# Enabling Technologies For High-accuracy Multiangle Spectropolarimetric Imaging From Space

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**Satellite remote sensing plays a major role in measuring the optical and radiative properties, environmental impact, and spatial and temporal distribution of tropospheric aerosols. In this paper, we envision a new generation of spaceborne imager that integrates the unique strengths of multispectral, multiangle, and polarimetric approaches, thereby achieving better accuracies in aerosol optical depth and particle properties than can be achieved using any one method by itself. Design goals include spectral coverage from the near-UV to the shortwave infrared; global coverage within a few days; intensity and polarimetric imaging simultaneously at multiple view angles; kilometer to sub-kilometer spatial resolution; and measurement of the degree of linear polarization for a subset of the spectral complement with an uncertainty of 0.5% or less. The latter requirement is technically the most challenging. In particular, an approach for dealing with inter-detector gain variations is essential to avoid false polarization signals. We propose using rapid modulation of the input polarization state to overcome this problem, using a high-speed variable retarder in the camera design. Technologies for rapid retardance modulation include mechanically rotating retarders, liquid crystals, and photoelastic modulators (PEMs). We conclude that the latter are the most suitable. Two approaches for using a PEM to achieve high polarimetric accuracy are presented. In the first approach, *amplitude modulation*, the device is used intermittently to modify the incoming polarization state so that different detectors--those with polarizing filters in different orientations--can be accurately cross-calibrated. In the other approach, *synchronous demodulation*, signals accumulated during sub-cycles of the modulation are sorted and stored using a high-speed electronic charge-caching circuit built into the detector array.**

## Acronym glossary

AATSR ........ Advanced Along-Track Scanning Radiometer
APS ........ Aerosol Polarimeter Sensor
ATSR-2 ........ Second Along-Track Scanning Radiometer
BRDF ........ Bidirectional Reflectance Distribution Function
CCD ........ Charge-Coupled Device
CMOS ........ Complementary Metal-Oxide Semiconductor
CTIA ........ Capacitive Trans-impedance Amplifier

DOLP ............................................... Degree of Linear Polarization
FLC ............................................... Ferroelectric Liquid Crystal
FOV ............................................... Field of View
LCVR ............................................... Liquid Crystal Variable Retarder
MISR ............................................... Multi-angle Imaging SpectroRadiometer
MODIS ............................................... Moderate resolution Imaging Spectroradiometer
NA ............................................... Not Applicable
OMI ............................................... Ozone Monitoring Instrument
PEM ............................................... Photoelastic Modulator
POLDER ............................................... Polarization and Directionality of Earth's Reflectances
RPM ............................................... Revolutions per Minute
SWIR ............................................... Shortwave Infrared
TOMS ............................................... Total Ozone Mapping Spectrometer

## I. Introduction

Satellite mapping and imaging of aerosols provide global perspectives on spatial distributions and long-range transport. Spaceborne sensor data are also used in sophisticated retrievals of aerosol column abundances and microphysical properties. Parameters such as optical depth, single scattering albedo, chemical composition, size distribution, particle shape, and aerosol height are needed to evaluate the performance of three-dimensional chemical and aerosol transport models, which are essential for understanding the underlying causes of climate change and environmental impacts. However, since the aerosol parameters jointly govern top-of-atmosphere radiances, retrievals from space are highly underdetermined. Furthermore, separating effects due to aerosols from other environmental factors, and distinguishing anthropogenic from natural aerosols, require high measurement accuracy and stability. Compounding this complexity are the effects of the underlying surface and clouds.

Multispectral intensity techniques, e.g., from MODIS, provide sensitivity to particle size along with column optical depth using spectral bands ranging from the visible to the shortwave infrared[1,2]. Near-ultraviolet mapping from TOMS[3] (and with the recent launch of the Aura satellite, OMI[4]) offers a unique approach in that most surfaces are dark at these wavelengths, and the interaction between aerosol and Rayleigh scattering provides sensitivity to aerosol absorption. Unlike MODIS, however, which has spatial resolution in the nadir of 1 km or better, the footprint size of TOMS/OMI is tens of km. Multiangle intensity data provide constraints on particle size and sphericity along with optical depth by virtue of sampling the particle scattering phase function[5,6]. Over many aerosol source regions, e.g., desert and urban areas, where the ground reflectance is high, multiangle intensity imaging, e.g., from ATSR-2, AATSR, and MISR takes advantage of differences in the spatial and angular reflectance signatures of the surface and atmosphere to retrieve aerosol properties over these and other surface types[7-11]. With sufficiently high spatial resolution, multiangle stereoscopic perspectives enable the geometric retrieval of cloud-top and plume-top heights[12-14].

