MAUVE/SWIPE: An Imaging Instrument Concept with Multi-Angular, -Spectral, and -Polarized Capability for Remote Sensing of Aerosols, Ocean color, Clouds, and Vegetation from Space

Robert Frouin[a], Pierre-Yves Deschamps[b], Richard Rothschild[c],
Edward Stephan[c], Philippe Leblanc[c], Fred Duttweiler[c], Tony Ghaemi[d], Jérôme Riedi[b]
[a]Scripps Institution of Oceanography University of California San Diego,
9500 Gilman Drive, La Jolla, California 92093-0224
[b]Laboratoire d'Optique Atmosphérique, Université des Sciences et Technologies de Lille,
59655 Villeneuve d'Ascq, France
[c]Center for Astrophysics and Space Sciences, University of California San Diego,
9500 Gilman Drive, La Jolla, California 92093-0424
[d]Malin Space Science Systems, Inc., San Diego, California 92191-0148

ABSTRACT

The Monitoring Aerosols in the Ultraviolet Experiment (MAUVE) and the Short-Wave Infrared Polarimeter Experiment (SWIPE) instruments have been designed to collect, from a typical sun-synchronous polar orbit at 800 km altitude, global observations of the spectral, polarized, and directional radiance reflected by the earth-atmosphere system for a wide range of applications. Based on the heritage of the POLDER radiometer, the MAUVE/SWIPE instrument concept combines the merits of TOMS for observing in the ultra-violet, MISR for wide field-of-view range, MODIS, for multi-spectral aspects in the visible and near infrared, and the POLDER instrument for polarization. The instruments are camera systems with 2-dimensional detector arrays, allowing a 120-degree field-of-view with adequate ground resolution (i.e., 0.4 or 0.8 km at nadir) from satellite altitude. Multi-angle viewing is achieved by the along-track migration at spacecraft velocity of the 2-dimensional field-of-view. Between the cameras' optical assembly and detector array are two filter wheels, one carrying spectral filters, the other polarizing filters, allowing measurements of the first three Stokes parameters, I. Q, and V, of the incident radiation in 16 spectral bands optimally placed in the interval 350-2200 nm. The spectral range is 350-1050 nm for the MAUVE instrument and 1050-2200 nm for the SWIPE instrument. The radiometric requirements are defined to fully exploit the multi-angular, multi-spectral, and multi-polarized capability of the instruments. These include a wide dynamic range, a signal-to-noise ratio above 500 in all channels at maximum radiance level, i.e., when viewing a surface target of albedo equal to 1, and a noise-equivalent-differential reflectance better than 0.0005 at low signal level for a sun at zenith. To achieve daily global coverage, a pair of MAUVE and SWIPE instruments would be carried by each of two mini-satellites placed on interlaced orbits. The equator crossing time of the two satellites would be adjusted to allow simultaneous observations of the overlapping zone viewed from the two parallel orbits of the twin satellites. Using twin satellites instead of a single satellite would allow measurements in a more complete range of scattering angles. A MAUVE/SWIPE satellite mission would improve significantly the accuracy of ocean color observations from space, and will extend the retrieval of ocean optical properties to the ultra-violet, where they become very sensitive to detritus material and dissolved organic matter. It would also provide a complete description of the scattering and absorption properties of aerosol particles, as well as their size distribution and vertical distribution. Over land, the retrieved bidirectional reflectance function would allow a better classification of terrestrial vegetation and discrimination of surface types. The twin satellite concept, by providing stereoscopic capability, would offer the possibility to analyze the three-dimensional structure and radiative properties of cloud fields.

Key words: Remote sensing, satellite, polarization, aerosols, ocean color, vegetation, clouds, and radiation budget

Remote Sensing of the Marine Environment, edited by Robert J. Frouin, Vijay K. Agarwal,
Hiroshi Kawamura, Shailesh Nayak, Delu Pan, Proc. of SPIE Vol. 6406, 64060E, (2006)
0277-786X/06/$15 · doi: 10.1117/12.698061

1. MISSION OBJECTIVES

During the last decade or so, a new generation of satellite instruments has provided unique observations on aerosols, ocean color, vegetation, radiation budget, and clouds. They include the Total Ozone Mapping Spectrometer (TOMS), the MODerate resolution Imaging Spectroradiometer (MODIS), the Multi-angle Imaging SpectroRadiometer (MISR), and the POLarization and Directionality of the Earth's Reflectance (POLDER) instrument. The observations by these instruments have contributed to climate research on aerosol cycling, cloud-radiation interactions, ocean biogeochemistry, and continental biosphere dynamics. Each of the instruments has unique capabilities and performance, and one may envision combining these capabilities into an integrated sensor with improved measurement accuracy for a space mission with the following, multi-disciplinary science objectives.

<u>Aerosols</u>: To monitor aerosols globally (land and ocean), including their properties (absorption, scattering, vertical structure), sources, and transport, to quantify their influence on climate, and to assess their impact on our environment and human life.

<u>Ocean Color</u>: To observe accurately spectral marine reflectance in both open and coastal waters, determine inherent optical properties and water composition, and identify functional phytoplankton types for studies of global ocean dynamics, marine biosphere resources, and the role of biology in the global carbon cycle.

<u>Clouds</u>: To determine cloud amount and characteristics (optical properties, type, altitude, thermodynamic phase, 3-dimensional structure) for radiation budget studies and climate modeling.

<u>Land Surfaces</u>: To identify land cover and detect/monitor its change (anthropogenic, natural), and to determine surface properties and canopy parameters (bidirectional reflectance, albedo, leaf area index, ratio of leaf size and canopy height, etc.) for carbon cycle studies (sinks and sources of carbon dioxide) and climate modeling.

