Progress in airborne polarimeter intercomparison for the NASA Aerosol/Cloud/Ecosystems Mission

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The Aerosol/Cloud/Ecosystems (ACE) mission, recommended by the National Research Council's Decadal Survey, calls for a multi-angle, multi-spectral polarimeter devoted to observations of atmospheric aerosols and clouds. In preparation for ACE, NASA funds the deployment of airborne polarimeters, including the Airborne Multi-angle SpectroPolarimeter Imager (AirMSPI), the Passive Aerosol and Cloud Suite (PACS) and the Research Scanning Polarimeter (RSP). These instruments have been operated together on NASA's ER-2 high altitude aircraft as part of field campaigns such as the POlarimeter DEfinition EXperiment (PODEX) (California, early 2013) and Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC4RS, California and Texas, summer 2013). Our role in these efforts has been to serve as an assessment team performing level 1 (calibrated radiance, polarization) and level 2 (retrieved geophysical parameter) instrument intercomparisons, and to promote unified and generalized calibration, uncertainty assessment and retrieval techniques. We will present our progress in this endeavor thus far and describe upcoming research in 2015.

Intercomparison Dataset: PODEX (POlarimeter DEfinition EXperiment)

PODEX comprised ten flights of the NASA ER-2, deploying airborne prototypes of three types of optical polarimeters. Although they have variable characteristics, these instruments determine climate relevant properties of clouds, aerosols, ocean and land surfaces. Heritage of these instruments include POLDER (CNES) and APS-Glory (which failed during launch). They are also prototypes for potential future orbital instruments on ACE and PACE missions of the Decadal Survey.

Scene Type	AirMSPI	PACS	RSP	*in situ* observations
No cloud and few aerosols over ocean	Yes	No	Yes	No
No cloud and few aerosols over land	Yes	Yes	Yes	No
Aerosol over land	Yes	Yes	Yes	Yes
Aerosol over urban surface	Yes	Yes	Yes	Yes
Aerosol over ocean	Yes	Yes	Yes	Partial
High aerosol loading	No	No	No	Yes
Broken Clouds over ocean	Yes	Yes	Yes	Yes
Tropospheric clouds	Yes	Yes	Yes	Yes
Cirrus clouds over ocean	No	No	No	No
Cirrus clouds over land	Yes	Yes	Yes	Yes
Cirrus clouds over lower clouds	Yes	Yes	Yes	Yes

PODEX was based at the NASA Dryden (now Armstrong) Aircraft Operations Facility in Palmdale, California. In addition to the three polarimeters described below, the ER-2 also flew the Autonomous Modular Sensor (AMS), Cloud Physics Lidar (CPL) and the Solar Spectral Flux Radiometer (SSFR). Flight paths are shown above. Some were coordinated with the DISCOVER-AQ field campaign, which deployed a variety of *in situ* sampling equiment. A table describing observed scenes is shown at left.

PODEX dataset: **www-air.larc.nasa.gov/missions/discover-aq/podex-links.html**
(AirMSPI data available: eosweb.larc.nasa.gov/project/airmspi/airmspi_table)

Passive Aerosol and Cloud Suite (PACS): Imager that uses Philips prisms to split into polarized components. Principal Investigator is J. Vanderlei Martins, University of Maryland, Baltimore County.

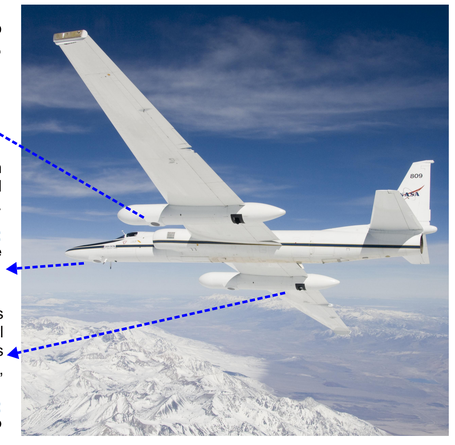
Data are not yet availale for analysis

Airborne Multiangle SpectroPolarimetric Imager (AirMSPI): Pushbroom imager that uses a photoelastic modulator based technique. Principal Investigator is David J. Diner, Jet Propulsion Laboratory. See Diner et al. 2013a, 2013b.

Full dataset available:
eosweb.larc.nasa.gov/project/airmspi/airmspi_table

Research Scanning Polarimeter (RSP): Scanner that uses Wollaston prisms to split into polarized components. Was the airborne prototype for the Aerosol Polarimetry Sensor (APS) on the NASA Glory Mission. Principal Investigator is Brian Cairns, NASA Goddard Institute for Space Studies. See Cairns et al., 2003, Chowdhary et al, 2012 and Knobelspiesse et al., 2011.

Full dataset available:
data.giss.nasa.gov/pub/rsp



Instrument characteristics

	Type	Approximate polarimetric accuracy @reflectance=0.2	# view angles	Nadir ground resolution for ER-2 altitude	Channel center wavelength (nm): 355	380	410	445	470	550	555	660	670	766	865	870	935	960	1593	1880	2263	total # obs. per pixel
AirMSPI	Photoelastic modulation, imager	1%: Step & Stare mode; 0.5%: sweep mode; 0.25%: averaged to RSP spatial resolution	varies, 1 to 31	7m footprint, 9m along track 'smear'	▨	▨		▨	■		▨	■			■		▨					up to 420
PACS	Philips prisms + linear polarizers, imager	?	varies, max ~65	37m footprint, smear?					■	■	■		■	■		■						up to 1170
RSP	Wollaston Prisms, not an imager	0.075%	~152	277m footprint, 277m along track 'smear'			■		■		■		■		■			■	■	■	■	~4100

