Hyperspectral Imagers

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From Pinhole Camera to Pushbroom Spectrometers

The Design Requirements:
• High Data Rate
• High Signal-to-Noise Ratio
• High Performance Detectors
• High Image Uniformity
• High Calibration Accuracy

APEX experiment 2008

MOS experiment 1997

Camera obscuras, Reinerus Gemma−Frisius, 1555

Sir Isaac Newton’s prism experiment, 1666–72
<table>
<thead>
<tr>
<th>Scanning approach</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Whiskbroom        | • simple over-all design  
|                   | • wide FOV  
|                   | • easy calibration  
|                   |               | • mechanical scanner (moving parts in vacuum)  
|                   |               | • post-processing required (spatial incongruence)  
|                   |               | • constraints of high spectral and spatial resolution requirements (low integration time)  
| Pushbroom         | • no moving parts  
|                   | • congruence of spectral images  
|                   | • longer integration time for each ground pixel  
|                   |               | • complex focal plane  
|                   |               | • narrow FOV  
|                   |               | • complex calibration  
|                   |               | • complex optics  
|                   |               | • spectral curvature  
| Staring           | • simple and compact  
|                   |               | • post-processing required (spatial and spectral incongruence)  
|                   |               | • constraints when many spectral bands and high spatial resolution requirements |

**Spectral Unit of Pushbroomers**

Filter Method  
Absorption / Interference Filter

Dispersion Method  
Grating: Diffraction of Light  
Prisma: Refraction of Light

Fourier Transform Spectrometers (FTS)  
Time Domain FTS:  
=> Michelson Interferometer  
Spatial Domain FTS:  
=> Sagnac Interferometer
### Design challenge: Data stream

- **Data Rates of well-known systems:**
  - Hyperion: 12 bit x 1254pix x 35 Hz = 150 Mbit/sec = 18 MB/s
  - AVIRIS: 22474 x 12 bit x 614 pix x 12 Hz = 22 Mbit/sec = 2.8 MB/s

<table>
<thead>
<tr>
<th>System</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVIRIS</td>
<td>2.8 MB/s</td>
</tr>
<tr>
<td>Hyperion:</td>
<td>18 MB/s</td>
</tr>
<tr>
<td>APEX:</td>
<td>32 MB/s</td>
</tr>
<tr>
<td>MODIS:</td>
<td>1.35 MB/s</td>
</tr>
<tr>
<td>MERIS (FR):</td>
<td>6.25 MB/s</td>
</tr>
<tr>
<td>ASAR HR:</td>
<td>12.5 MB/s</td>
</tr>
</tbody>
</table>

- **APEX Data Rates:**
  - **High Spatial:** (114+199) x 16 bit x 1024 pix x 50 Hz = 256 Mbit/sec = 32 MB/s
  - **High Spectral:** (312+199) x 16 bit x 1024 pix x 17 Hz = 140 Mbit/sec = 18 MB/s
Design challenge: Detector

- Requirements for “Scientific Detectors”
  - “Large Area” Detector
  - “Large” pixel size
  - Low read out noise
  - Dynamic range
  - High quantum efficiency
  - High fill factor
  - High radiation hardness (for space applications)
  - Low system power
  - Low system mass
  - System volume
  - Low calibration complexity

- Constraints
  - The Detector Market is driven by consumer electronics needs
  - Only very few manufacturers (E2V, SOFRADIR, AIM) having developed detectors for the niche of scientific imaging
  - Export restricted due to military or custom design
  - Certain fiscal restrictions

Design challenge: Image Uniformity

- Punctual defects,
- Linear defects,
- Areal defects,
  (spectral and spatial misregistration)
- Stability defects,
- Discontinuity defects.
Design challenge: Calibration accuracy

- State-of-the-art are new generation of satellites, which deliver remote sensing data in *unprecedented quantity and quality*, such as SeaWiFS, ENVISAT, TERRA, AQUA and ADEOS-2.