2. MEASUREMENT REQUIREMENTS

The scientific objectives require daily, global measurements with a ground resolution of 1 km or better in the ultraviolet, visible, near infrared, and short wave infrared, measurements at multi-angles, and measurements of the polarized state of the incident light.

<u>We must observe in the ultraviolet</u>

In addition to observing in the visible, near infrared, and short-wave spectral range, as it is currently done with instruments like MODIS, the radiometer must observe in the ultraviolet spectral range to allow detection of the aerosol absorption that prevails in that range, as experienced by TOMS. This is illustrated in Figure 1, which gives the spectral variation of the single scattering albedo for various aerosol models, from maritime M98 and troposheric T70 types with little absorption to background dust and desert dust storm types with high absorption. Absorption increases towards the ultraviolet for all models. The effect of absorbing aerosols in the ultraviolet is even more dramatic if we examine the top-of-atmosphere reflectance. In Figure 2, the spectral variation of the top-of-atmosphere reflectance of a cloudless atmosphere is displayed for the same models as in Figure 1. In the computations, The aerosol optical thickness is 0.5 at 865 nm, the altitude of the aerosol layer is 5 km, the ground reflectance is null, the solar zenith angle is 36 degrees, and the view zenith angle is 70 degrees in the backward scattering plane. Variable scattering is noticed in the near infrared that vanishes in the ultraviolet, i.e., the difference between the computations for an atmosphere with scattering, M98 or T70, and a molecular atmosphere becomes small in the ultraviolet compared to the near infrared. But the two situations with dust, thus with large aerosol absorption, show a substantial negative deviation of the top-of-atmosphere reflectance in the ultraviolet, compared to the molecular case.

The decrease, ΔR, in top-of-atmosphere reflectance results from attenuation of the molecular scattering below the absorbing aerosol layer (Torres et al., 2000), and it may be written as:

$$\Delta R = R_m - R_{TOA} \approx (1-\omega_a)t_a(P_s - P_a)R_m \quad (1)$$

where R_m is the reflectance due to molecular scattering, R_{TOA} is the top-of-atmosphere reflectance, ω_a is the aerosol single scattering albedo, τ_a is the aerosol optical thickness, P_s is the surface pressure, and P_a is the pressure level of the aerosol layer.

Observing R_{TOA} in the ultraviolet is the only way to get direct information on aerosol absorption, because of the explicit and large influence of aerosol absorption on the measurements. Obviously, the inversion problem is not easy since aerosol scattering and surface reflectance also affect the measurements, as well as the paramount altitude of the aerosol layer. Furthermore, knowledge of τ_a is require to deduce ω_a from the absorption optical thickness $(1 - \omega_a)\,\tau_a$.

<u>We must observe in the visible, near infrared, and short-wave infrared</u>

Knowledge of not only aerosol absorption in the ultraviolet, at 350 and 380nm, but also aerosol scattering properties, is required for the applications envisioned. Over the ocean, this is usually achieved using spectral bands in the red and near infrared, centered at 670, 745 or 770, 865, and 1020 nm. Spectral bands in the middle infrared, e.g., centered at 1240, 1600 and 2130 nm, are useful since sensitive to the relative importance of the aerosol fine and coarse size modes, whatever the absorption. Over the land, DDV (Dense Dark Vegetation) algorithms use shorter wavelengths, i.e., bands centered at 412, 443, and 670 nm (Kaufman et al., 1997b; Kaufman and Tanré, 1998), but they require measurements in the short-wave infrared to estimate surface reflectance.

Surface reflectance must be derived to correct its effect on the retrieval of aerosol absorption in the ultraviolet, especially over the ocean where reflectivity can be high. Spectral bands centered at at 490, 510, and 555 nm, currently used by ocean color sensors, allow one to retrieve a model of ocean optical properties that can be extrapolated to the ultraviolet.

Spectral information in the ultra-violet, visible, and near infrared is needed to derive ocean optical properties, determine water composition, and identify functional phytoplankton types. Also, spectral signatures of various vegetation types show marked discrimination in red, near infrared, and middle infrared.

Last, the average altitude of the aerosol layer, or better the vertical profile of aerosol concentration, should be retrieved. This can be accomplished with lidar systems, which are adapted to the problem, and a companion lidar experiment on the same spacecraft is possible. However, differential absorption using dual spectral bands located inside and outside the O_2 absorption band around 763 nm offers a cheaper, yet reasonable alternative. It gives an average altitude of the aerosol layer, which is needed to derive the absorption optical thickness (see Equation 1).

All the spectral bands, except the one located inside the O_2 absorption band should be 10 to 20 nm wide, to allow good signal-to-noise ratio, to avoid gaseous absorption bands and take into account Fraunhofer lines, and to capture features of interest in the atmosphere and ocean. The spectral band located in the O_2 absorption band should be sufficiently narrow to achieve adequate sensitivity to aerosol altitude, i.e., 3 to 5 nm wide.

A total of about 16 spectral bands from 350 to 2200 nm should allow accurate retrieval of the optical properties of aerosols and the surface.

<u>We must observe polarization</u>

Polarization measurements contain a wealth of information on aerosol scattering properties (Herman et al., 1971) and, therefore, constitute a powerful tool for remote sensing of aerosols, over both ocean and land. The polarized scattering matrix depends largely on the refractive index of the particles, giving more clues on the aerosol type. Over the ocean, they complement multi-spectral measurements in differentiating aerosol models (Deuzé et al., 1999). Over the land, they allow aerosol retrievals over non-DDV surfaces that are weakly polarized (Deuzé et al., 1993).