Polarimetry can provide data exceeding the capabilities of intensity measurements alone by providing sensitivity to size-resolved refractive index (hence constraining composition) and improving accuracy in optical depth and single-scattering albedo. The power of multiangle polarimetric data, acquired at visible and shortwave infrared wavelengths, has been demonstrated through sensitivity studies[15], airborne measurements[16-18], and with the spaceborne POLDER[19] instrument. The POLDER design provides global coverage at a spatial resolution of about 6-7 km, with polarimetric uncertainty of ~2%[20]. The satellite Aerosol Polarimeter Sensor (APS) will improve upon POLDER's polarimetric accuracy and spectral coverage (linear polarization uncertainty is estimated at 0.2% and measurements will extend to the SWIR), but with coarser resolution (6-20 km, depending on view angle). Furthermore, APS spatial coverage is non-imaging, limited to a single along-track scan one pixel wide.

Because each of the aforementioned measurement techniques has a unique set of strengths, fusing their capabilities into an integrated sensor is a powerful way of reducing indeterminacy and improving measurement accuracy. We have explored the feasibility of designing such a sensor. Table 1 illustrates how we have taken the attributes of multiple sensors and incorporate the salient features into an integrated aerosol instrument concept. We selected 380, 412, 446, 558, 672, 866, 1375, 1630, and 2130 as the nominal wavelengths bands for the integrated sensor. The spectral bands selected for polarization measurements are 672 and 1630 nm. The rationale for this choice is to achieve refractive index sensitivity for both accumulation and coarse mode aerosols.

**Table 1: Aerosol sensor characteristics**

| | Spatial resolution | Along-track angle range | Spectral range | Polarization accuracy | Global coverage |
|---|---|---|---|---|---|
| MISR | 275 m - 1.1 km | 70° fore - 70° aft | 446 - 866 nm | NA | 9 days |
| MODIS | 250 m - 1 km | NA | 469 - 2130 nm | NA | 2 days |
| ATSR-2/AATSR | 1 - 2 km | 0°, 55° fore | 550 - 1610 nm | NA | 5 days |
| POLDER | 6 - 7 km | 60° fore - 60° aft | 443 - 910 nm | ~2% | 2 days |
| APS | 6 - 20 km | 60° fore - 60° aft | 412 - 2250 nm | 0.2% | No |
| TOMS/OMI | 20 - 40 km | NA | 270 - 500 nm | NA | 1 day |
| Design goals | 250 m - 2 km | 70° fore - 70° aft | 380 - 2130 nm | 0.5% | 3 - 4 days |

## II. Polarimetric imaging approaches

Of the measurement requirements listed as design goals, the most challenging is achieving 0.5% uncertainty in degree of linear polarization (DOLP), particularly for an imager. This requirement results from the recommendations of climate workshops[21,22], which seek accuracies of ~0.01 in optical depth and ~0.03 in single scattering albedo, i.e., about a factor of 2-3 better than the current state-of-the art. We have performed simulations indicating that accuracy of 0.5% in DOLP is needed to reach this goal. DOLP uncertainty of 2% is not sufficient to improve sensitivity relative to what can be achieved with multiangle intensity radiometry, though there is a gain in sensitivity to refractive index.

There are several methods for multiplexing the incoming light in order to capture the Stokes components of a polarized beam. Spatially multiplexed (snapshot) or spectrally multiplexed (spectrum channeling) imagers use optical elements--gratings, prisms, or birefringent crystals--to encode the polarization state within a spatially or spectrally varying signal recorded on an area array detector[24-27]. These approaches are elegant, but have several drawbacks, the most fundamental of which is that their polarization uncertainties are 10-20%.

Division-of-amplitude polarimeters optically divide the incoming light using beamsplitters and direct the resulting beams toward multiple analyzers and detectors. However, optical aberrations and scattered light can be introduced by the beamsplitters, and misalignments of the beams cause intensity gradients at the target that couple into polarization errors. These polarimeters generally perform most poorly in measurements of the polarization of point sources, and obtaining accuracy at the 3% level in stringent tests is difficult. Another technique, division of aperture, employs detectors operating side-by-side. The MISR instrument, for example, acquires multispectral observations using a division-of-aperture approach: Adjacent line arrays are overlain by filters passing different wavelengths[23]. The analog of this approach for polarimetry is to overlay different line arrays with analyzers in different orientations. In a pushbroom system the different line arrays pass over the same point within a short time interval. MISR experience shows that the data can be digitally superimposed after the fact to better than 1/10 of a pixel, but cross-calibration uncertainty of 1-2% is possible only after extensive effort. Thus, because the method uses separate line arrays to reconstruct the Stokes vector, some special means of achieving highly accurate cross-calibration will be required to reach a verifiable and reliable measurement uncertainty of 0.5%.

