HIGH-ACCURACY MULTIANGLE SPECTROPOLARIMETRIC IMAGING CONCEPT FOR AEROSOL REMOTE SENSING FROM SPACE

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Science background

A multiangle spectropolarimetric imager would provide many key aerosol measurements

Aerosol direct radiative forcing	Separation of anthropogenic component	Air quality	Indirect radiative effects

- Associating aerosol properties with radiation requires disentangling variables whose effects are intertwined
  - optical depth, single scattering albedo, and phase function
  - constraints on vertical distribution
  - subpixel clouds and cirrus

- Separating aerosol forcing into natural and anthropogenic forcing and assessing air quality requires identification of aerosol chemistry
  - particle size, shape, refractive index
  - location of sources

- Quantifying indirect forcing requires simultaneous cloud measurements
  - cloud fraction and albedo
  - isolation of cloud-aerosol interactions from meterological covariability

Fusion of measurements

A multiangle spectropolarimetric imager combines the salient attributes of multiple aerosol sensors into a single instrument

	Spatial resolution	Along-track angle range	Spectral range	Polarization accuracy	Global coverage
MISR	275 m - 1.1 km	70º fore - 70º aft	446 - 866 nm	NA	9 days
MODIS	250 m - 1 km	NA	469 - 2130 nm	NA	2 days
AATSR	1 - 2 km	2 angles: 0º, 55º fore	550 - 1610 nm	NA	5 days
POLDER	6 - 7 km	50º fore - 50º aft	443 - 910 nm	~2%	2 days
APS	10 - 35 km	60º fore - 60º aft	412 - 2250 nm	0.2%	No
TOMS	40 km	NA	330 - 380 nm	NA	1 day
Concept	250 m - 2 km	70º fore - 70º aft	380 - 2130 nm	0.5%	3 - 4 days

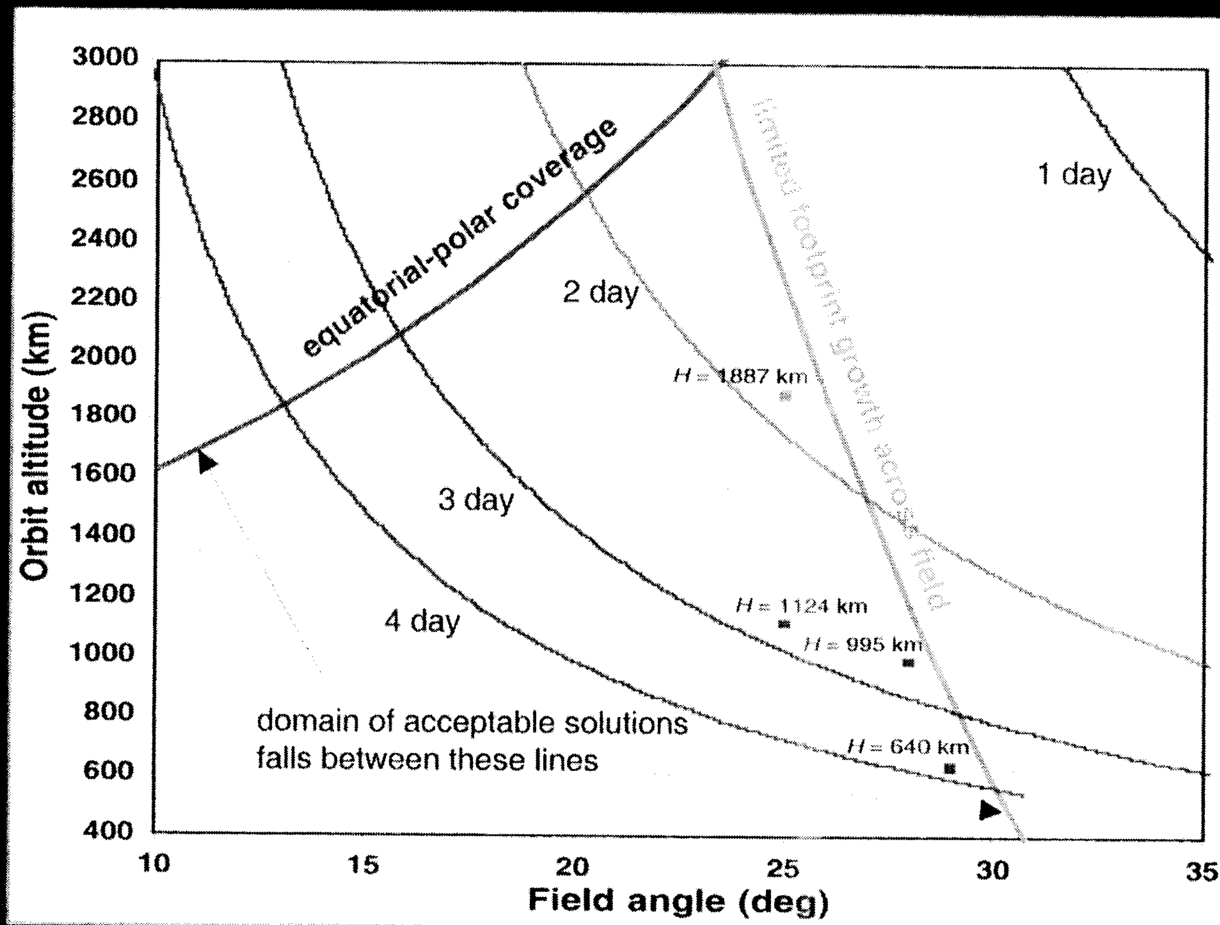
Benefits of combination into a single instrument

