and suffers no tilt gaps. Therefore, MISR will cover the same area in significantly less time, perhaps 7 days.

MEASUREMENT ANGLES. The second important factor is the angular position of the measurements with regard to the hotspot. As stated above, measurements near the hotspot will be most useful for accurate parameterization of the BRDF function. However, under the scenario for MODIS-T above, the seven looks at each target are distributed evenly across the possible range of view angles (that is, +/- 50 degrees at the platform). A better scenario will be to make fewer scans between tilts, for a higher angular resolution, while acquiring measurements only near the hotspot position. Thus, the two-scans-between-tilts mode provides an angular resolution of about 3 degrees; 7 such measurements will give a range of angles of about +/- 12 degrees around the hotspot. Although fewer scans between tilts are acquired, collecting only these measurements will leave the instrument free to focus again on a new target much sooner. We have not done the exact calculation for this scenario, but the two effects should roughly cancel, and thus the areal coverage rate would be about the same for either tilt strategy.

With regard to MISR, there is no flexibility about the choice of angles -- they are evenly spaced along the measurement transect through the hemisphere. A dense sample near the hotspot position is not possible with MISR.

EFFECTIVE SWATH WIDTH. Of course, the same logic for along-track measurements needs to be applied to the measurements collected across the swath. That is, those ground points far from the track of the shadow of the platform will not be viewed from positions near the hotspot, in spite of any refinements in the tilting strategy. If we assume that only measurements within +/- 5 degrees of the hotspot are acceptable, the effective swath width of MODIS-T is reduced from 1500 km to about 200 km. This width can still provide global coverage, but at a much slower rate. Considering cloud cover, this means that the BRDF of a point on the ground might be determined with accuracy by MODIS-T perhaps 3-4 times per year.

For MISR, this is a non-issue, since the swath is restricted to 350 km centered at nadir and will miss a +/- 5 degree window around the platform shadow track most of the time._4/ Only near the solar equator will the shadow of the platform move into MISR's nadir-pointed swath. Thus, if measurements must be collected near the hotspot, MISR simply cannot provide global coverage.

_4/ Note that if MISR could execute a roll maneuver, and look to the side toward the track of the platform's shadow, it would collect data very much nearer the principal plane.

GLOBAL BRDF ESTIMATION. Given that the objective of multiangle measurements is to obtain perhaps 2-4 physical parameters which describe the surface sufficiently to model the BRDF well, the critical question is how accurately they may be obtained with either instrument. For MODIS-T operated in the strategy described above, we clearly have an advantage because the hotspot behavior can be measured much more carefully. For MISR, the measurements are less likely to produce an accurate result because they do not have the desired geometry.

ATMOSPHERIC EFFECTS. Atmospheric effects will also be important in BRDF retrieval. According to an analysis made by Diner in developing MISR, the atmospheric "hotspot," generated by the backward scattering of aerosols, is sufficiently similar in magnitude and angular width as to confound the effects of surface BRDF's; accurate BRDF inference will then be sensitive to error in retrieval of such parameters as aerosol refractive index. However, with MODIS-T we have good angular measurements of the hotspot that include both effects, and further, there is full spectral coverage, which adds degrees of freedom for better fitting of aerosol scattering models.

MOSAICING. Another problem is posed by merging and mosaicing observations. For MODIS-T, the coverage will be built up from blocks acquired on different orbits and/or different days. If there are systematic inaccuracies in BRDF retrieval, or temporal changes in the BRDF of surface covers within a region, the mosaic pattern will be evident in the final product. MISR suffers from the same problem in merging BRDF's obtained from adjacent swaths, but to a lesser degree.

SPECTRAL CAPABILITIES. The MODIS-T and MISR instruments also differ significantly in their spectral capabilities. From the viewpoint of BRDF extraction, the hotspot effect is primarily one of shadowing, and thus is independent of wavelength. However, the shadowing applies only to singly-scattered photons, and not to multiply-scattered ones. The importance of multiple scattering will vary with wavelength due to differential scattering by the atmosphere and by surface materials. Considering only the BRDF, multiple scattering will be included, for example in the strong near-infrared scattering of leaf canopies.

The single-scattering spectral albedo of surface materials will also be important when it interacts with surface geometry, as in an open forest where the surface has green leaves at the top, dark brown trunks and stems in the middle, and tan soil on the ground surface. Because illumination and view geometry condition the relative flows of photons from these materials, there will be a spectral differentiation to the BRDF that may enhance the accuracy of surface-parameter BRDF retrieval with MODIS-T, which has continuous spectral coverage. However, MISR has the important bands that are most likely to show spectral differentiation, and thus in practice the difference may not be significant.

OPERATIONAL CONSTRAINTS. A disadvantage of MODIS-T for land BRDFs is that it will also be used for ocean observations. In ocean mode, the instrument will slowly tilt as needed to obtain high-spectral resolution, low-noise measurements free of sun glint. Since this mode of operation is not compatible with land BRDF measurements, operation in ocean mode near continental margins will increase the amount of time needed to build the global BRDF database. If MISR is not selected or does not prove able to make accurate BRDF retrievals, and MODIS-T flies with MODIS-N, the BRDF requirement will necessitate shared priority between land and ocean studies for coastal regions.

GLOBAL BRDF DATABASE. For MODIS-T, the inability to provide global BRDF coverage more than a few times a year implies that the global BRDF database will have to depend in part on ancillary information. For example, we may use the MODIS-N land cover data product in connection with digital terrain information to assume some "average" values, checking and updating these when the BRDF for the location can actually be accessed. For regions in which land cover changes are occurring that strongly influence the BRDF, we may be able to flag changes by use of the land-cover change product and reassess BRDF's more quickly by concentrated sampling.