Another polarimetric approach is time-multiplexing, where measurements corresponding to various components of the Stokes vector are acquired sequentially. Between each measurement, the orientation of a polarization analyzer or retarder is varied, or the retardance of a variable retarder is changed. The benefit of this approach is that each measurement is acquired by the same detector, so relative gain differences between detectors is not an issue. However, if the modulation is done too slowly, then for a changing scene (as is the case for a moving space platform) the detector does not view the same target as the different measurements are acquired, and intensity fluctuations couple into spurious polarization. A solution is high-frequency temporal modulation, in which the polarization measurement state is varied at a much higher frequency than the frame rate. If the detection system is phase locked to the high-frequency fluctuations of the modulator, than the time-averaged signal encodes intensity and the time-varying signal encodes the polarimetric components. In this approach, the measurements to reconstruct the Stokes vector are temporally interlaced. For a pushbroom system, this results in interlacing at a spatial frequency which is high compared to an individual pixel's footprint. For all practical purposes this results in a spatial superposition of the measurements.

We conclude the most accurate polarimetric imaging approach is either (a) a division-of-amplitude method, provided that some means of accurately cross-calibrating adjacent detectors with analyzers in different orientations is included, or (b) high frequency temporal modulation. Either of these can be achieved by using a rapidly-varying retardance modulator in the optical train. In the first approach, which we call *amplitude modulation*, the modulator is used on an intermittent basis (i.e., during calibration sequences) to "scramble" the polarimetric state of the incoming beam, making it possible to cross-calibrate different detectors and compensate for gain differences between them. In the second approach, *synchronous demodulation*, the sub-frame rate modulation of the polarization state of the incoming beam is temporally resolved using a charge-caching detector that sorts and stores sub-line time information.

## III. Retardance modulation: theoretical background

The polarimetric state of light incident on an optical system can be represented by the Stokes vector $\vec{I} = (I, Q, U, V)$, where the component $I$ is the total intensity; $Q$ represents the excess of light at 0° orientation to a specified plane relative to the intensity at 90°; $U$ is the excess of intensity at 45° relative to 135°; and $V$ is the excess of right-handed circular polarization to left-handed circular polarization. DOLP is given by:

$$\text{DOLP} = \frac{\sqrt{(Q^2 + U^2)}}{I} = \sqrt{\left(\frac{Q}{I}\right)^2 + \left(\frac{U}{I}\right)^2} \qquad (1)$$

The amount of circular polarization is expected to be on the order of 0.1% of the total intensity, and is ignored in the subsequent discussion. Even though this is small, the requirement to measure linear polarization to 0.5% means that the optical system needs to be designed such that cross-talk of $V$ into $Q$ or $U$ is avoided. In addition, circular polarization introduced by the instrument needs to be minimized, since this causes a loss of efficiency in measuring $Q$ and $U$.

Polarization retarders, or waveplates, are manufactured from birefringent materials in which there is a different refractive index along two orthogonal axes. If the retarder is chosen to be a half-waveplate ($\delta = \pi$) and the focal plane contains one line array overlain by an analyzer at 0° and another line array with an analyzer at 45°, then the measurements on the two detectors are:

$$I_0 = \frac{1}{2}[I + \cos 4\theta Q + \sin 4\theta U] \qquad I_{45} = \frac{1}{2}[I + \sin 4\theta Q - \cos 4\theta U] \qquad (2)$$

which means it is possible to modulate the portions of the signals depending on $Q$ and $U$ by rotating the retarder. An alternative approach is to keep the element stationary but to modulate the retardance. This can be done mechanically (e.g., with compensators) or electro-optically. In this case, the relevant equations are

$$I_0 = \frac{1}{2}[I + \cos\delta Q + \sin\delta U] \qquad I_{45} = \frac{1}{2}[I - \sin\delta Q + \cos\delta U] \qquad (3)$$

where $\delta = \delta(t)$, i.e., the retardance is a function of time.