Provides synergy, accuracy, simultaneity, imaging, and economy

- **Synergy**
  - multiangle: particle size, shape, and retrievals over bright regions (deserts, cities)
  - multispectral: particle size (visible and SWIR), absorption and height (near-UV)
  - polarimetric: size-resolved refractive index
- **Accuracy**
  - 1 W m^{-2} is estimated magnitude and uncertainty of aerosol climate forcing
  - corresponds to optical depth of ~0.04, which is current measurement uncertainty
  - combining multiple techniques expected to reduce errors by factor of 2-3 (NACIP)
- **Simultaneity**
  - measurements acquired from one platform
  - aerosol mesoscale variability requires simultaneity within ~20 km and 3 hrs
- **Imaging**
  - resolution: can discern cloud and intercloud scales
  - coverage: frequent sampling of validation sites and usefulness for assimilation
- **Economy**
  - resource requirements for one instrument less than sum of individual components

Orbit analysis

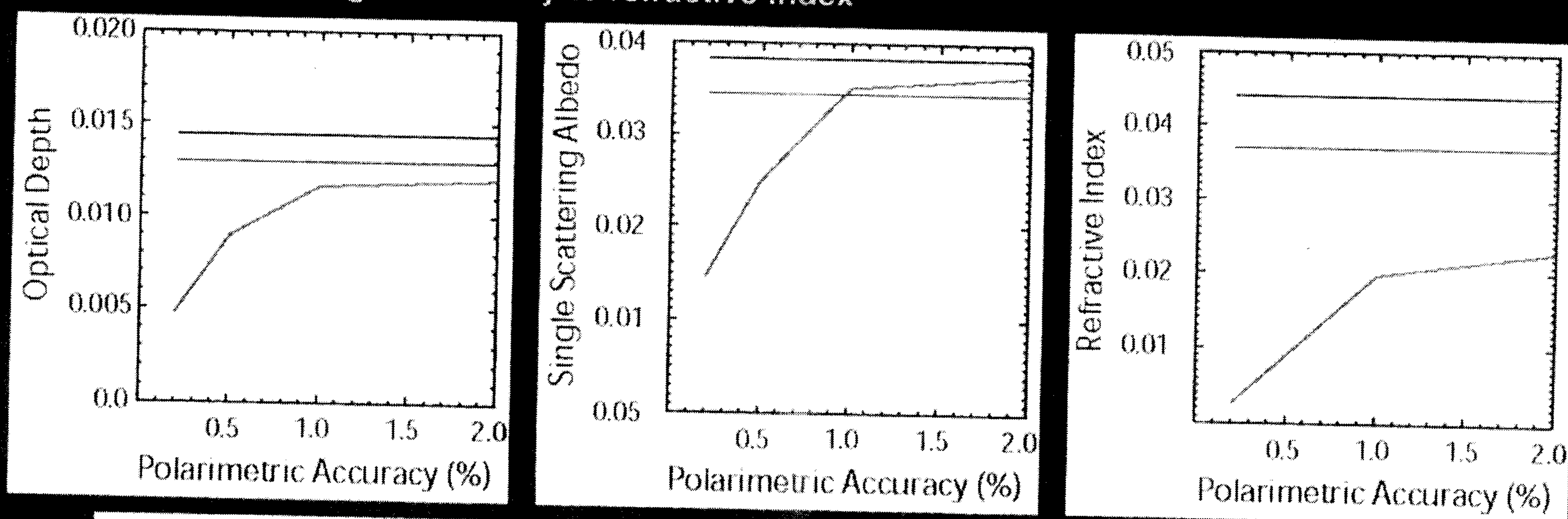
Establishing orbit requirements and constraints is first step to defining instrument parameters, particularly size of the optics