Accurate retrieval of aerosol scattering properties from polarization measurements requires some flexibility on the viewing geometry to achieve a desired set of characteristic scattering angles. The same target must be viewed under multiple angles. The polarization measurements are most helpful in the red and near infrared, where molecular scattering is relatively ineffective (Herman et al., 1997). Measurements in the short wave infrared would allow a better determination of the surface contribution to the polarized reflectance. In the ultraviolet the polarization signature originates mostly from molecular scattering. Nevertheless, polarization data remain useful in this spectral range to discriminate aerosol models.

The polarization of cloud-reflected radiance in specific directions (in the rainbow region, 140° scattering angle) is very sensitive to cloud thermodynamic phase, either ice or liquid water (Goloub et al., 1994). The polarized phase function of cloud droplets, hence the polarized radiance, exhibits fluctuations with scattering angle, in the range 150-170°. As the size distribution broadens, however, the fluctuations decrease in amplitude (Bréon and Goloub, 1998).

Polarization measurements of the first three Stokes parameters, i.e., I, Q, and V, require three observations of the same target through polarizers with axes rotated by 60 degrees and must be performed in a subset of spectral bands in the ultraviolet to the near infrared.

<u>We must observe at multiple angles</u>

Multi-angular observations are essential to exploit polarization information effectively. Like polarized observations, however, they are sensitive to the scattering phase function. They allow, even without polarization information, a better determination of the aerosol model by fitting the multi-angular measurements in the visible and near infrared. Furthermore, preliminary computations of the top-of atmosphere reflectance, such as those displayed in Figure 2, have shown that the effect of aerosol absorption in the ultraviolet can be greatly enhanced compared to the effect of aerosol scattering at specific angles, namely at backward large viewing angles (i.e., above 60 degrees).

Over the oceans, multi-angular observations can be used to improve atmospheric correction in the presence of absorbing aerosols. In this approach, after a standard correction for aerosol scattering is performed, the estimated water reflectance in all viewing directions is linearly regressed versus an absorption predictor, i.e., a function representing the directional effect of an absorbing aerosol, essentially the molecular reflectance. Extrapolation to zero absorption gives the water reflectance. An illustrative example is presented in Figure 3, and results obtained with POLDER data acquired over the Mediterranean Sea during a dust event are displayed in Figure 4. The retrieved water reflectance imagery is more realistic with aerosol absorption correction.

Using multi-angular observations of differential absorption in the O_2 band may also give more clues on the vertical profile of aerosol concentration. When the viewing angle increases, so do the air mass, and the associated vertical profile of the atmospheric weighting function for aerosol scattering changes, and will have a maximum at a higher altitude. Retrieving some parameters of the vertical profile is a classic inverse problem. Combining spectral differential absorption and multi-angular observations is a new and exciting field that has not been explored yet for practical application to atmospheric sounding.

The bidirectional signature of the reflectance of land surfaces may be used to classify land cover types, to design new vegetation indices that minimize various effects (atmosphere, soil reflectance), and to derive information about the surface and/or canopy structure Leroy et al. (1996). Multi-angular measurements are also needed to estimate land albedo. (Albedo, not the bi-directional reflectance, is the key parameter in radiation budget studies.) Since the solar radiation field reflected by the earth system is not isotropic, bidirectional measurements are also needed to compute the reflected flux at the top of the atmosphere.

The requirement is to observe the surface backward and forward at incidence up to 70 degrees from zenith.

<u>Daily global coverage</u>

Daily global coverage from a sun-synchronous polar orbiting satellite at the altitude of 800 km requires a cross-track field-of-view of about ± 60 degrees in order to avoid gaps between orbits at the Equator on a daily product.

When combined, multi-angular and global coverage requires measurements in all directions within a field-of-view of ±60 degrees.

Geometry

Current satellite sensors like SeaWiFS, MODIS, and MERIS, have demonstrated the benefit of observing the Earth's surface with a ground resolution of 1 km or better at nadir, in order to cloud-screen the imagery effectively. Heterogeneity of the land surface and cloud fields, and spatial variability in the coastal zone, however, require a ground resolution much better than 1 km. This translates into a pixel field-of-view of better than one milliradian, and this should be the specification for a space experiment. However, this specification must be viewed like a goal, and it might be relaxed to ease the technical feasibility if it conflicts with other requirements.

Geometric registration of multi-spectral, -angular, and -polarized imagery is a function of the instrument performance, and also of the attitude control of the instrument-vector system. It must be performed accurately, commensurate to the pixel field-of-view.

The pixel field-of-view must be one milliradian or better. Multi-angular geometric registration must be achieved to within a fraction of one milliradian in all bands, spectral and polarized.

Radiometry

To fully exploit the polarization, multi-angular, and multi-spectral capabilities of the instrument for aerosol properties, the radiometric requirements are as follows.

The instrument should not saturate when viewing a surface of albedo equal to 1, and the response should be linear in the entire dynamic range. The signal-to-noise ratio must be better than 500 in all the channels at maximum radiance level, i.e., corresponding to a surface albedo of 1. At low signal level, the noise expressed in terms of reflectance, i. e., radiance multiplied by π and normalized by the extraterrestrial solar irradiance, must be better than 0.0005. The instrument must be able to measure the polarization rate of the input light with an accuracy of 0.5% in all channels and in all the field of view.