- Driver applications:
  - Climatology
  - Ocean color

- Various methods were developed to improve the accuracy of remote sensing systems, such as
  - Spectral calibration
  - Geometric calibration
  - Radiometric calibration
  - Onboard calibration
  - and vicarious calibration of the sensor output (Level 1B data)
  - Validation of scientific algorithms (higher level output)

Airborne Hyperspectral Imager

<table>
<thead>
<tr>
<th>Airborne Hyper-IS</th>
<th>Year</th>
<th>Number of Spectral Bands</th>
<th>Spectral Range (µm)</th>
<th>Spectral Resolution (λ/Δλ)</th>
<th>FOV / IFOV (°, mrad)</th>
<th>Imaging Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIS (JPL, US)</td>
<td>1982</td>
<td>128</td>
<td>0.9-2.4</td>
<td>80-200</td>
<td>3.7° 2 mrad</td>
<td>1D whiskbroom grating</td>
</tr>
<tr>
<td>AVIRIS (JPL, US)</td>
<td>1989</td>
<td>224</td>
<td>0.4 - 2.5</td>
<td>40-200</td>
<td>30° 1 mrad</td>
<td>1D whiskbroom grating</td>
</tr>
<tr>
<td>FLI (Moniteq, Itres, CA)</td>
<td>1984</td>
<td>288</td>
<td>0.4-0.8</td>
<td>200-300</td>
<td>70° 1.3 mrad</td>
<td>2D pushbroom grating</td>
</tr>
<tr>
<td>CASI (ITRES, CA)</td>
<td>1990</td>
<td>288</td>
<td>0.4-1.0</td>
<td>40° 1.5 mrad</td>
<td></td>
<td>2D pushbroom grating</td>
</tr>
<tr>
<td>HYMAP (Intergrated Spectronics, AU)</td>
<td>1994</td>
<td>128</td>
<td>0.4-2.5</td>
<td>30-125</td>
<td>65° 2 mrad</td>
<td>1D whiskbroom grating</td>
</tr>
<tr>
<td>ARES (Intergrated Spectronics, AU/DLR, DE)</td>
<td>from 2006</td>
<td>128 (VIS-SWIR); 30 (TIR)</td>
<td>0.4-2.5 8-12</td>
<td>30-125 64-100</td>
<td>65° 2 mrad</td>
<td>1D whiskbroom grating</td>
</tr>
<tr>
<td>APEX (ESA / CH, BE)</td>
<td>from 2008</td>
<td>313-500</td>
<td>0.4-2.5</td>
<td>1000-277</td>
<td>28° 0.5 mrad</td>
<td>2D pushbroom prism</td>
</tr>
</tbody>
</table>
AISA Airborne Hyperspectral System

AISA Eagle
Spectral bands: 340
Range: 400 - 970 nm
FOV: 37.7 deg
Cross-track pixels: 1024

AISA Hawk
Spectral bands: 255
Range: 97 - 2450 nm
FOV: 24 deg
Cross-track pixels: 320

Prism-Grating-Prism (GRISM)
Mass: 47.5 kg
Company: SPECIM

AVIRIS Instrument
Spectral bands: 224
Range: 400 - 2500 nm
FOV: 34 deg
Cross-track pixels: 677
four whiskbroom grating spectrometer with four detectors (200 x 200 micron)
Mass: 300 kg
Company: JPL/NASA

AVIRIS Technology Development
- Thermal control 1997
- Low Altitude 1998
- INU/GPS 1998
- Geo rectification 1998
- Onboard calibrator 1999
- Detector arrays 2000
- Digital signal chain 2001
- Onboard data storage 2001
- Scanner and fore optics 2003
**Hyperspectral Spaceborne Imaging Spectrometer**