Polarization accuracy requirements

Polarimetric accuracy is design driver

- **"Satellite Instrument Calibration for Measuring Global Climate Change" (Ohring et al., 2003) establishes accuracy requirements**
  - aerosol optical depth (τ) -- 0.01   aerosol single scatter albedo (ω) -- 0.03
- **Limiting factors on accuracy:**
  - instrument calibration, disentangling optical depth and particle microphysical properties
- **Polarimetry can be done as a relative measurement. With accuracy of 0.5%:**
  - potentially improves intensity retrievals of τ and ω by ~factor of 2
  - provides high sensitivity to refractive index

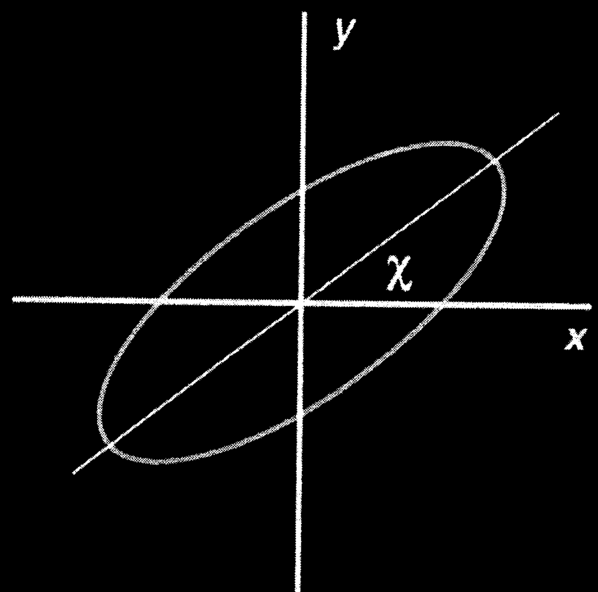


intensity only (9 angles), intensity only (17 angles), intensity + polarization (9 angles)

Sensitivities for model with $\tau = 0.2$, $\omega_0 = 0.9$, fine mode 0.2 µm $n_r = 1.45$, coarse mode 1 µm $n_r = 1.35$

Required polarimetric measurements

Measurement objectives are degree of linear polarization (DOLP) and orientation of polarization plane relative to the plane of scattering



- Scattered light from the Earth is the sum of an unpolarized component and a polarized component, i.e., $I = I_{unpol} + I_{pol}$
- In general, characterizing the radiation field requires measuring 4 components of the Stokes vector:
  - I is intensity
  - Q is preference for horizontal over vertical polarization
  - U is preference for 45º over 135º polarization
  - V is preference for right-handed over left-handed circular polarization
- Circular polarization is negligible in practice (V/I < 0.1%) for aerosol scattering

$$DOLP = \frac{I_{pol}}{I} = [(Q/I)^2 + (U/I)^2]^{1/2} \qquad \tan 2\chi = \frac{(U/I)}{(Q/I)}$$

Measurement challenges

Meeting 0.5% accuracy in DOLP is an exceptional challenge for an imaging instrument

- Instrumental effects must be carefully controlled. High-performance optics are essential
  - all-reflective design to obtain UV-SWIR spectral coverage
  - high optical quality for imaging
  - low instrumentally-induced polarization
  - low depolarization (conversion of linearly polarized light to unpolarized or circular)
  - low diattenuation (difference in transmission for orthogonal polarizations)

- Intrinsic limitations of detector-to-detector gain differences must be overcome

- Image motion and spatial co-registration must be considered to avoid "false" polarization signals