The absolute radiometric calibration in all channels and in all the field-of-view must be accurate to better than 2%. The requirements are stricter for relative multi-angular calibration, i.e., accuracy better than 0.5%. This may involve an onboard calibrator for a space experiment and/or vicarious radiometric calibration using in-situ measurements. Polarization must be calibrated to better than a few percent.

The signal-to-noise ratio must be better than 500 for a target of albedo equal to 1 and the noise equivalent differential reflectance better than 0.0005. Absolute radiometric calibration must be known to better than 2 %, and relative calibration between viewing angles to better than 0.5%. Polarization must be measured to better than 0.5 % and calibrated to a few percent.

In summary, we are looking for instrumentation that combines the merits of TOMS in the ultraviolet, MISR in terms of field-of-view range, SeaWiFS and MODIS for multi-spectral aspects, and POLDER for polarization aspects. A comprehensive instrument concept that builds upon the heritage of all these instruments would constitute a breakthrough in our ability to observe Earth's atmosphere and surface (land, ocean).

3. INSTRUMENT CONCEPT, SPECIFICATIONS, AND PRELINIMARY BUDGETS

Concept/Principle

In the instrument concept envisioned, the measurements of light intensity will be accomplished by two complementary camera systems, MAUVE (350-1050 nm) and SWIPE (1050-2200 nm). These camera systems, depicted in Figure 6, are based on the POLDER concept (Deschamps et al., 1994), but they have significant improvements. They allow a 120-degree field-of-view with adequate resolution (1 km) from satellite altitude. Unlike the POLDER radiometer, which uses a single camera and wide field-of-view optics, MAUVE and SWIPE have four identical cameras with a field-of-view of ±30 degrees and the optical axis oriented at 30 degrees from nadir, forward and backward with respect to the satellite motion. Multi-angle viewing is achieved by the along-track migration at spacecraft velocity of the two-dimensional field-of-view. Two filter wheels are installed between optical assembly and detector array, one carrying spectral filters, the other polarizing filters (plus open and closed positions), allowing measurements of the first three Stokes parameters I, Q, and V of the incident radiation in selected spectral bands. The filter wheels do not rotate steadily, but step-by-step to allow greater flexibility in observing modes. The filter wheels do not rotate steadily, but step-by-step for greater flexibility in observing modes. The spectral bands are centered at 350, 380, 412, 443, 490, 510, 555, 620, 670, 763, 750, 865, 1020, 1240, 1600, and 2130 nm. Band pass is 10-20 nm, except at 763 and 750 nm (3-5 nm). The polarization measurements (i.e., analysis in 3 orientations of polarization) are made in the spectral bands centered at 350, 412, 670, 865, 1040, and 1600 nm.

Compared with the POLDER radiometer, the field-of-view is larger, the ground resolution better, and the spectral range extended to the ultraviolet (aerosol absorption) and short wave infrared (aerosol size). Radiometric quality is improved thanks to the 4-camera system that reduces stray light and polarization of the optics at large viewing angles. The registration of the multi-spectral and polarized imagery will be achieved in the ground segment, by re-sampling all the data in a same geometric Earth projection. The geo-located pixels will contain spectral, polarized, and directional information.

Optical elements

A conceptual optical design is displayed in Figure 6 for the MAUVE cameras (similar for the SWIPE cameras). The design is telecentric, with focus adjustment onto the 2-dimensional detector array using a spectral filter/polarizer combination. It assumes that the corners of the detector array are illuminated, and that the ±30-degree field-of view mapped onto a 1024x1024x18μm detector array. The specifics are:

a. MAUVE Optics. Effective focal length: 24.5mm; F#: 4.0; Field-of-view: ±31.0Deg; IFOV: 1 milliradian, Format: ±12.75mm (illuminated corners of 1kx1kx18μm CCD); Spectral bands: 350, 380, 412, 443, 490, 510, 555, 620, 670, 750, 865, and 1040 ±5nm, 763±1.5nm; Overall length (from front surface of element 1 to focal plane): 150.0mm, ~33.2mm diameter; Transmission 0.8 except at 350 nm (0.65); Mass Estimate (glass only, to clear aperture): 40g; Image performance: near diffraction-limited, MTF > 0.8; Back Focal Length: 28.0mm; Front element substrate is SiO2 for radiation control; Tele-centric image plane.

b. SWIPE Optics. Effective focal length: 24.5mm; F#: 4.0; Field-of-view: ±31.1Deg; IFOV: 1 milliradian, Format: ±12.75mm (illuminated corners of 1kx1kx18μm CCD); Spectral band: 1600±20 nm; Overall length (from front surface of element 1 to focal plane): 150.0mm, ~33.5mm diameter; Transmission: 0.85; Mass Estimate (glass only, to clear aperture): 69g; Image performance: near diffraction-limited, MTF >0.6; Back Focal Length: 26.0mm; Front element substrate is rad-hardK5G20 for radiation control; Tele-centric image plane.

Detector Arrays

The focal plane detector arrays are the TCM8020A/Si-PIN and TCM8020A/HgCdTe products from Rockwell Scientific Inc. They are composed of an optical detector combined with a read out integrated circuit that allows the electronic access of every pixel in the array. The TCM8020A/Si-PIN, sensitive in the spectral range 350-1,050 nm, and the TCM8020A/HgCdTe, sensitive in the spectral range 900-2,500 nm, will be used for MAUVE and SWIPE, respectively. Total pixels are1024x1024, and pixel pitch is 18 μm, but a 2048x2048 version exists, that would allow a ground resolution of 400 m instead of 800 m at nadir. The charge storage capacity is adjustable from one picture to the next, with 0.7, 1.5, and 3M electrons (standard product), but the various gains can be optimized for the MAUVE and SWIPE measurement configurations. Quantum efficiency is above 70%, except at 1,040 nm (30%). An electronic shutter is activated in readout mode. Read noise is 500, 1000, and 2000 electrons at 5MHz, respectively. Dark current is negligible.