## IV. Retardance modulation technologies

### A. Mechanically rotating retarder

For a rotating half-wave plate, described by Eq. (2), a complete measurement of the linear polarization state can be accomplished with 90° of rotation. The line repeat time from low-Earth orbit to achieve a line spacing of 250 m is about 40 ms. Therefore, during this time, the retarder must rotate through integer multiples of 90° of rotation. Achieving a high degree of spatial interlacing indicates that it is desirable to complete at least two full rotations during the line repeat time, giving a total of 8 separate measurements of the polarization state. This corresponds to a rotation rate of 3000 RPM, which raises several technical issues. An actuator rotating at this speed will introduce some vibrations into the system. Fabrication tolerances and bearing wear will cause some wobble of the reflected light as well as optical wave-front phase shifts. To achieve a multi-year lifetime in space, lubrication of the bearings will be necessary;

however, lubricants in the vicinity of optical components introduce outgassing problems. Although technical solutions exist, space qualifying this system would be problematic, since the typical requirement is to test it to twice its anticipated life. With a lifetime requirement of 5 years at 100% duty cycle, a life test would last 10 years. A late failure in the qualification test would become a serious problem.

Magnetic levitation (Maglev) bearings have the potential to overcome these limitations. Maglev bearings have non-contacting interfaces, so there is no friction and theoretically, no wear occurs. Lubrication is not needed and the operational life of Maglev bearings is longer than with regular bearings. However, Maglev bearings are bulky and not available in the small sizes needed for our application. Development of Maglev designs with decreased size, mass and power consumption would make them feasible for this and many other space applications.

An alternative solution to the lifetime requirement is to utilize the rotating retarding in flight on an intermittent basis only. In this approach, the polarimetric measurement is routinely acquired using three line arrays, one with a polarization analyzer at 0°, one at 45°, and one with no analyzer. During science-data gathering, the retarder does not rotate. Occasionally, cross-calibration is accomplished by rotating the retarders. At high rotation speeds, the sinusoidal terms in Eq. (2) average to zero, enabling intensity to be retrieved individually from each of the line arrays. The detector gain coefficients can then be adjusted to equalize these intensities. In this scenario, the requirements on the motor are significantly relaxed, and the total number of rotations is drastically reduced.

### B. Electro-optic modulators

Avoidance of moving parts and issues such as vibration, bearing wear, and beam wander are circumvented by using an electro-optic device. Here, the relevant theory is given by Eq. (3). Variable retarders can be constructed from liquid crystals, fluids whose molecules are elongated. For so-called nematic devices, switching times are tens of ms[29,30], i.e., too slow. On the other hand, ferroelectric liquid crystals (FLCs) have a permanent polarization and respond much more quickly to externally applied fields; tuning speeds are advertised to be 30 μs-250 μs[31]. FLCs can be used to make bistable electro-optic devices when placed between closely-spaced, electrically conducting glass plates. However, the main drawback for our application is that liquid crystal chromophores transmit only over limited spectral range, e.g., 400 - 700 nm.

Fortunately, another solution exists. Uniform materials such as glass become birefringent when compressed along one axis. This is commonly referred to as stress-induced birefringence, or the photoelastic effect. By making use of mechanically resonant oscillation, it is possible to construct a variable retarder with a power requirement of only about 1 W. By coupling a piezoelectric transducer to a glass or fused silica bar, a standing sound wave that oscillates at the bar's fundamental frequency is induced. This causes a modulation of the birefringence at a frequency, ω, equal to $c_s/(2L)$, where $c_s$ is the speed of sound in the glass and $L$ is the length of the bar. For bars several cm long the frequency is ~50 kHz. The stress-induced retardance δ for these photoelastic modulators (PEMs) is given by

$$\delta(t) = \delta_0 \sin\omega t \quad (4)$$

where $\delta_0$ is the amplitude of the oscillation. The amplitude $\delta_0$ can be regulated with an electronic feedback circuit.

Because the material out which PEMs are constructed is glass or fused silica, transmittance over a wide spectral range is possible. The principal drawback of PEMs is that they are mechanically delicate. In order to produce a standing sound wave, the oscillating parts can only be held (softly) at a few points. The joint between the piezoelectric transducer and the glass is also weak. During launch, it may be necessary to clamp the PEM and then remove that clamp in orbit. Nonetheless, this technology seems to be the most promising electro-optic solution to providing a high temporal frequency retardance modulation over a broad spectral range. Polarimetric sensitivities (i.e., precision) of about 3 parts in $10^6$ have been demonstrated[32]. Its solid-state construction, high optical quality, and broad spectral transmittance make it more attractive as a variable retarder than liquid crystals.