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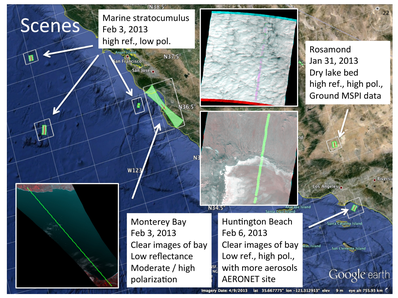
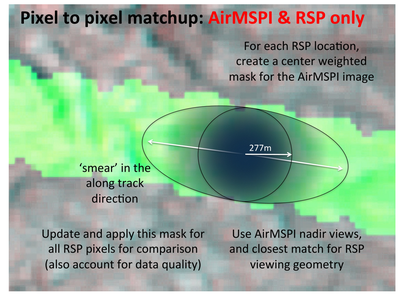
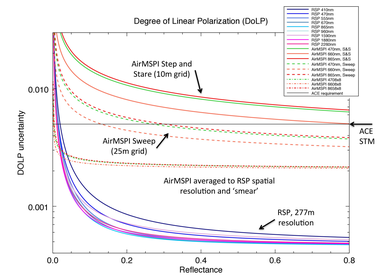
Pixel-to-pixel matchup and intercomparison



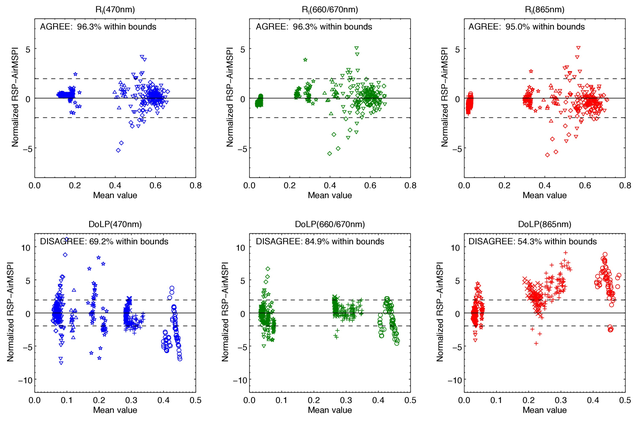




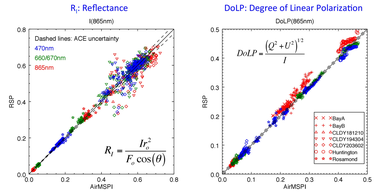
Seven PODEX scenes (**above, left**) were chosen for intercomparison of AirMSPI and RSP reflectances and Degree of Linear POlarization (DoLP). Selections were made based on spatial homogeneity, high data quality, and variety of reflectance and DoLP values. Overall, more than 425 pixel-to-pixel matchups were performed, more details can be found here: earthscience.arc.nasa.gov/sgg/ACEPWG/Level1.html . The matchup procedure is described in the **center image above**, which is an AirMSPI image with an RSP ground track overlay in green. For the coordinates of each RSP pixel center, all AirMSPI pixels within a 277m radius were found. To account for staring time 'smear', this circle was stretched to be an ellipse in the along track direction. A center weighted version of this mask was used to determine the AirMSPI comparison data. Finally, the uncertainty associated with each pixel and channel was determined with the analytical model for instrument uncertainty provided by each instrument PI. Plots of instrument uncertainties for DoLP are shown at **above, right**. Note that AirMSPI has two targeting modes: "Step and Stare," which produces multiple angle observations of a scene and is gridded to 10m, and "Sweep", which observes each scene at a single varying observation angle and is gridded to 25m. Because of the different spatial resolution scales, the contribution of random noise to uncertainty is different for each target mode. More details about the uncertainty models can be found here: earthscience.arc.nasa.gov/sgg/ACEPWG/Uncertainty.html

Intercomparison results

Comparison normalized by uncertainty



Direct comparison



r_o – solar distance in AU; θ – Solar Zenith Angle; F_o – Solar constant.

At **left** are the uncertainty normalized bias between RSP and AirMSPI, as a function of the paired value mean. Thus, a value of 1 indicates that the RSP value is larger than AirMSPI by an amount equal to the sum of their uncertainties. Assuming Gaussian normal distributed biases, 95% of matchup points should fall within +/- 1.96. This is the case for Reflectance, but not the for the DoLP, which has worst agreement for 865nm. Low reflectance, moderate to high DoLP cloudless ocean scenes contributed the most to this bias.

The same data are shown **above** as a scatterplot. We include comparisons of this form for the sake of familiarity, but note that this method cannot indicate the (variable) uncertainty of every matchup point.

This work is ongoing, details and progress for the ACE mission Polarimetry Working Group (ACEPWG) can be found in an online forum:

earthscience.arc.nasa.gov/sgg/ACEPWG

Conclusions

1. AirMSPI and RSP reflectances agree within stated uncertainties.
2. AirMSPI and RSP Degree of Linear Polarization (DoLP) does NOT agree within stated uncertainties. 865nm is worst, 660/670 is best.
3. This analysis DOES NOT indicate which instrument is 'right', but means that retrieved product biases between instruments is possible.
4. AirMSPI DoLP analytical uncertainty is greater than ACE requirements for 'Step and Stare' (multi-angle) mode, equivalent to ACE requirements for 'Sweep' (single view) mode, and better than ACE requirements when downsampled to RSP spatial resolution. RSP DoLP uncertainty is smaller than both ACE requirements and AirMSPI uncertainty.
5. Results call for a discussion of polarimetric calibration techniques, possibly cross-calibration.
6. Analytical expressions for instrument uncertainty should be determined in a unified manner.
7. There is urgent need for full PACS data availability and uncertainty characterization.

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