A typical observation will consist of 29 and 9 sequences for MAUVE and SWIPE, respectively, where the spectral filter and/or the polarizer wheels move to the desired positions with the electronic shutter closed. An image will then be collected with the shutter open, and after 20 to 40 ms, the shutter is closed and the image is read. The cycle then repeats for the next image acquisition. The desired spatial resolution on the ground dictates the integration time and how often the cycle occurs, and places requirements on the detector readout and the filter wheel motion. Presently, we have, as a baseline, 5 images per second, i.e., it will take 5.8s and 1.8 s to acquire, for a given gain, a full set of MAUVE and SWIPE data, respectively. Two gains will be used, one for high-reflectance signals (cloudy atmosphere, glint), and one for low-reflectance signals (ocean, clear atmosphere).

Using 20ms for integration time, 0.8 for the transmission of the optics, 0.6 for the transmission of the spectral filters, and the actual quantum efficiency of the detectors, and assuming that we are at the center of the field-of-view, typical noise figures are as follows. For a target of albedo equal to 1 and the Sun at zenith, the signal-to-noise ratio is 730 at 490 nm and 1090 at 865 nm, using a charge storage capacity of 3 million electrons. For a target of albedo equal to 0.1, the noise-equivalent-differential reflectance is 0.00037 at 490 nm and 0.00025 at 865 nm, using a charge capacity of 0.7 million electrons. These figures, based on the specifications of the "off-the-shelf" detector arrays, can be much improved by designing the detector arrays with adapted gains.

Radiometric calibration

The basic plan is a deployable diffuser like the SPECTRALON diffuser onboard MERIS. This solution applied to the MAUVE and SWIPE instruments demand further study mainly because of the large field-of-view of the instruments. Thanks to the large field-of-view, vicarious calibration using the Moon is also a good candidate to monitor the calibration drift with time.

Cooling System

Passive cooling of the detector arrays should be adequate. Operating temperatures for the detectors would be approximately -10C. If spacecraft or mission dynamics cannot support this approach, simple Peltier cooling of the detector arrays could be implemented.

Data Rate

Without implementing a compression scheme, the 1 Mpixels converted to 12 bits resolution requires 12 Mbits per readout. If readouts are done each 200 ms, or 5 per second, this produces 5x12 Mb/s, or 60 Mb/s for each detector. Therefore, we would have a 240 Mb/sec for MAUVE and 240 Mb/sec for SWIPE. However, it would be sufficient, for the scientific requirements of the mission, to transmit at a rate of about 1 image per second, i.e., 48 Mb/s, or even less if necessary.

Power

The 8 detectors and detector electronics require 5W(1 detector + electronics) x 8 = 20W/0.8 (efficiency) = 50W. The Central Electronic Units (two are planned for redundancy) require 8W x 2 = 16W/0.8 (efficiency) = 20W. Motor power is estimated at 5 watts per motor, 4 motors = 20W.

Twin satellite concept

The instruments will be installed on two mini satellites (i.e., one MAUVE/SWIPE instrument pair per satellite) operating from sun-synchronous interlaced polar orbits to ease daily coverage. The equatorial crossing time of the two satellites will be adjusted to allow simultaneous observations of the overlapping zone from the two parallel orbits. The advantage, in addition to improved coverage, is enhanced bi-directional sampling, facilitating inversion of the top-of-atmosphere measurements, and stereoscopic viewing. The use of two mini satellites will also allow for a more complete range of scattering angles when using observations from the two adjacent objects. Figure 7 illustrates the interest of this concept applied to POLDER data: using one single orbit one has access only to scattering angles ranging around 180 degrees or 120 degrees; using two adjacent orbits a complete coverage of backscattering angles is obtained. Applicability of the adjacent orbits is restricted to high latitudes using the single POLDER radiometer. The dual-satellite concept proposed for the MAUVE/SWIPE instruments will allow observation from adjacent orbits at all latitudes.

Budgets

A schematic view of the MAUVE/SWIPE assembly is given in Figure 8. Preliminary budget figures are as follows. The total mass of the MAUVE and SWIPE instruments is 35 kg. Dimensions are 0.6mx0.5mx0.25m. Total power is 100W (including 10% for active thermal control, no Peltier cooling). Data rate is 96 Mb/s. The payload can be easily accommodated on a mini-satellite LEO platform such as PROTEUS (main budgets are compatible). The objective would be to use as many as possible off-the-shelf sub-systems from the platform family, in order to match a low-cost development.

The plan is for 5-year missions (with two mini satellites per mission). Cost is $50M for two sets of instruments, $50M for two mini-satellites, $40M for dual launch, $30M for ground segment, control, level 1 processing, operational level 2 processing, and scientific level 2 processing over the 5-year duration of the missions, i.e., a total cost of $170M. There is no direct dependence on other satellite missions. The proposed mission will achieve experimental aspects that are not covered by future operational satellite programs like NPOESS and GMES.

4. SIGNIFICANCE

The prospective scientific benefits of MAUVE/SWIPE instrument are in varied application areas:

Aerosols: The MAUVE/SWIPE instrument concept would constitute a breakthrough for global aerosol knowledge, by allowing monitoring of the complete optical aerosol properties from space on a global daily basis. The measurements would also allow the exploration and application of new techniques for remote sensing of aerosol properties, such as using multi-angular measurements in the ultraviolet for absorption and multi-angle differential absorption in the 763 nm O_2 absorption band for vertical distribution. The new information about aerosols would provide a better understanding of their effect on the Earth's radiation budget and global climate.