## V. Achieving high-accuracy imaging polarimetry

To understand the implications of using a PEM, we use the Bessel function expansions of the cosine and sine of a sinusoid[33] and combine Eqs. (3) and (4) to obtain:

$$I_0 = \frac{1}{2}[I + J_0(\delta_0)Q] + \left[\sum_{k=1}^{\infty} J_{2k}(\delta_0)\cos 2k\omega t\right]Q + \left[\sum_{k=0}^{\infty} J_{2k+1}(\delta_0)\sin([2k+1]\omega t)\right]U$$

$$I_{45} = \frac{1}{2}[I + J_0(\delta_0)U] + \left[\sum_{k=1}^{\infty} J_{2k}(\delta_0)\cos 2k\omega t\right]U - \left[\sum_{k=0}^{\infty} J_{2k+1}(\delta_0)\sin([2k+1]\omega t)\right]Q \quad (5)$$

Therefore, $I_0$ is a modulated intensity whose time-average is proportional to $I + J_0(\delta_0)Q$, and its time-varying component is proportional to $Q$ modulated at a frequency of $2\omega$ (and higher even harmonics) and $U$ modulated at $\omega$ (and higher odd harmonics). The measurement $I_{45}$ is analogous, with $Q$ and $U$ reversed (and a sign change). We identify two distinct methods of using these signals to accomplish our polarization measurement objective.

**A. Amplitude modulation**

In this approach the high frequency retardance modulation provided by the PEM is used as a means to temporally average out various Stokes vectors components. Referring to Eq. (5), we see that after an integration time of tens of ms (a long time compared to the period of one cycle of the PEM), the time-averaged signals are given by

$$\overline{I_0} = \frac{1}{2}[I + J_0(\delta_0)Q] \qquad \overline{I_{45}} = \frac{1}{2}[I + J_0(\delta_0)U] \quad (6)$$

By varying the voltage applied to the PEM it is possible to vary the modulation amplitude $\delta_0$ and therefore the value of the coefficient $J_0(\delta_0)$. The amplitude modulation would have to be slow enough such that the PEM controller can stabilize. Laboratory experimentation shows this adjustment time to be on the order of 400 ms. Since this is much longer than the frame rate, the camera must be viewing a uniform target, which can be a calibration panel or a homogeneous Earth scene such as an ice sheet. By choosing $\delta_0$ such that $J_0(\delta_0) = 0$, $I$ can be independently derived from each array. The gains would then be set to provide the same intensity value as a non-polarimetric measurement, thus achieving the desired detector cross-calibration. This is the same approach described for the intermittently-activated rotating retarder, and is accomplished without moving parts.

**B. Synchronous demodulation**

For a PEM oscillating at 50 kHz, there are 2000 cycles in the 40-ms frame rate. Each cycle therefore lasts 20 μs. Solar astronomers[32,34-36] developed a clever approach in which modulation of the retardance takes place at high frequency using a PEM, and the resulting signal is demodulated by rapidly shifting charges within a CCD between optically unmasked and masked detector lines at a frequency phase-locked to the PEM resonant frequency. Equation (5) shows that for either the 0° or 45° line array, one complete cycle of the PEM can be divided into two sub-intervals in which the measurements are linear sums of $I$, $Q$, and $U$ with different coefficients multiplying $Q$ and $U$. Therefore, by accumulating these individual signals during an integration time, the signals can then be read out at the slower frame rate and processed to reconstruct the Stokes vector. Retrieval of $Q$ and $U$ requires combining the signals from both the 0° and 45° line arrays. However, since each line array provides relative measurements, this approach is immune to detector gain variations. For our application, where polarimetry up to 1630 nm is required, a CMOS multiplexer, in which charges are alternately shuttled to different caches[37], is required to demodulate the signals. This approach would make it possible to broaden the spectral range since different photoactive materials (e.g., Si in the visible/near-IR and InGaAs in the SWIR) can be integrated with a CMOS multiplexer. Such devices currently do not exist, but we have done preliminary design work suggesting that construction is feasible. The circuit performing the charge summing will need to be low noise to achieve the desired polarization sensitivity. This places severe constraints on the pixel readout circuits. Our calculations show that the circuit must not introduce equivalent noise >10-20 electrons per cycle, implying a fast switching capacitive trans-impedance amplifier (CTIA) technology.

## VI. Conclusions

Two approaches making use of a fast retardance modulator to achieve high-accuracy imaging polarimetry have been outlined. Relative to amplitude modulation, synchronous demodulation provides a continuous, rapidly interlaced signal that can better insulate against false polarization from rapid spatial or temporal variation in the observed scene. In addition, synchronous demodulation has greater potential scientific return; for example, it could be used for other rapid frame-differencing applications such as differential gas correlation spectrometric imaging. However, it is significantly more complicated. Making an informed trade-off between complexity and accuracy requires exploring both solutions. Laboratory studies are necessary to determine whether either will yield the desired DOLP accuracy. We are currently pursuing funding to build laboratory breadboards.

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