Aerosol Polarimetry Sensor (APS)

Design Summary, Performance and Potential Modifications

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Technology Readiness Level Assessment

- Successful completion of vibration, acoustic, EMI/EMC and thermal/vacuum (1232 APS operational hours) testing at both the sensor and spacecraft level per GEVS.
- Documented by APS Pre-Ship Review Package and Glory Pre-Ship Review Package together with RVM and other requirements verification documentation.
- TRL level was assessed to be 7.
• The APS instrument description
  – Size: 48 cm x 61 cm x 112 cm
  – Weight: 61kgs (134.2 lbs)
  – Operational Power: 55.0 Watts
  – The APS instrument scans the earth over a nominal field-of-view of +50/-60 degrees about Nadir
  – The APS instrument generates along-track, multiple angle radiometric and polarimetric data with a 5.6 km (8 mrad) circular IFOV
  – APS collects data simultaneously in nine VNIR/SWIR spectral bands and four polarization states
  – APS includes four on-board calibration sources to maintain high polarimetric and radiometric accuracy on-orbit
**APS Performance**

**Signal-to-Noise Ratio**

- Data (TP-241 Section 5.2.1):
  - 27 SIS levels
  - 100 scans at each level without linear Attenuator
- Analysis performed using Verification Analysis Tool (SNR.Scanning.xmcd)
  - Calculate scene, dark, and fixed noise terms and combine to compute SNR

### Results: SNR

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength [nm]</th>
<th>Req’t</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>412</td>
<td>235</td>
<td>662</td>
</tr>
<tr>
<td>2</td>
<td>443</td>
<td>235</td>
<td>652</td>
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<tr>
<td>3</td>
<td>555</td>
<td>235</td>
<td>593</td>
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<tr>
<td>4</td>
<td>672</td>
<td>235</td>
<td>491</td>
</tr>
<tr>
<td>5</td>
<td>865</td>
<td>235</td>
<td>412</td>
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<tr>
<td>6</td>
<td>910</td>
<td>94</td>
<td>306</td>
</tr>
<tr>
<td>7</td>
<td>1378</td>
<td>141</td>
<td>287</td>
</tr>
<tr>
<td>8</td>
<td>1610</td>
<td>235</td>
<td>463</td>
</tr>
<tr>
<td>9</td>
<td>2250</td>
<td>235</td>
<td>321</td>
</tr>
</tbody>
</table>

### Graphs:

- **Signal-to-Noise Ratio** vs. Wavelength [nm]
- **SNR vs. SDDA Temperature** [K] for Bands 7, 8, and 9

Band 7 Req’t

Band 8 & 9 Req’t
**APS Performance**

**Linearity**

- Analysis used ratios of Attenuator-In to Attenuator-Out, perform fitting to ratios, evaluate residuals

### APS Macrolinearity [%]

<table>
<thead>
<tr>
<th>Band</th>
<th>Req’t</th>
<th>Channel</th>
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<th>2</th>
<th>3</th>
<th>4</th>
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<tbody>
<tr>
<td>1</td>
<td>0.07</td>
<td></td>
<td>0.004</td>
<td>0.009</td>
<td>0.006</td>
<td>0.005</td>
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<tr>
<td>2</td>
<td>0.07</td>
<td></td>
<td>0.003</td>
<td>0.005</td>
<td>0.004</td>
<td>0.001</td>
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<tr>
<td>3</td>
<td>0.07</td>
<td></td>
<td>0.017</td>
<td>0.016</td>
<td>0.018</td>
<td>0.015</td>
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<tr>
<td>4</td>
<td>0.07</td>
<td></td>
<td>0.023</td>
<td>0.021</td>
<td>0.022</td>
<td>0.023</td>
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<tr>
<td>5</td>
<td>0.07</td>
<td></td>
<td>0.023</td>
<td>0.025</td>
<td>0.026</td>
<td>0.026</td>
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<tr>
<td>6</td>
<td>0.07</td>
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<td>0.019</td>
<td>0.021</td>
<td>0.020</td>
<td>0.020</td>
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<tr>
<td>7</td>
<td>0.07</td>
<td></td>
<td>0.023</td>
<td>0.021</td>
<td>0.020</td>
<td>0.019</td>
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<tr>
<td>8</td>
<td>0.07</td>
<td></td>
<td>0.013</td>
<td>0.014</td>
<td>0.016</td>
<td>0.013</td>
</tr>
<tr>
<td>9</td>
<td>0.07</td>
<td></td>
<td>0.039</td>
<td>0.044</td>
<td>0.040</td>
<td>0.037</td>
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</table>

