National Aeronautics and Space Administration

Airborne Multi-angle SpectroPolarimeter Imager (AirMSPI): Polarimetric Calibration, Validation and Aerosol Retrieval Example from the SEAC⁴RS campaign

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Summary

The Airborne Multi-angle SpectroPolarimetric Imager (AirMSPI)[1] is a pushbroom multi-angle spectro-polarimetric camera with spectral bands near 355, 380, 445, 470, 555, 660, 865, and 935 nm. Flying on NASAs's high-altitude ER-2 aircraft since 2010, AirMSPI uses dual photoelastic modulator (PEM)-based technology [2] to achieve accurate measurements of the Stokes linear polarization parameters Q and U in the 470, 660, and 865 nm bands. This provides unique observing capabilities for aerosol, cloud, and surface studies.

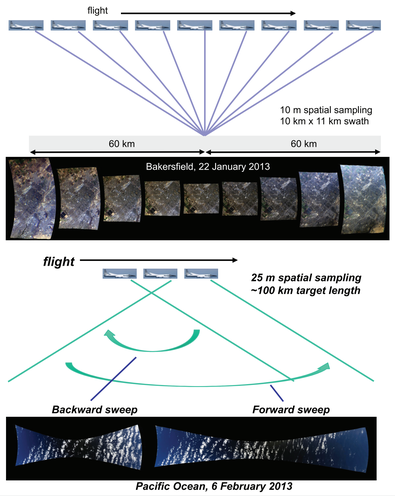
We describe the polarimetric measurement, calibration, and accuracy of the AirMSPI instrument. A well-calibrated Polarization State Generator is used to provide known polarimetric inputs. A high-extinction rotating wiregrid polarizer is used to derive polarimetric calibration coefficients for each pixel, and the results are then validated using partially polarized light generated using tilted glass plates.

We also provide an overview of the AirMSPI data collected during the SEAC⁴RS campaign in collocation with other remote sensing and in-situ data. And in addition, preliminary retrieval example of spatially resolved aerosol optical depth (AOD) and single scattering albedo (SSA) are shown in good agreement with reference data from the Aerosol Robotic Network (AERONET).

Instrument overview

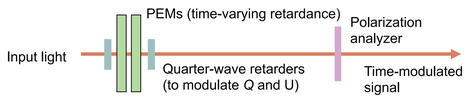
- Overview [1]
  - Spectral bands: 355, 380, 445, 470*, 555, 660*, 865*, 935 nm (*polarized)
  - Platform: NASA ER-2
  - Flight altitude: 20 km
  - Multiangle viewing: ±67°
  - Pixel size: ~10m

- Observation modes
  - Step and stare (ideal for aerosol and surface retrievals)
  - Sweeps (ideal for cloud retrievals



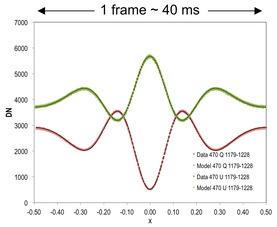
Polarimetric Measurement

- Polarized light
  - Describes the oscillation orientation of the electromagnetic wave
  - Contains information on the medium (e.g atmosphere) it has traveled through
  - Stokes parameters: $I_{Intensity}$, $Q_{horizontal/vertical}$, $U_{\pm 45°}$, $V_{circular}$ used to describe the polarization state
- Measurements of polarized light (I, Q, and U)
  - Dual PhotoElastic Modulators (PEM) [2] measure temporal modulation due to incident polarized light. The fitted function provides the retardances and phase allowing to solve for I,Q,U
  - *Q* and *I* share the same optics and detector for each pixel (similarly for *U* and *I*) enabling retrieval of degree of linear polarization (DOLP) as ***relative*** **measurements independent of absolute radiometric calibration**



