Next Generation Grating Spectrometer Sounders for LEO and GEO

Thomas S. Pagano
California Institute of Technology JPL
tpagano@jpl.nasa.gov

March 31, 2010

NASA Science Community Workshop on Polar Orbiting IR and MW Sounders
Top Recommendations

• November 1, 2, 2010, 140 People Registered
• Top 3 Recommendations Common to Weather, Climate and Composition Breakout Groups:
  – Recommendation I: The formation of a US based Sounding Science Team is required to identify the current and future needs of the weather, climate and atmospheric composition communities using data from the IR and MW sounders
  – Recommendation II: The JPSS enable the full spectral resolution possible with the FM-1 CrIS on NPP as soon as possible.
  – Recommendation III: NASA should begin development of an advanced IR sounder with high spatial resolution and improved spectral resolution to be ready to follow the current planned sounders expected to retire in the 2020 timeframe.
Improved Spatial Resolution from LEO Needed to Initialize & Validate GCM's

Observations of Temperature, Water Vapor, Clouds, etc. are used to initialize and validate forecast models.
Increasing resolution improves realism of forecasts of the details in nature 2-day Katrina forecasts.

Columbia allows high resolution and rapid time-to-solution.

GMAO: M. Rienecker
Higher Spatial Resolution Improves Ability to Sound in Presence of Clouds

- More Clear Observations
- Better Cloud Height Discrimination
- Better Characterization of Cloud Scale Dependent Variability
- Improved Boundary Layer Sensitivity

Adapted from Gettelman, 2006
Regardless of Scale: Still need parameterizations for most things
Goal: get interactions right (Mesoscale). Also extreme events

Adapted from Gettelman, 2006, Antes 1975
AIRS Greenhouse Gases

H₂O
500 mb Water Vapor (g/kg dry air)

CH₄
CH₄ VMR at 200 mb (ppm):

CO₂
Mid-Tropospheric CO₂ (ppm)

Other AIRS Atmospheric Climate Products

500 mb Temperature (K)

Cloud Fraction

Total Column CO (molecules/cm²)

Total Column Ozone (DU)

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Pagano, JPL, 2009
Higher Spatial Resolution Needed to Track Sources and Sinks of Trace Gases

Current: AIRS CO, Grating, 15 km IFOV Daily Global Coverage

Higher Spatial Resolution + Global Coverage CO, CO₂, CH₄

MOPITT CO Gas Cell 22 km IFOV Monthly Global Coverage

MODIS 1km Daily Regional Coverage
Imager Products Highly Synergistic with Sounder for Weather, Climate, GHG Flux

Aerosol

Polar Winds

Ocean Color

LST

SST

NDVI
MODIS Widely Used for Operational Government and Civil Applications

- Water Vapor Winds assimilated operationally at numerous NWP Centers
- 40 NWS Centers Regularly Use MODIS IMAPP Data
- Forecast Support for Johnson Spaceflight Center Meteorology Group
- Snow/ice/cloud discrimination
- Fog detection
- Sea Surface, Land, Lake Temperature
- Aerosols used for EPA Air Quality
- Disaster Monitoring: Volcanoes, Oil Spills, Fires, Hurricanes, Floods
- Agriculture, Commercial Fishing
- Military Operations
- Over 40+ Products
Almost 40,000 Users of Aqua Data

MODIS and AIRS have Most Users

Most Users Foreign

LEO Imagers and Sounders are Essential to Earth Science Investigations and Must be Priority for Advancement.

NASA NRC DS Assigned to NOAA

Courtesy of GES/DISC
Key Needs of Next Generation Imagers and Sounders

• Higher Spectral Resolution
  – Improved Product Accuracy and Calibration
  – Improved Sea Surface Temperature Accuracy
  – Improved LST, and Surface Emissivity
  – Improved Cloud and Aerosol Product Accuracy
  – Improved boundary layer sensitivity
  – Improved GHG observations: CH4, CO, CO2
  – Improved Water Vapor Transport: Higher H2O Vertical Resolution, HDO

• Higher Spatial Resolution (on the order of 1km)
  – Improved regional model initialization and characterization
  – Improved yield in cloudy scenes; closer to cloud boundaries
  – Improved characterization of cloud processes and variability
  – Aviation Alerts: Volcanic Ash and SO2, Storms, etc.
  – Improved Fire Detection
  – Greenhouse Gas, CO and SO2 Emissions from Anthropogenic Sources
  – Synergy with OCO-2, CarbonSat
Evolving Requirements and Technology Lead to New Architecture