- Band 1: Red
- Band 2: Pink
- Band 3: Green
- Band 4: Orange
- Band 5: Purple
- Band 6: Yellow
- Band 7: Light Green
- Band 8: Blue
- Band 9: Maroon

### Diagram

- Macro-linearity [%] vs Channel 1 to 4 for each band.
APS Performance

Absolute Radiometric Accuracy

- Analysis used data taken during performance testing and was verified over environments
  - 27 integrating sphere levels acquired consisting of both calibration and test levels
  - SDDA temp = 160K
  - Nominal integration time
  - No scrambler, no attenuator in optical path
- Calculate relative ($K_1$, $K_2$, $C_{12}$), absolute ($C_0$) radiometric gain coefficients, compute estimated radiance for test levels, compare to SIS radiance and compute sensor error. Error tree used to compute system ARA.

<table>
<thead>
<tr>
<th>ARA [%]</th>
<th>Band</th>
<th>Req't</th>
<th>Lmin</th>
<th>Ltyp</th>
<th>Lmax</th>
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<tr>
<td>Telescope #1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>5%+2/S</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5%+2/S</td>
<td>2.5</td>
<td>3.1</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5%+2/S</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5%+2/S</td>
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<td>2.8</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5%+2/S</td>
<td>2.8</td>
<td>2.8</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>5%+2/S</td>
<td>4.9</td>
<td>4.3</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>8%+2/S</td>
<td>4.6</td>
<td>4.4</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>5%+2/S</td>
<td>5.2</td>
<td>4.2</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>8%+2/S</td>
<td>5.2</td>
<td>4.2</td>
<td>4.1</td>
<td></td>
</tr>
</tbody>
</table>

| Telescope #2 | | | | | |
| 1 | 2.5 | 2.5 | 2.5 |
| 2 | 2.5 | 3.1 | 2.6 |
| 3 | 2.9 | 2.8 | 2.8 |
| 4 | 2.9 | 2.8 | 2.8 |
| 5 | 2.8 | 2.8 | 2.8 |
| 6 | 4.9 | 4.3 | 4.3 |
| 7 | 5.0 | 4.4 | 4.4 |
| 8 | 4.7 | 4.4 | 4.4 |
| 9 | 5.2 | 4.2 | 4.1 |

Example Absolute Radiometric Accuracy vs. Radiance

Verdict was demonstrated through a combination of test and analysis because of integrating sphere uncertainties at lower end of dynamic range.

VNIR radiances adjusted for lamp drift
APS Performance

**Polarimetric Accuracy**

- Same data and analyses described on previous slide

**Calibrated Stokes Parameters**

Application of calibration algorithm with measured coefficients accurately recovers input polarization state

**Polarization Accuracy Margin vs. Radiance and Polarization**

Results consistent with ODM test results

Errors well below requirements

Polarimetric Accuracy met requirements over dynamic range and input polarization states
APS Assembly

- Signal Processor Digital CCA
  12 non-vac thermal cycles

- Signal Processor Analog CCA
  12 non-vac thermal cycles

- Scan Controller CCA (Pri & Rdt)
  12 non-vac thermal cycles

- Digital Processor CCA (Pri & Rdt)
  12 non-vac thermal cycles

- Auxiliary - Power Supply Assembly
  12 non-vac thermal cycles

- Electronics Module
  Sine Burst
  Sine Vibration
  Random Vibration
  1 non-vac thermal cycles
APS Assembly

- **Pedestal SWIR Focal Plane Assembly**
  - *Sine Burst*
  - Cover, Module, SWIR Detector Module

- **SWIR Detector Module Assembly (SDA)**
  - *Random Vibration*
  - 1 thermal-vac cycle
  - Mount, Detector Module, SWIR Dewar
  - *Sine Vibration*
  - Isolator Assembly, Cold Stage, SWIR Dewar
  - *Static Loads*

- **SWIR Dewar Base Assembly (SDBA)**
  - *Sine Vibration* (includes Thermal Link)
  - *Random Vibration* (includes Thermal Link)