$S_0 = 0.5\,[I + Q \cdot F(t)]$
→ $q = Q/I$ from each pixel

$S_{45} = 0.5\,[I + U \cdot F(t)]$
→ $u = U/I$ from each pixel



23 samples read out each frame

x = relative temporal position within the frame

Modulation function

$$F(x_n) \approx J_0[z'(x_n)]$$

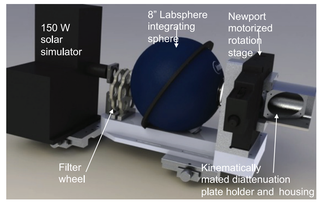
$$z'(x_n) = -2\delta_0 \sin(\pi x_n - \eta)\left[1 + \left(r^2 / \tan^2(\pi x_n - \eta)\right)\right]^{1/2}$$

mean PEM retardance phase ratio of difference/sum of dual PEM retardances

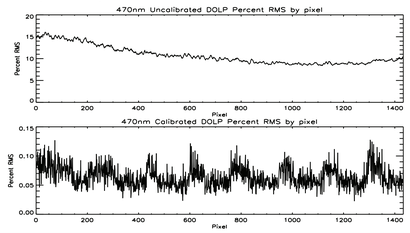
δ_0 is inversely proportional to wavelength, η and r are wavelength independent

Polarimetric Calibration

- Laboratory calibration to account for optical polarization aberrations
  - E.g., mirror diattenuation
  - Crosstalk between I, Q, and U
  - Accomplished with high-accuracy Polarization State Generator (PSG)
- Rotating high extinction polarizer illuminates camera with 100% and variable orientation angle
  - Polarization aberrations in the camera cause linear crosstalk between *I*, *Q*, and *U*
  - A set of 10 calibration coefficients are derived from these data
  - Results are validated using partially polarized light generated using tilted glass plates
- Polarization State Generator (PSG) [3]
  - Generates DOLPs of: 0%, 1%, 5%, 10%, 20%, 40%, 100%
  - Illumination: >10% of Earth's radiance
  - Pol. orientation: variable over 360°
  - DOLP uncertainty: < 0.0002
  - Bandwidth: 350 - 2130 nm
  - Field of view: ±3

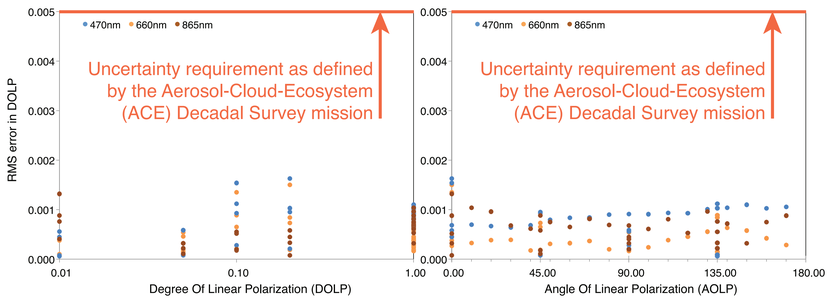


- Verification of PEM retardances and phase using an on-board polarization "validator"
- Examples of pre- and post-calibration %RMS in DOLP



Polarimetric Accuracy

- The Degree of Linear Polarization (DOLP) measurement accuracy is well within the requirement.
- The Angle of Linear Polarization (AOLP) measurement for fully polarized light is within 0.5°.



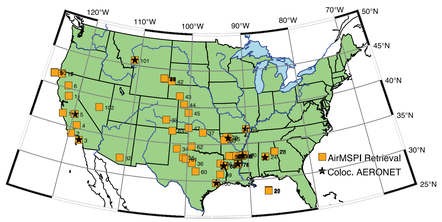
- Experiment:
  - DOLP of 0.01, 0.05, 0.10, and 0.20 measured for polarizer angles 0°, 45°, 90°, 135°
  - DOLP of 1.0 measured for polarizer angles from 0 - 170° in 10° steps.

Post-calibration systematic DOLP residuals over all angles and bands:
median: 0.0006, maximal: 0.0016
This is nearly an order of magnitude smaller than the requirement

Preliminary SEAC⁴RS Aerosol Retrievals

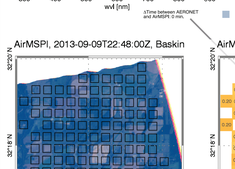
Polarized radiative transfer modeling and aerosol retrieval algorithm:

- Forward model [4]: Linearized Markov Chain and Doubling/Adding formalism for polarized radiative transfer in a plane-parallel atmosphere / polarizing surface system (Water: lambertian water-leaving radiance, Land: Modified Rahman-Pinty-Verstraete and Micro-factets).
- Inversion: Levenberg-Marquardt with smoothness constraints on aerosol size distribution, spectral refractive indices, surface properties in time, and aerosol properties in space.