Ocean color: The MAUVE/SWIPE instrument concept would improve significantly the accuracy of ocean color observations from space, and of the derived products, i.e., chlorophyll-a concentration and, beyond, parameters that are crucial to determine the carbon pumping of the ocean (POC and chlorophyll ratio, phytoplankton speciation). The accuracy of retrievals at shorter wavelengths is currently limited in the presence of absorbing aerosols. This affects severely our ability to study western boundary upwelling systems, since they occur in the lee of many continental aerosol sources, from biomass burning to dust storms. The MAUVE/SWIPE instrument concept would allow accurate atmospheric correction in the presence of such aerosols. More generally, the retrieval of ocean optical properties would be extended to the ultraviolet, where they become very sensitive to detritus material and dissolved organic matter.

Land surface: The improved aerosol correction and bi-directional reflectance information provided by the MAUVE/SWIPE instrument concept would enhance the accuracy of the land surface classification and allow a better monitoring of land cover for global change studies.

Clouds: Beyond the classical problem of retrieving the optical properties of plane-parallel clouds, the MAUVE /SWIPE instrument concept would offer the possibility, using stereoscopy (twin satellite concept), to analyze the 3-dimensional structure and radiative properties of complex cloud fields.

ACKNOWLEDGMENTS

This work was supported by grants from the National Aeronautics and Space Administration, the National Science Foundation, and the Scripps Institution of Oceanography.

REFERENCES

Bréon, F.-M., and P. Goloub, Cloud droplet effective radius from spaceborne polarization measurements', *Geophys. Res. Lett.*, 25, 1998.

Deschamps et al, 1994 Deschamps, P. Y., F. M. Bréon, M. Leroy, A. Podaire, A. Bricaud, J. C. Buriez and G. Sèze, 'The POLDER mission: Instrument characteristics and scientific objectives', *IEEE Trans. Geosci. Rem. Sen., 32*, 598-615, 1994.

Deuzé, J.-L., M. Herman, P. Goloub, D. Tanré, and A. Marchand, 'Characterization of aerosols over ocean from POLDER/ADEOS-1', *Geophys. Res. Lett.,* 26, 1421-1424, 1999.

Goloub P., J.-L. Deuzé, M. Herman, Y. Fouquart, and P.-Y. Deschamps, Analysis of the POLDER Airborne Instrument Observations over Cloud Covers*, IEEE Trans. Geosc. Rem. Sens., 32*, 78-88, 1994.

Herman, B. M., S. R. Browning, and R. J. Curran, 'The effect of atmospheric aerosols on scattered light', *J. Atmos. Sci*., 419-428, 1971.

Herman, M., J.-L. Deuzé, P. Goloub, F.-M. Bréon, and D. Tanré, 'Remote sensing of aerosols over land surfaces including polarization measurements and application to POLDER measurements', *J. Geophys. Res.,* 102, 17039-17049, 1997.

Kahn, R. A., R. West, D. McDonald, B. Rheingans, and M. I. Mishchenko, 'Sensitivity of multiangle remote sensing observations to aerosol sphericity', *J. Geophys. Res*., 102, 16861-16870, 1997.

Kaufman, Y. F., D. Tanré, H. R. Gordon, T. Nakajima, J. Lenoble, R. Frouin, H. Grassl, B. M. Herman, M. D. King, and P. M. Teillet, 'Passive remote sensing of tropospheric aerosol and atmospheric correction of the aerosol effect', *J. Geophys. Res., 102*, 16815-16830, 1997a.

Kaufman, Y. J., D. Tanré, L. A. Remer, E. F. Vermote, A. Chu, and B. N. Holben, 'Operational remote sensing of tropospheric aerosol over land from EOS moderate resolution imaging spectroradiometer', *J. Geophys. Res.*, 102, 17051-17067, 1997b.

Kaufman, Y., and D. Tanré, 'Algorithm for remote sensing of troposheric aerosol from MODIS', ATBD MOD04, http://modis.gsfc.nasa.gov/ data/atbd/atbdmod04.pdf, 1998.

King, M. D., W. Paul Menzel, Y. J. Kaufman, D. Tanré, B.-C. Gao, S. Platnik, S. A. Ackerman, L. A. Remer, R. Pincus, and P. A. Hubanks, 'Cloud and aerosol properties, precipitable water, and profiles of temperature and water vapor from MODIS', *IEEE Trans. Geosci. Rem. Sen*., 41, 442-457, 2003.

Leroy, M., J.-L. Deuzé, F.-M. Bréon, O. Hautecoeur, M. Herman, J.-C. Buriez, D. Tanré, S. Bouffiès, P. Chazette, and J.-L. Roujean, 'Retrieval of atmospheric properties and surface bidirectional reflectances over land from POLDER/ADEOS', *J. Geophys. Res.*, 101, 1996.

Tanré, D., M. Herman, and Y. F. Kaufman, 'Information on aerosol size distribution contained in solar reflected spectral radiances', *J. Geophys. Res*., 101, 19043-19060, 1996.

Torres, O., P. K. Bhartia, J. R. Herman, A. Sinyuk, P. Ginoux, and B. Holben, A long term record of aerosol optical depth from TOMS observations and comparison to AERONET measurements. *J. Atmos. Sci*., 59, 398-413, 2002.