**AIRS**
Atmospheric Remote-sensing Imaging Emission Sounder

AIRS on Aqua
14 km GSD, ±49.5°
2378 Channels
0.4-15.4 μm
177 kg, 256 W
0.9 m³, 1.3 Mbps

**ARIES (IR Only)**

1 km GSD. ±55°
4096 Channels
3.3-15.4 μm
100 kg, 150 W
0.5 m³, 60 Mbps
Unplanned

**MODIS**

**AIRS and MODIS around till ~2020**

MODIS on Aqua
1 km GSD, ±55°
0.4-14.4 μm
220 kg, 160 W
1.5 m³, 11 Mbps

**ORCA+ (UV/VIS/NIR)**
Ocean Radiometer for Carbon Assessment

1 km GSD. ±58°
108 Channels
0.24-2.14 μm
140 kg, 130 W
0.5 m³, 13 Mbps
NASA Planned
(For PACE)

• ARIES and ORCA Meet all Requirements of AIRS and MODIS + More!!!

Next Gen Imaging Sounders Give Hyperspectral UV through LWIR

ORCA
108 UV/Vis/NIR Ch.
345-885 nm, $\Delta \lambda = 5$ nm
3 SWIR Channels

ARIES
4096 Channels
~2x Better than AIRS

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral Range</th>
<th>Spectral Resolution</th>
<th>No. Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW1</td>
<td>2100 - 2950 cm$^{-1}$</td>
<td>1.6 cm$^{-1}$</td>
<td>1024</td>
</tr>
<tr>
<td>MW2</td>
<td>1150 - 1613 cm$^{-1}$</td>
<td>1.0 cm$^{-1}$</td>
<td>1024</td>
</tr>
<tr>
<td>LW1</td>
<td>880 - 1150 cm$^{-1}$</td>
<td>0.6 cm$^{-1}$</td>
<td>1024</td>
</tr>
<tr>
<td>LW2</td>
<td>650 - 880 cm$^{-1}$</td>
<td>0.5 cm$^{-1}$</td>
<td>1024</td>
</tr>
</tbody>
</table>

ARIES Enters New Domain of Earth Observation
Spectral and Spatial Space

Spectral Resolution vs. Spatial Resolution For Spaceborne Optical Sensors
Wide Field Optics Improve Spatial Resolution and/or Coverage

- **Whiskbroom**: Wide field slows scan, enabling higher spatial resolution
- **Pushbroom**: Wide field directly extends E/W Swath

Wide Field Grating Spectrometer
Demonstrated on IIP 2001

\[
\theta_{E/W} = \theta_{N/S} \cdot H \cdot \frac{\alpha}{\tau_{int_{AIRS}}} \cdot \varepsilon
\]

- \(\theta_{E/W}\) is the Field of View (km)
- \(\theta_{N/S}\) is the Resolution (km)
- \(H\) is the Height
- \(\alpha\) is the Angle
- \(\tau_{int_{AIRS}}\) is the Intensity
- \(\varepsilon\) is the Efficiency
New Technologies Enable Compact Wide Field Grating Spectrometer Sounders

BAE Systems
HgCdTe
15 μm Cutoff
512 x 512

SIRAS IIP1
Refractive 16°
Grating Spectr

AIRS
Reflective 1.1°
Grating Spectr

Next Generation
LEO or GEO
Sounder
TRL 5

BAE Systems
PV/PC HgCdTe
17 modules
2 x ~180
100 x 50 um

MODIS
Raytheon Vision
Systems
PV/PC HgCdTe
4 FPAs
10 x ~10
400 x 400 um

AIRS
Large Dewar

High Efficiency
Mini Dewars

NGST
Small Single
Pulse Tube
Cooler

AIRS
Large Dual Pulse
Tube Coolers

AIRS
Large Dual Pulse
Tube Coolers
Modular Mini-Grating Spectrometers
Reduce Cost and Complexity

- On Aqua, IR/MW frequencies distributed amongst 4 instruments. Single Retrieval

Mini-Spectrometer Instrument Modules
- 1 WF Grating Spectrometer / FPA per Module
- Optics / FPA Tailored for Each Band
- Commonality Reduces Cost. Low RE
- Easier to accommodate
- < 50 kg, < 50W, < 1 Mbps