Nr.	Date in 2013	UTC Time [hh:mm:ss]	Location of 9 Angle Step&Stare Scene	Cloud [%]	AOD 550nm AirMSPI	AERONET	station within 20km
1	1-Aug	225659Z	Pacific-34N120W	1	0.21		
2	1-Aug	221938Z	Monterey	0	0.08		
3	2-Aug	183955Z	Pacific-34N118W	10	0.26	0.18	USC_SEAPRISM
4	2-Aug	210535Z	Pacific-41N125W	0	0.10		
5	2-Aug	212730Z	Pacific-41N125W	0	0.10		
6	2-Aug	214912Z	Pacific-42N125W	0	0.12		
7	2-Aug	191557Z	Bakersfield	0	0.19		
8	2-Aug	192952Z	Fresno	0	0.12	0.04	Fresno_2
9	2-Aug	200529Z	Cottonwood	0	0.19		
10	2-Aug	204042Z	KlamathMountains	100			
11	6-Aug	192423Z	Pacific-41N125W	100			
12	6-Aug	194452Z	Pacific-41N125W	100			
13	6-Aug	200717Z	Pacific-41N125W	100			
14	6-Aug	183303Z	YubaCity	0	0.15		
15	6-Aug	212634Z	Kneeland	50			
16	6-Aug	214827Z	DelNorte	0	0.65		
17	6-Aug	220915Z	DelNorte	10	0.33		
18	6-Aug	223003Z	DelNorte	20			
19	6-Aug	235541Z	SouthwestOregon	100			
20	12-Aug	143251Z	GulfOfMexico-28N87W	30	0.21		
21	12-Aug	145452Z	GulfOfMexico-28N87W	30	0.15		
22	12-Aug	151747Z	GulfOfMexico-28N87W	30	0.22		
23	12-Aug	160130Z	Cantonment	50			
24	12-Aug	162455Z	Bibb	30	0.22	0.13	SEARCH-Centreville2
25	12-Aug	164205Z	HazelGreen	50			
26	12-Aug	170711Z	RockmartPaulding	100			
27	12-Aug	172828Z	Helfin	20	1.14		
28	12-Aug	175043Z	Helfin	20	0.31		
29	12-Aug	181345Z	Helfin	30			
30	14-Aug	185038Z	PoplarBluff	10			
31	14-Aug	193257Z	PoplarBluff	0			
32	16-Aug	163803Z	Tucson	0	0.09		
33	16-Aug	190612Z	Fowler	0	0.39		
34	16-Aug	195520Z	Kress	0	0.21		
35	16-Aug	200948Z	Clairemont	0	0.15		
36	16-Aug	202245Z	Putnam	0	0.13		
37	19-Aug	162330Z	Lamont	40	0.67		
38	19-Aug	180602Z	ThunderBasin	0	0.20		
39	19-Aug	182731Z	ThunderBasin	0	0.18		
40	19-Aug	184925Z	ThunderBasin	0	0.21		
41	19-Aug	191046Z	ThunderBasin	0	0.23		
42	19-Aug	192811Z	HotSprings	0	0.29		
43	19-Aug	194917Z	WestNebraska	0	0.29		
44	19-Aug	200101Z	SouthwestNebraska	0	0.32		
45	19-Aug	201251Z	NorthwestKansas	0	0.34		
46	19-Aug	203604Z	SouthwestKansas	0			
47	19-Aug	205755Z	SouthwestKansas	0	0.50		
48	23-Aug	160603Z	LakeVillage	0	0.32		
49	23-Aug	161612Z	SouthArkansas	0	0.29		
50	23-Aug	163517Z	SouthArkansas	20			
51	23-Aug	164725Z	Greenville	20	0.36		
52	23-Aug	170926Z	Greenville	40	0.40		
53	23-Aug	172137Z	SouthArkansas	60	0.45		
54	23-Aug	194015Z	SoutheastArkansas	20	0.69		
55	23-Aug	195153Z	SouthArkansas	20	0.36		
56	23-Aug	201041Z	SouthArkansas	40	0.37		
57	23-Aug	205457Z	SouthArkansas	80			
58	23-Aug	210751Z	SouthArkansas	40	0.33		