Basic concept

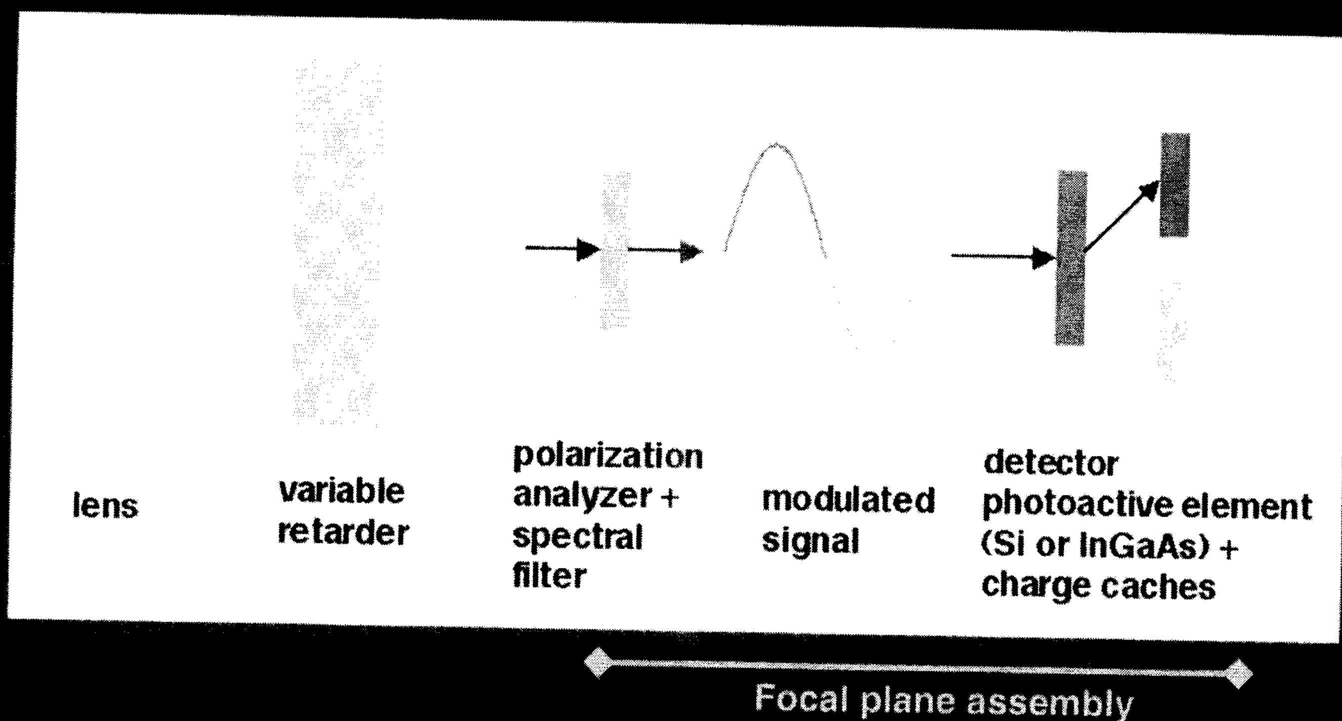
Rapidly interlaced time-modulated polarimetry

- A rapidly varying retarder causes the plane of polarization to rotate at high speed
- In conjunction with a focal plane polarization analyzer, this causes the detected intensity to have a rapid sinusoidal modulation
  - the average signal records the intensity, I
  - a single line array with a polarization analyzer can be used to retrieve Q and U from the modulated signal
  - another arrangement is to have two line arrays with analyzers at 45º to each other; one obtains Q from the modulated signal, the other obtains U
- A charge-caching focal plane demodulates the time-varying signal

Key elements of the approach

Design has 4 key components

- High-performance lens
- Rapid retardance modulator
- Polarization analyzer
- Synchronously demodulating focal plane



Features of this approach

Uses concepts demonstrated by the astronomy community

- Has been used to obtain high precision (0.001%) polarimetric imaging for solar astronomy using rapid charge-shifting CCDs to demodulate the signals
- The rapid modulation causes measurements of I and Q (or I and U) to be interlaced at sub-pixel scale, thus insulating against false polarization ("self-registering")
- The ratios Q/I and U/I are insensitive to detector gain or camera transmittance ("self-calibrating")