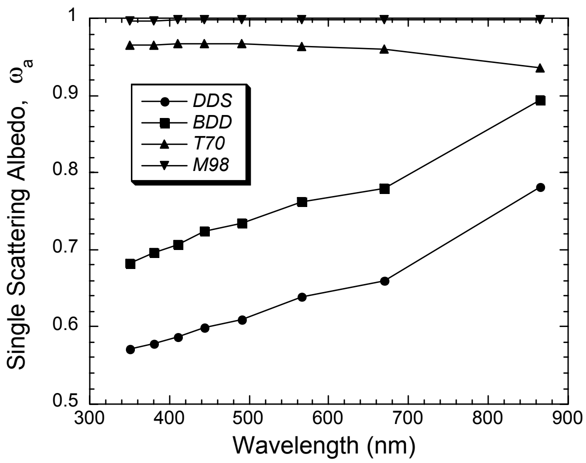

Figure 1. Spectral variation of the aerosol single scattering albedo for various aerosol models, i.e., maritime M98 and tropospheric T70 with little absorption, and background dust and desert dust storm types with large absorption.

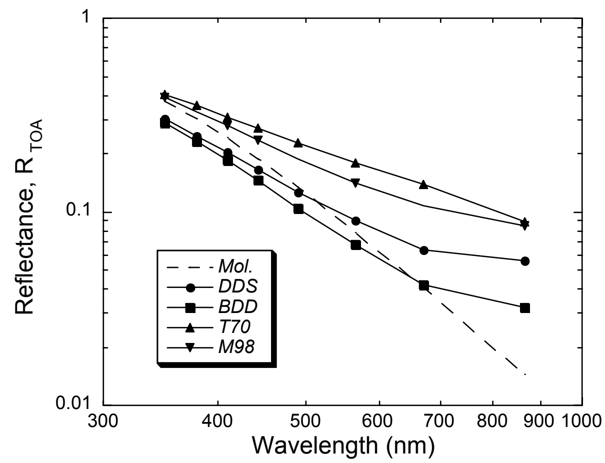

Figure 2. Spectral variation of the top-of-atmosphere reflectance for the same aerosol models as in Figure 1. The optical thickness is 0.5 at 865 nm, the altitude of the aerosol layer is 5 km, the ground reflectance is null, the solar zenith angle is 36 degrees, and the view zenith angle is 70 degrees in the backward scattering plane.

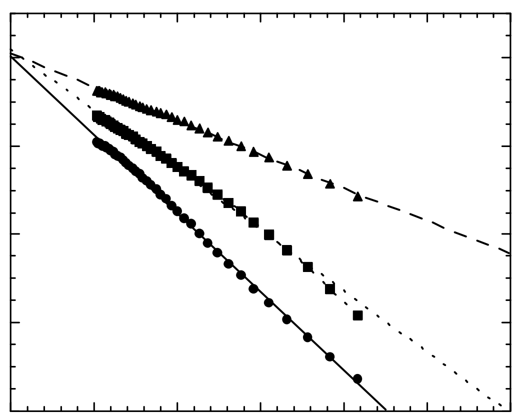

Figure 3. Estimated marine reflectance at 443 nm versus absorption predictor. The aerosol layer, $\tau = 0.2$ at 865 nm, is located at 3.76 nm. Sun zenith angle is 36 degrees and view zenith angle varies from 0 to 75 degrees, backward, in the principal plane. The marine reflectance is 0.02, and it is retrieved as the intercept of the linear regression between estimated marine reflectance and absorption predictor. Error is less than 0.002 for the three absorbing aerosol models (U80, BDD, and DDS) considered.

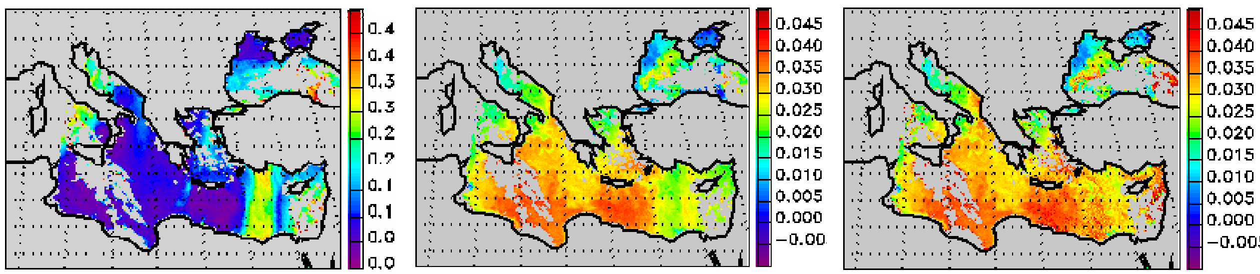

Figure 4. Application of the multi-angle atmospheric correction algorithm to POLDER imagery acquired over the Mediterranean Sea during a dust outbreak from Africa. Left: Aerosol optical thickness at 865 nm; Middle: Marine reflectance at 443 nm obtained without aerosol absorption correction; Right: Marine reflectance at 443 nm obtained with aerosol absorption correction.

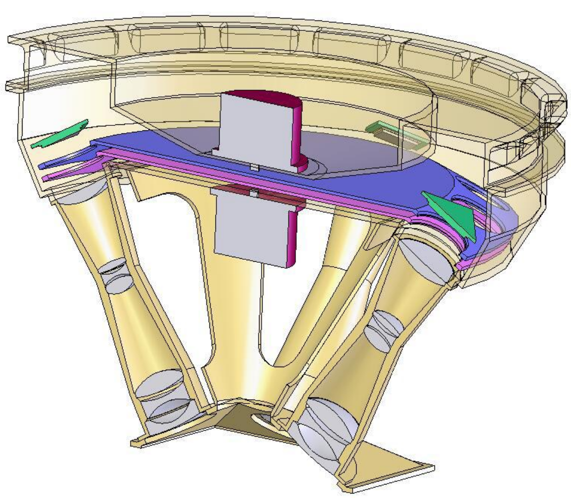

Figure 5. MAUVE (SWIPE) camera system.