<table>
<thead>
<tr>
<th>Spaceborne-IS (Producer, Satellite, Agency)</th>
<th>Year</th>
<th>Number of Spectral Bands</th>
<th>Spectral Range (μm)</th>
<th>Spectral Resolution</th>
<th>FOV / IFOV (km, m)</th>
<th>Imaging Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIMs (John Hopkins University, MSX, DoD)</td>
<td>1996</td>
<td>272</td>
<td>0.4–1.0</td>
<td>15 nm</td>
<td>15 km 770 m</td>
<td>LEO grating, pushbroom</td>
</tr>
<tr>
<td>HYPERION (TRW, EO-1, NASA)</td>
<td>2000</td>
<td>220</td>
<td>0.4–2.5</td>
<td>10 nm</td>
<td>7.5 km 30 m</td>
<td>LEO grating, pushbroom</td>
</tr>
<tr>
<td>AFRL MightySat II (Sindri) FTHSI</td>
<td>2000</td>
<td>256</td>
<td>0.4–1.0</td>
<td>2–6 nm</td>
<td>15 km 50 m</td>
<td>LEO FTS, pushbroom</td>
</tr>
<tr>
<td>CHRIS (SIRA, PROBA, ESA)</td>
<td>2001</td>
<td>19–62</td>
<td>0.4–1.0</td>
<td>1.25–11 nm</td>
<td>13 km 25–50 m</td>
<td>LEO, multi-viewing Prism, pushbroom</td>
</tr>
<tr>
<td>Moon Mineralogy Mapper (JPL, NASA) on</td>
<td>2008</td>
<td>261</td>
<td>0.45–3.0</td>
<td>10 nm</td>
<td>40 km 70 m</td>
<td>Moon orbit, Offner Grating, on Chandrayaan-1 (ISRO)</td>
</tr>
<tr>
<td>ENMAP (Keyser Trede, DLR)</td>
<td>2011</td>
<td>220</td>
<td>0.43–2.5</td>
<td>10 nm</td>
<td>30 km 30 m</td>
<td>LEO, 30deg tiling grating, pushbroom</td>
</tr>
</tbody>
</table>

**HYPERION on EO-1**

EO-1, launched November 21, 2000
Payload (90kg):
- Advanced Land Imager (ALI)
- HYPERION first high spatial resolution imaging spectrometer
- LEISA (Linear Etalon Imaging Spectral Array)
- Atmospheric Corrector (AC)

Hyperion
- 220 x 10 nm bands in 400 nm - 2500 nm range
- 6% absolute radiometric accuracy
- Image swath width of 7.5 km
-IFOV of 42.4 microradian
- GSD of 30 m at 705 km altitude
- 12-bit image data
- Power: 51 W orbit avg., 126 W peak
- Mass: 49 kg
- One year Life (2 year Goal)
- Lewis Hyperspectral Imager (HSI) heritage
- using JPL convex grating design
- and Offner configuration

**HYPERION SNR**

[Graph showing SNR vs. Wavelength]
CHRIS on PROBA

Platform: PROBA*
- PROBA is the ESA Project for On-Board Autonomy
- Launched: 22nd October 2001, by Indian PSLV
- 100 kg, 100W,
- 800 x 600 x 600 mm³

Orbit: Sun-synchronous, polar, 553km

Platform agility:
- Pitch range: ±55° - Images at ±55°, ±36° and 0°
- Roll range: ±25°
- Pitch during imaging to increase integration time x 3

Payload:
CHRIS (Compact High Resolution Imaging Spectrometer)**:
- Front baffle, carries solar calibration device
- Telescope, images ground onto entrance slit
- Prism dispersed image relayed to area-array CCD detector
- LED and diffuser placed close to detector

Wide Angle Camera (WAC), High Resolution Camera (HRC)***

Standard Radiation Environment Monitor (SREM)****

* Prime: Verhaert Design and Development (BE)
** SIRA (UK)
*** OIP Systems (BE)
**** Contraves (CH)

Total costs US$ 14.5m (1996)

Airborne Prism Experiment (APEX)
APEX Timeline

OSU = Optical Sub-Unit
TRR = Test Readiness Review
MIP = Mechanical Interface Plate
CDR = Critical Design Review
ATP = Acceptance To Proceed
AR = Acceptance Review
PM = Progress Meeting
APEX Team during Exploitation Phase E

APEX science center

Applications Development (PAF, Algorithms ...)

APEX operations center

Request

Standard Product (Custom/Research Product)

Support

User community

Science Policy
- Foster the use of imaging spectrometer data
- Implementation of the science policy defined in the APEX science board
- Conception of the Level 2/3 product strategy
- Call for experiments, workshops

New Applications
- Development of new scientific algorithms
- Interaction with scientists