- **SWIR Optics & Dewar Assembly (SODA)**

- **VNIR Optics & Detectors Assembly (VODA)**

- **Optics & Detectors Module (ODM)**
APS Assembly

Scan Mirror Rotating Assembly (SMRA)
Sine Burst

Scan Mirror Motor/Encoder Assembly (SMMA)
Sine Vibration
Random Vibration
Life Test
3 thermal-vac cycles

Optics & Detectors Module (ODM)
APS Assembly

Ejector Actuator Assembly
Life Test

Solar Reference Door Assembly (SRDA)
Mechanical Functions
6 non-vac thermal cycles

Aperture Door Assembly (ADA)
Mechanical Functions
6 non-vac thermal cycles

Panel Assembly, Earth Shield
8 non-vac thermal cycles

Bipod Assembly, Radiative Cooler Static Loads

Cryoradiator Assembly (CA)

Polarimeter Module
APS Modification

- **Active cooling using a TEC provides greater flexibility in terms of accommodations than a passive cooler**
  - Aluminum radiator plate (40.64 cm x 25.3 cm x 0.203 cm) with white paint
  - Radiator has three Advanced Cooling Technologies ammonia heat pipe spreaders mounted to backside
  - Two Marlow Industries 4-stage thermoelectric coolers (TECs) are attached to backside of radiator to increase contact area and reduce temperature gradient
  - A small aluminum cold plate is bonded to cold side of TECs and thermally isolated from radiator by G10 standoffs
  - One end of an Advanced Cooling Technologies ethane heat pipe is mounted to TEC cold plate, and the other end is mounted a copper strap (flexible linkage to detector assembly)
APS Modification

- Copper Strap (Flex Link)
- Cold Plate
- Ethane Heat Pipe
- TEC
- Ammonia Heat Pipe

Mass of heat rejection system: 0.99 kg
## APS Modification

- **Thermal Test Results**

<table>
<thead>
<tr>
<th>Component</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator</td>
<td>-25.0</td>
</tr>
<tr>
<td>TEC Cold Side</td>
<td>-87.1</td>
</tr>
<tr>
<td>Ethane Heat Pipe/Copper Strap Interface</td>
<td>-84.5</td>
</tr>
<tr>
<td>Copper Strap/Detector Assembly Interface</td>
<td>-83.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEC current (total)</td>
<td>5 A</td>
</tr>
<tr>
<td>TEC voltage</td>
<td>5 V</td>
</tr>
<tr>
<td>TEC power (total)</td>
<td>25 W</td>
</tr>
</tbody>
</table>
• Simple 4-stage TEC cooling system provides adequate performance for APS
• Thermal testing verified SWIR heat rejection system thermal performance
• Using indium foil as thermal interface material at following interfaces will decrease thermal resistances and achieve colder temperature at detector assembly
  – TEC and radiator
  – TEC and cold plate
  – Ethane heat pipe and cold plate
  – Ethane heat pipe and copper strap
• Improving MLI insulation for TEC, cold plate, ethane heat pipe and copper strap will decrease parasitic heat load and achieve colder temperature at detector assembly
• Shorter copper strap and larger number of copper foils will decrease thermal resistance and achieve colder temperature at detector assembly
APS-like Retrieval Approach
• A scanner such as the RSP, or the Glory APS, has a ground pixel size that increases as a function of (roughly) \( \cos^2 \theta v^{-2} \).

• Retrievals need to explicitly account for view angle cloud fraction variations.

• For broken cumulus, cloud fraction can (and does) decrease, or increase with view angle depending on whether the field is centered on a clear, or cloudy scene.
• The example below is for the less cloudy scene from the previous slide