TRL 5
Mini Grating Spectrometers Compatible with Launch on Iridium Constellation

Iridium NEXT Hosted Payload Accommodation

- Provides Unprecedented Geospatial and Temporal Coverage
  - Coverage – Global, Continuous, 24/7
  - Real Time Control and Low Latency – Real-time 24x7 Relay of Data to and from Payloads in Space with < 9 sec Latency
  - Cost Effective - A Fraction the Cost of a Dedicated Mission
  - Unique – No Other Similar Opportunity Likely to Be Available for Decades
- All 72 Iridium NEXT Satellites Can Host Additional Payloads

<table>
<thead>
<tr>
<th>Standard Hosted Payload Accommodations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>50 kg</td>
</tr>
<tr>
<td>Payload Dimensions</td>
</tr>
<tr>
<td>30 x 40 x 70 cm</td>
</tr>
<tr>
<td>Payload Power</td>
</tr>
<tr>
<td>50 W average (200 W peak)</td>
</tr>
<tr>
<td>Payload Data Rate</td>
</tr>
<tr>
<td>1 Mbps peak, Orbit average ~100Kbps</td>
</tr>
<tr>
<td>Latency</td>
</tr>
<tr>
<td>&lt; 9 sec</td>
</tr>
<tr>
<td>Pointing</td>
</tr>
<tr>
<td>~0.25 deg knowledge/control</td>
</tr>
</tbody>
</table>

C. Schueler (OSC)
Key to Affordable GEO Instrument is Modest Set of Requirements

- Gratings offer advantages for GEO
  - High Reliability
  - Low sensitivity to pointing
  - Smaller Spectrometers (wide field allows high magnification)
  - Low Power (Minimal signal processing)
  - **But**: Fewer Channels than FTS

- GEO sounder need not be big
  - SIRAS-G, AIRS+ from GEO
  - JPL NMP Concept Proposal 1998
  - Spectrometers Same as LEO
  - Compatible with Orbital STAR

### SIRAS-G (NMP 1998)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSD (km)</td>
<td>5.0</td>
</tr>
<tr>
<td>IFOV (km/µr)</td>
<td>10.0/280</td>
</tr>
<tr>
<td>Size (m)</td>
<td>0.7 x 0.5 x 0.4</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>100</td>
</tr>
<tr>
<td>Power (W)</td>
<td>150</td>
</tr>
<tr>
<td>Aperture (cm)</td>
<td>12.5</td>
</tr>
<tr>
<td>Integration (ms)</td>
<td>100</td>
</tr>
<tr>
<td>No. Channels</td>
<td>2400</td>
</tr>
<tr>
<td>Data Rate (kBps)</td>
<td>&lt;300</td>
</tr>
</tbody>
</table>

### Assumptions

- **Aperture**: $D = 2.44 \lambda / a$
- $\lambda = 15.4 \mu m$
- **Scan Time**: 3000x4000 km Region
- 500 km Swath N/S
  - Same $A_d O_d T_{int}$ as AIRS
Summary

- AIRS and MODIS Widely Used for Weather, Climate, Composition, Carbon Cycle, Cross-Calibration, and Applications
- Community asking for new capability in the 2020 timeframe
  - Hyperspectral UV to LWIR, High Spatial ≤1km IFOV
  - Maximize Synergies of Solar Reflected and IR. Synergies with OCO-2.
- Expect more users and applications of next gen LEO IR Sounder than GEO
  - Weather, Climate, GHG Monitoring, Aviation, Disaster Response
- New Direction for Imagers and Sounders
  - Separate Vis/NIR/SWIR from MWIR/LWIR Instruments Reduces Technology Risk and Complexity
  - Expect Costs to be lower than CrIS & VIIRS
- Additional Ideas to Reduce Costs:
  - Minimum Set of Requirements
  - Mini-Grating Spectrometers. Supports Constellation for Higher Revisit
  - New Technology to Reduce Instrument Size (Large Format FPA’s)
  - Hosted Payloads
Issues and Recommendations

• **Issues**
  – Currently no plan to advance capability of LEO IR sounder at NASA or NOAA = No Study Funds
  – NRC Decadal Survey did not make IR sounders a priority at NASA
  – Currently no technology development program for LEO IR sounders at NASA or NOAA

• **Recommendations**
  – Initiate studies for advanced imager and sounders at NASA and NOAA
  – Initiate a technology development program focused on retiring key risk areas for next generation LEO imager and sounder
Special Thanks to Mous Chahine for His Vision of ARIES

A Brilliant Scientist
A Great Visionary
A Gentle Mentor
A Good Friend