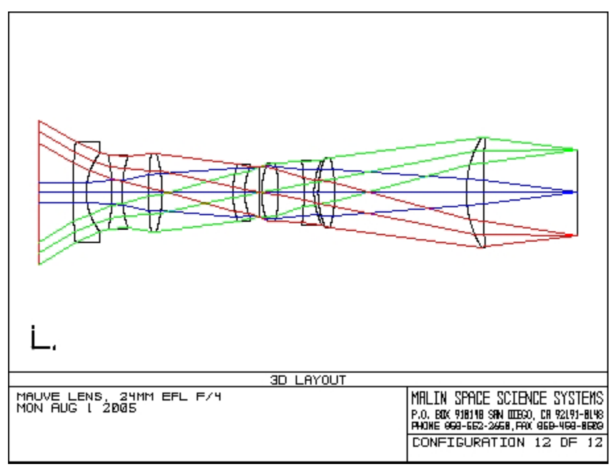

Figure 6. MAUVE optical design.

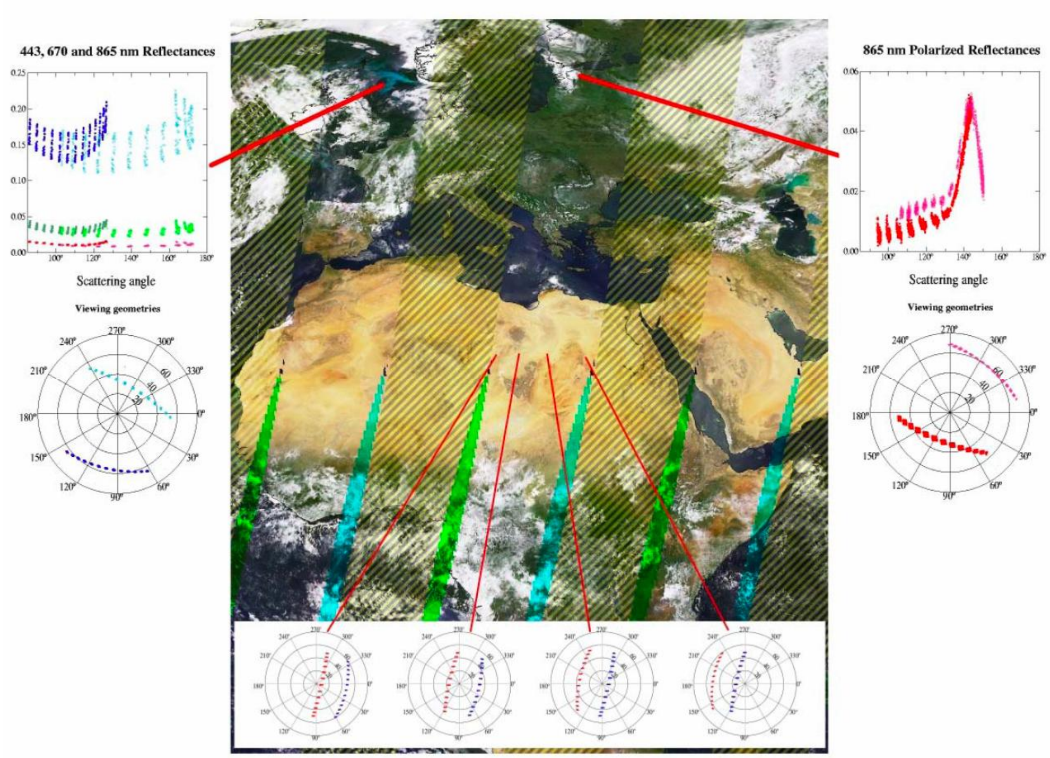

Figure 7. Twin view concept from adjacent orbits using POLDER data. Center: daily coverage for two satellites with the POLDER field of view. Shaded areas are viewed simultaneously by the two satellites and will allow for stereoscopic views if the Equator Crossing Time (TU) is the same. Bottom: BRDF viewing geometry of the twin satellites respectively in red and blue. Left: BRDF TOA radiances at TOA over a phytoplankton bloom, at 443, 670, and 865 nm. Right: BRDF TOA polarized radiance over a cloud.

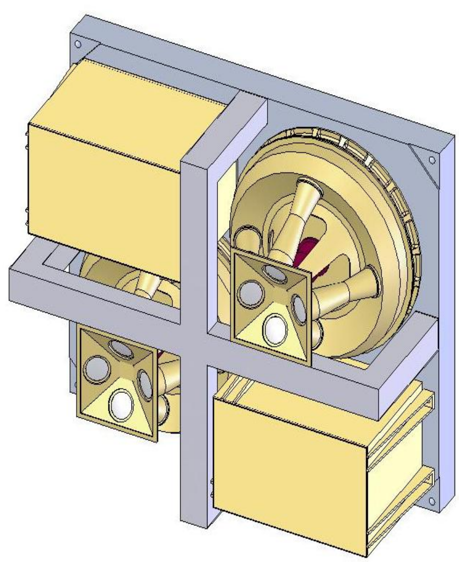

Figure 8. MAUVE/SWIPE assembly.