Dual photoelastic modulator (PEM)-based polarimetry with the Airborne Multiangle SpectroPolarimetric Imager (AirMSPI)

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AirMSPI

Spectral bands:
355, 380, 445, 470*, 555, 660*, 865*, 935 nm
(*polarimetric)

The AirMSPI camera flies in the nose of NASA’s ER-2 aircraft (20 km flight altitude)
AirMSPI is mounted in a gimbal for multi-angle viewing between ±67°
“The largest uncertainties in global climate change prediction involve the role of aerosols and clouds in the Earth’s radiation budget”

A “highly accurate multiangle-multiwavelength polarimeter” is a key component of NASA’s future Aerosol-Cloud-Ecosystem (ACE) mission

—NRC Decadal Survey (2007)

AirMSPI is a prototype for a candidate ACE polarimeter
2013 field campaigns

- **ACE Polarimeter Definition Experiment (PODEX)**
  - Jan 14, 16, 18, 22, 28, 31; Feb 1, 3, 6: California

- **Hyperspectral Infrared Imager (HyspIRI)**
  - Apr 19; May 3, 7: California

- **Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC⁴RS)**
  - Aug 1, 2, 6, 8, 12, 16, 19, 23, 30; Sep 2, 4, 6, 9, 11, 13, 16, 18, 22, 23:
  - Western US, Central US, Southeast US, Honduras, Canada

- **Targets**
  - Clear ocean with visible wave structure, sunglint patterns
  - Farmland, foothills, mountains, rivers, lakes, urban areas, snow fields, desert
  - Smoke and pollution aerosols
  - Fog, broken stratus, stratocumulus, scattered cumulus, and cirrus
  - Glories, supernumerary bows, cloudbow
  - Calibration targets: Rosamond Dry Lake, Ivanpah Playa, Railroad Valley
AirMSPI dual-PEM polarimeter approach

- Photoelastic modulators (PEMs) time-modulate the linear Stokes components $Q$ and $U$ – leaving intensity $I$ unmodulated
  - PEMs are glass elements with stress-induced birefringence modulation at resonant frequencies of ~42 kHz
  - Using dual PEMs with their fast axes aligned, modulation of $Q$ and $U$ occurs at the difference frequency (nominally ~25 Hz)
  - The high frequency oscillation is averaged out during each sample, permitting slower demodulation
  - Enables retrieval of $q = Q/I$ and $u = U/I$ as relative measurements

![Diagram of the AirMSPI dual-PEM polarimeter approach]
AirMSPI optical system

- Dual PEM
- 3-mirror reflective anastigmatic, telecentric telescope
- Focal length = 29 mm
- Achromatic quarter-wave plates

Retardance of Quartz, MgF2, Sapphire waveplate

- Wavelengths: 470 nm, 660 nm, 865 nm
Polarimetry using temporal modulation

1 frame ~ 43 msec

Detector row with 0° polarizer

\[ I_0 = 0.5 \left[ I + Q \cdot F(t) \right] \]

Measures both Q and I → q

Detector row with 45° polarizer

\[ I_{45} = 0.5 \left[ I + U \cdot F(t) \right] \]

Measures both U and I → u

Degree of linear polarization

\[ DOLP = \sqrt{q^2 + u^2} \]

Angle of linear polarization

\[ AOLP = \frac{1}{2} \arctan \frac{u}{q} \]
DOLP of 0.01, 0.05, 0.10, and 0.20 measured for polarizer angles 0°, 45°, 90°, 135°

DOLP of 1.0 measured for polarizer angles from 0 – 170° in 10° steps

NASA Aerosol-Cloud-Ecosystem (ACE) DOLP uncertainty requirement: ≤ 0.005
Step and stare  

Sweep
Step and stare imaging

10 m spatial sampling
10 km x 11 km swath

Bakersfield, 22 January 2013
Sweep mode imaging

25 m spatial sampling
~100 km target length

Backward sweep
Forward sweep

Santa Barbara, 1 August 2013
Example AirMSPI imagery

Bakersfield, CA  18 January 2013  18:01 UTC
47.4° view angle

wastewater treatment ponds

Intensity (470, 660, 865)

DOLP (470, 660, 865)
6 August 2013
18:59 UTC
Off the Oregon coast

Smoke over cloud

brownish color
due to smoke
from Big Windy
Fire

Intensity (445, 555, 660)

glory at 180°
scattering angle
The cloudbow, glory, and supernumeraries indicate spherical drops.

The supernumerary bows are interference fringes.

Their angular positions and relative magnitudes are governed by the particle size distribution at the cloud top.
Fits to supernumerary bow observations

$r_{\text{eff}} = 12 \, \mu\text{m}$

$v_{\text{eff}} = 0.03$

Glory and supernumerary bows in step and stare

Clouds over the Pacific Ocean, 3 Feb 2013, 19:01 UTC
58.0° view angle

In sweep images, scattering angle varies both along-track and cross-track, so supernumerary fringes are circles.

In step-and-stare, along-track angle is fixed, so fringes are stripes.

Intensity: 445, 555, 660 nm

DOLP: 470, 660, 865 nm

Discontinuity in fringe indicates change in droplet size.
Cloudbow analysis of broken cumulus

The droplet size retrieval also works for broken clouds.

A simple intensity threshold was used to separate clouds from ocean. These data are fitted with a distribution having an effective radius of 12 µm and effective variance of 0.02.

Intensity (470, 660, 865 nm)

DOLP (470, 660, 865 nm)

6 February 2013, 22:26 UTC
- Pacific sweep image
Identification of cirrus from atmospheric optics

The subsun is the reflection of the solar disk from horizontally-oriented ice crystal plates.

The DOLP of the subsun is 0.65, less than for pure specular reflection, possibly due to:
- light from a lower cloud deck
- plates with non-horizontal orientations

Clouds over ocean – 1 February 2013, 21:11 UTC

Cloud Physics Lidar (CPL) data show cirrus above lower cloud
Feature at antisolar point

Possible causes:

- Glory from quasi-spherical ice particles (Sassen et al., 1998)
- Anthelion from horizontal hexagonal columns (Lynch and Schwartz, 1979)
- “Antisolar halospot”: superimposed subparhelic circles from hexagonal plates (Können et al., 2008)

Clouds over ocean
1 February 2013, 21:11 UTC

Figures from Können et al. (2008), Appl. Opt., vol. 47
Other features of interest

- 47° forward view
- 47° backward view
- Seeing into shadows
- Droplet size variations
- Cloudbow
- Flight direction
- Stereo parallax
- Line of constant scattering angle

Palmdale, CA
28 January 2013
19:14 UTC

Intensity (470, 660, 865)
DOLP (470, 660, 865)
AirMSPI data facilitate aerosol retrieval algorithm development

Hanford, CA
22 January 2013, 19:59 UTC

Enhanced scattering in the UV and blue

An aerosol retrieval algorithm using a Markov Chain vector radiative transfer code and optimized inversion is currently being tested
Public release of AirMSPI data

AirMSPI data are made publicly available in HDF5 format at the NASA Langley Atmospheric Science Data Center (ASDC)

Documentation available online
https://eosweb.larc.nasa.gov/project/airmspi/airmspi_table
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