For MISR, none of these are important issues, since the instrument can build a global database much more quickly. The real issue is accuracy -- can the surface parameters that control the BRDF be estimated accurately by measurements that are far from the hotspot? The problem is that we do not know the answer to that question at present, and so a conservative position must rely on MODIS-T.

Global Albedo

ALBEDO FROM MODIS-T. Global albedo from MODIS-T may be obtained in two ways. First, it may be derived from the BRDF with some assumptions about the angular distribution of incoming irradiance. Second, it may be estimated directly from a single measurement obtained at 90 degrees to the principal plane and 60 degrees from nadir. This special measurement angle has been shown to be very good predictor of hemispherical albedo (Kimes and Sellers, 1986). In the first case, the full BRDF must be derived, with good accuracy. Since this is a slow process with MODIS-T, it is not very desirable, although it is likely to be most accurate way of deriving albedo. In the second case, what is implied is an "albedo mode" of operation, in which the instrument is positioned so as to collect radiance data from a ground swath at the appropriate viewing position. In practice, the 60-degree zenith angle is not uniformly achievable, but if 45 degrees is used, a swath of about 350 km width can be obtained, thus providing nine-day coverage. Note that tilting MODIS-T for albedo measurement precludes its operation in a BRDF mode, thus inducing competition between the two applications, in addition to competition between land and ocean studies.

ALBEDO FROM MISR. On the other hand, MISR provides the same swath width, and eight additional observations, in the same time. Although none of the nine will be exactly at the Kimes-Sellers angle, the transect across the hemisphere of the full set of values should be more than sufficient to yield albedo with good accuracy. Further, spatial resolution is slightly better, since a tilted MODIS-T will produce an effective pixel size of about 2.5 km and MISR's global resolution mode is 1.9 km. The only disadvantage of MISR for global albedo is MISR's limited spectral resolution. However, MODIS-N can provide much additional spectral information, if it is needed.

Atmospheric Correction of MODIS-N Products

For the atmospheric correction necessary for land-leaving radiances and BRF's, the primary algorithms will depend only on MODIS-N data. However, since retrieval of atmospheric parameters will be more accurate from multiangle measurements, the values derived from MODIS-T or MISR can serve as validators for the MODIS-N algorithm. MISR will provide this capability continuously, but only for the central portion of the MODIS-N swath and at about half its spatial resolution. MODIS-T will provide the capability across nearly the full MODIS-N swath and at a very similar resolution, but only for limited regions due to the coverage gap between tilts. Of the two, MODIS-T may be the slightly better choice, since validation does not need to be continuous and it can validate the MODIS-N algorithm at strongly off-nadir angles.

Summary of Comparisons

BRDF. For local and regional BRDF work, it seems clear that MODIS-T will retrieve BRDF parameters more accurately, since it can acquire BRDF transects near the hotspot under a much broader range of orbital scenarios and with much finer angular resolution than can MISR. In a global mode, it can provide perhaps 3-4 BRDF interrogations of the surface per year, which should be sufficient for correction of MODIS-N data. Although MISR will provide much more frequent multiangular coverage, the fact that it will not sample the hotspot in most cases implies that it will not be able to retrieve the BRDF with good accuracy. The higher spectral resolution of MODIS-T is a possible advantage.

ALBEDO. For global albedo, MISR is the instrument of choice. Although it may not view the hotspot, it seems likely that the nine angular measurements that it will make will be sufficient to estimate the albedo with good accuracy. MODIS-T can also be used to make albedo measurements independently of BRDFs by collecting a single measurement at the Kimes-Sellers viewing position, but the albedo estimate derived from a single measurement may be expected to be less accurate, even though it is obtained from the best position.

ATMOSPHERIC CORRECTION. Here the requirement is to check atmospheric correction of MODIS-N data, and either instrument will suffice. MODIS-T will be able to validate the off-nadir angles better than MISR, since MISR sees only the center swath of MODIS-N. MODIS-T has the further advantage of multiple spectral bands, which should make it more directly applicable to the large number of MODIS-N channels in the VNIR. On the other hand, MISR will provide a regular, systematic evaluation with little effort, whereas MODIS-T availability would have to be traded off against use for land BRDF, albedo, and ocean color.

Instrument Selection -- Conclusions

MODIS-T. If MODIS-T is selected and MISR deselected, the primary impact will be to force BRDF, albedo, and atmospheric correction duties onto one instrument. In that event, all can be accomplished, but not with ideal frequency. Further, ocean operations will have to concede shared priority (50-50) for instrument operation over continental margins, where both land and ocean targets are present.

MISR. If MISR is selected and MODIS-T is deselected, then the primary impact will be to reduce the accuracy of BRDF estimation and subsequent correction of MODIS-N, perhaps to unacceptable levels. Albedo will be done very well (unless high spectral resolution is essential), and atmospheric correction of MODIS-N will be validated in the most useful range of the swath.

CONCLUSION

Multiangle directional radiance measurements contemporaneous with MODIS-N data acquisitions are required for the delivery of the MODIS

Land Group's planned products. With neither MODIS-T nor MISR, the accuracy and usability of MODIS-N land data products will be very severely compromised. Although the two instruments are quite different, the MODIS Land Group believes that at least one is required for delivery of their products, which have been identified by interdisciplinary teams as vital to their missions. For the MODIS Land mission, we believe that MODIS-T is the instrument of choice, primarily because it can parameterize the land surface BRDF more accurately.