• Things to note:
  • The lines overlaying the left hand figure show what happens when the accumulation/coarse mode optical depths are reduced by 50%
  • Cloud droplet size is 5 µm but could be anywhere from 4-6 µm
  • 864 nm is most sensitive to accumulation mode at side-scattering angles
  • Coarse mode sensitivity is in same angular range as rainbow
• Evaluate screening of surface at 1880 nm.
  – With more than 0.4 precipitable cm there is x100 attenuation of the surface.
  – Evaluation used RSP band, which is wide, but has no out of band.
  – Out of band characterization and control is as, if not more, important than bandwidth.
• Cirrus clouds primarily attenuate the polarized signal from aerosols and molecules lower in the atmosphere.
  – They do not generate much polarization themselves.
  – They do attenuate the aerosol signal and contribute significantly to the total intensity signal.
• In the case shown aerosols are more homogeneous than cirrus.
  – Cirrus optical thickness larger than aerosol, but aerosols still detectable (uncertainty ~ 50% at AOT of 0.04)
  – Total intensity has cloud contributions that are larger than that from aerosol and do not contribute to the aerosol retrieval
• There are a lot of different ways to combine active (lidar) and passive (polarimeter) data.
  – The best way of getting the most out of multi-angle data is using optimal estimation methods, which require iterative searches.
  – The addition of vertical information has no cost penalty in terms of computations provided a self-adjoint (e.g. Doubling/adding, VLIDORT etc.) calculation is used since the vertically resolved radiation field and its interactions with clouds and aerosols is calculated anyway.
Combining Active and Passive

Cloud representation:
Three-dimensional cloud

Consider 3D retrievals to extend coverage to broken cloud fields

Solver 3D VRTE
- SHDOM [Evans, 1998 and 2014]
- Adjoint derivative [Martin, 2014]

Inverse problem
- Retrieval of 1D cloud properties [Evans, 2008]
- Stability and data requirements?

How do we represent clouds for doing 3D retrievals of the atmosphere and surface?
Adjoint method: scalable adjustments to 3D properties

Iterative minimization of the misfit function with only two calls to the 3D VRTE (per wavelength):
- Solve the 3D VRTE once to compute the residual
- Solve the adjoint 3D VRTE once calculate the derivative
- Solve a system of linear equations for the parameter adjustment

Procedure scales to very large problems with . . .
- Many measurement constraints
- Many unknown cloud, aerosol and surface properties

Adjoint method makes 3D retrievals with the 3D VRTE worth discussing
- Future project 1: Test derivative calculations and performance
- Future project 2: Synthetic retrievals and inverse problem analysis

Probably still can't do 3D cloud retrievals on your smart phone.
Potential for Expanded Future Use of Observational System Simulation Experiment (OSSE) Approach?

• **Context**
  — optimization of multi-instrument platform choices
  — target aerosol-cloud-precipitation conditions of interest
  — large-eddy simulations representing range of target conditions

• **Considerations**
  — bin microphysics probably required, especially for drizzle, rain or ice
    ▪ drizzle, rain and ice size distributions generally not exponential and often not unimodal
    ▪ droplet dispersion distribution not obtained with diagnostic bulk scheme
  — forward simulation skill should be tested in complex natural conditions that are well constrained observationally
    ▪ may pose unique requirements on field experiment measurement suite
      • supermicron aerosol
      • ice particle properties
    ▪ simulations can’t be trusted without detailed comparison to measurements
      • too many uncertainties in aerosol-cloud-precip processes
      • special demands posed by forward simulation (e.g., reflectivity)
• **Question**: why are lidar depolarizations < 20% (often associated with drizzle or rain) commonly observed beneath ice-precipitating clouds in the Arctic?

• **Hypothesis**: depolarization signal from ice is reduced by scattering from humidified aerosol

• **Approach**: use large-eddy simulations with realistic ice size distributions (Fridlind et al., JAS, 2012) to calculate depolarization resulting from mixture of aerosol and ice below cloud

• **Results**: humidified aerosol can explain observed covariance of lidar depolarization and radar reflectivity, as well as prominent reduction of depolarization with height

• **Future work**: determine whether drizzle can be distinguished from humidified aerosol owing to differing influences on lidar depolarization profile (see van Diedenhoven et al., JGR, 2009)

Summary

- APS is a mature design that has already been built and has a TRL of 7.
- Algorithmic and retrieval capabilities continue to improve and make better and more sophisticated use of the data.
- Adjoint solutions, both in 1D and 3D are computationally efficient and should be the preferred implementation for the calculation of Jacobians (1D), or cost-function gradients (3D).
- Adjoint solutions necessarily provide resolution of internal fields and simplify incorporation of active measurements in retrievals, which will be necessary for a future ACE mission.
- It's best to test these capabilities when you know the answer: OSSEs that are well constrained observationally provide the best place to test future multi-instrument platform capabilities and ensure capabilities will meet scientific needs.