59	4-Sep	170018Z	GulfOfMexico-27N91W	20			
60	6-Sep	170323Z	Goldthwaite	40	0.41		
61	6-Sep	173325Z	CentralTexas	20	0.27		
62	6-Sep	175056Z	Altus	1	0.24		
63	6-Sep	185443Z	Cimarron	0	0.10		
64	6-Sep	221702Z	Puxico	0	0.22	0.27	Mingo
65	6-Sep	224158Z	Arkansas	0	0.10	0.09	Upper Buffalo
66	6-Sep	231632Z	Easton	30	0.25		
67	9-Sep	200417Z	Keatchie	50	0.31	0.15	Calipso_Carthage
68	9-Sep	202337Z	Keatchie	50	0.31	0.15	Calipso_Carthage
69	9-Sep	204705Z	Keatchie	40	0.23	0.16	Calipso_Carthage
70	9-Sep	211634Z	Sunflower	10	0.42		
71	9-Sep	214442Z	Baskin	0	0.18	0.24	Baskin
72	9-Sep	220603Z	Baskin	0	0.19	0.20	Baskin
73	9-Sep	222649Z	Baskin	0	0.16	0.17	Baskin
74	9-Sep	224839Z	Baskin	0	0.19	0.17	Baskin
75	9-Sep	230927Z	Baskin	0	0.16	0.19	Baskin
76	11-Sep	195555Z	Baskin	20	0.42	0.23	Baskin
77	11-Sep	201723Z	Leland	40	0.50	0.26	Leland_HS
78	11-Sep	210343Z	Kingston	10	0.62		
79	11-Sep	211914Z	Alpena	100			
80	11-Sep	220549Z	Ozark	40	1.16		
81	11-Sep	222156Z	Paris	100			
82	18-Sep	180313Z	Fowlerton	100			
83	18-Sep	181101Z	Fowlerton	100			
84	18-Sep	191620Z	Fowlerton	90			
85	18-Sep	200233Z	Conroe	60			
86	18-Sep	202106Z	Conroe	80			
87	18-Sep	203828Z	NewCaney	60			
88	18-Sep	205534Z	Dayton	90			
89	22-Sep	131814Z	GulfOfMexico-28N95W	100			
90	22-Sep	133420Z	GulfOfMexico-28N95W	100			
91	22-Sep	135320Z	GulfOfMexico-28N95W	100			
92	22-Sep	141120Z	GulfOfMexico-28N95W	100			
93	22-Sep	143045Z	GulfOfMexico-28N95W	100			
94	22-Sep	144901Z	GulfOfMexico-28N95W	100			
95	22-Sep	174125Z	GulfOfMexico-29N92W	100			
96	22-Sep	175848Z	GulfOfMexico-29N92W	100			
97	22-Sep	181516Z	GulfOfMexico-29N92W	100			
98	22-Sep	183228Z	GulfOfMexico-29N92W	100			
99	22-Sep	191214Z	Chester	0	0.06		
100	22-Sep	192409Z	Houston	30	0.14	0.08	DRAGON_Clinton
101	23-Sep	205603Z	Bozeman	0	0.10	0.03	Bozeman
102	23-Sep	221141Z	RailroadValley	0	0.04		

- Example over Baskin, Louisiana, with 190 independent retrievals (500x500m each)



- Aerosol Optical Depth (AOD), Single Scattering Albedo, refractive indices, size distribution, albedo, etc.
- AOD and SSA maps indicate the potential of AirMSPI to resolve local sources and transport of aerosols
- AOD agrees with AERONET
- Cloud-mask not yet applied

References / Acknowledgments

[1] D. J. Diner et al. AMT. 6, 2007 (2013)

[2] D. J. Diner et al. Appl. Opt. 49, 2929 (2012)

[3] A.-B. Mahler and Chipman. Appl. Opt. 50, 1726 (2011)

[4] F. Xu et al. Appl. Opt. 51, 3491 (2012)

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