Candidate polarization retarder approaches

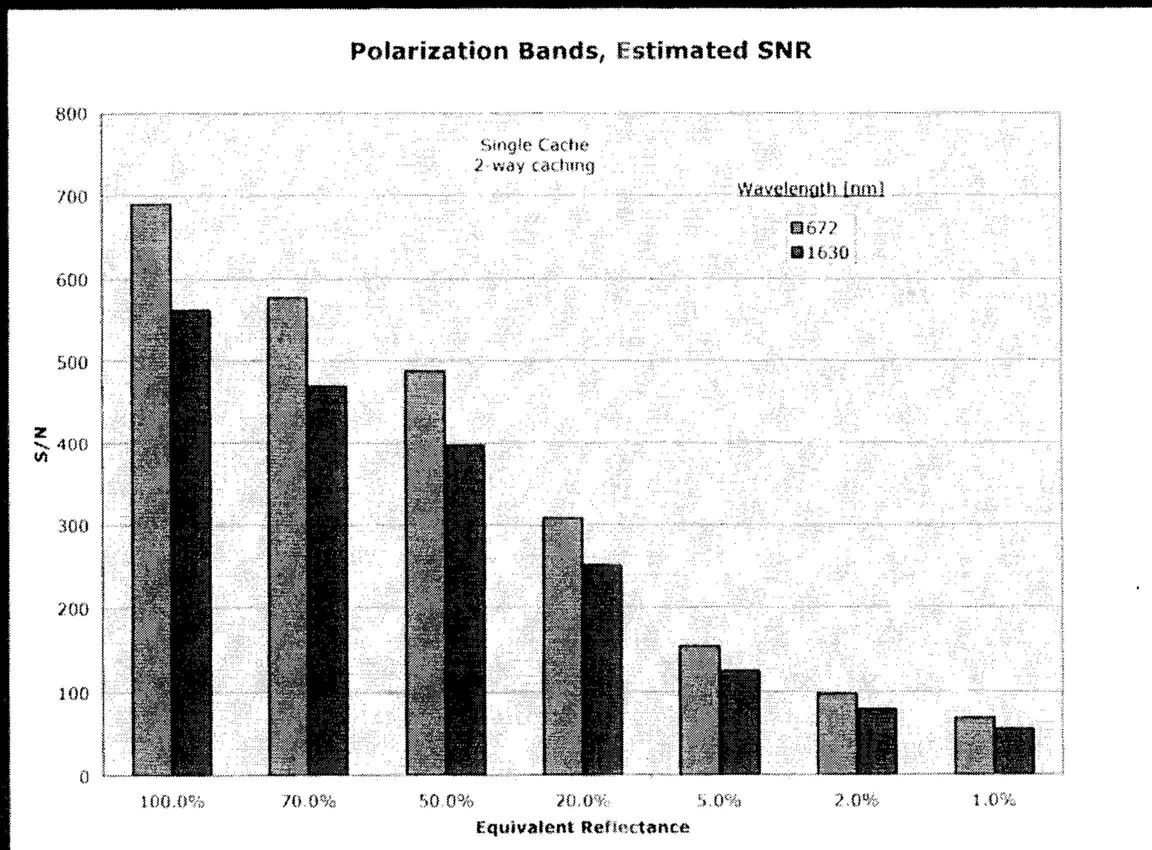
(1) Mechanically rotating retarder
- consists of a half-wave retarder
- advantages: high polarization quality
- disadvantages: need for long-life, high-speed mechanical actuator (> 3000 RPM); magnetic levitation technology development could resolve this

(2) Photoelastic modulator (PEM)
- consists of a glass bar bonded to a piezoelectric transducer (PZT) that induces modulated stress birefringence (25-50 kHz)
- advantages: low power, no moving parts, high polarization quality
- disadvantages: devices susceptible to mechanical shocks

(3) Liquid crystals
- consists of birefringent fluids with elongated molecules that tip perpendicular to the substrate when an electrical field is applied, reducing the effective birefringence
- advantages: low power, no moving parts, high polarization quality
- disadvantages: slow switching speeds, limited transmittance range

Radiometric performance

Required signal-to-noise ratios for polarization channels at very low signal levels can be met by averaging pixels to 1-2 km resolution



Signal-to-noise ratio for single pixel (250 m in nadir)
- can be improved by pixel averaging

Instrument system parameters

The integrated instrument concept has modest resource requirements

Estimated power
51-96 W (depending on retardance modulator option)

Estimated mass
< 50 kg

Estimated volume
0.5 m x 0.5 m x 0.3 m

Estimated orbit-averaged data rate (no compression)
10-20 Mbps (with pixel summing and editing)

These numbers are based on an assumed 640-km altitude orbit, which would provide 4-day global coverage