Quality Control

APEX Selected Specifications

<table>
<thead>
<tr>
<th>Observation parameter</th>
<th>Zeppelin (H&lt; 500 m)</th>
<th>DO-228 (H&lt; 5000 m)</th>
<th>HALO (H&lt; 14000 m)</th>
<th>Platform independent specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swath</td>
<td>0.25 km</td>
<td>&lt; 2.5 km</td>
<td>8 km</td>
<td>FOV = 28 deg</td>
</tr>
<tr>
<td>Ground pixel size</td>
<td>0.25 m</td>
<td>&lt; 2.5 m</td>
<td>8 m</td>
<td>IFOV = 0.028 deg</td>
</tr>
<tr>
<td>High spatial mode</td>
<td>0.4 m</td>
<td>&lt; 4 m</td>
<td>15 m</td>
<td>~ 500 bands</td>
</tr>
<tr>
<td>High spectral mode</td>
<td>0.25 km</td>
<td>&lt; 2.5 km</td>
<td>8 m</td>
<td>~ 300 bands</td>
</tr>
<tr>
<td>Flight line length</td>
<td>100 km</td>
<td>&lt; 250 km</td>
<td>700 km</td>
<td>~ 60 min with standard hard disk array</td>
</tr>
</tbody>
</table>
Instrument Set-up in Aircraft

APEX Instrument
with Stabilizing Platform integrated in
Environmental Thermal Control Box

Aircraft I/F

Rack

Operator
Monitor
Flight Management System

Navigation Sub System

Control and Storage Unit

Power Distribution Unit

Opto/Mechanical Unit
(spectrometer hermetic sealed) with IFC*

Optical Baseplate
(actively cooled)

Connectors

Baffle

QTH-Lamp, stabilized

* In-Flight/on-board Characterisation facility
**VNIR and SWIR - Detector Technology**

**CCD 55-30 from E2V Technologies (GB)**
- Frame transfer mode,
- 1252 x 1152 pixel (used 1000 x 393)
- Pixel pitch 22.5 x 22.5 μm²,
- fill factor 100%,
- Back illuminated,
- Read out frequency 7 Mpix/s.

**HgCdTe CMOS from SOFRADIR (F)**
- hybridized on multiplexer,
- 1000 x 256 square pixel, 30 micron,
- addressable readout, fast operation,
- Integrated in cryostat cooler assembly,
- wavelength range: 0.94 – 2.50 micron,
- QE: > 70 % average, T_{op}: 150 K.

*under ESA-EOP contract

**APEX Electronic: Data Streams Overview**

- POS/AV: 200 kbps (Ethernet), 10 kbps (Serial)
- Hard Disk: Max. 40 Mpbs (SCSI)
- Hard Disk Array: > 60 Mpbs (SCSI)
- Tape Drive
- FMS: 65 Mpbs (Optical), 20 Kbps (G9422)
- OSU: 78 Kbps (Ethernet)
- CSU
- GUI
Calibration Home Base (CHB)

Optical bench (granite)

APEX-instrument

Rotary stage with folding mirror, mounted on linear stage

Mirror-Collimators for spectral and spatial calibration

Optical bench (granite)

1.6 m Integrating Sphere

Collimator

Monochromator

* Under ESA-EOP Contract
Status: Acceptance review successfully in Jan 2007
Conclusions

- APEX Instrument is in the manufacturing phase,
- PAF version 0.6 will be released in Dec-2007,
- Calibration Home Base CHB:
  - Acceptance review was in Jan 2007
- current activities:
  - Establishment of the APEX Science Center (2006-2011)
  - Preparation of the HALO “Earth Observation” Demo-Mission
  - EU-FP6 Project HYPER-I-NET
  - EU-FP6 Project HYRESSA
  - Support activity for ENMAP, TRAQ and other EO missions.

First data for the scientific user community shall be available in 2009!
<table>
<thead>
<tr>
<th>Status</th>
<th>Project name</th>
<th>Founding Source</th>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>ongoing</td>
<td>HYPER-I-NET</td>
<td>EU FP-6</td>
<td>Marie-Curie Hyperspectral Networking Programme (15 partners)</td>
</tr>
<tr>
<td>ongoing</td>
<td>HYRESSA</td>
<td>EU FP-6</td>
<td>Infrastructure for hyperspectral research in Europe (10 partners)</td>
</tr>
<tr>
<td>ongoing</td>
<td>GCOM-C-sim</td>
<td>JSPS/JAXA</td>
<td>Simulation and Calibration of GCOM-C</td>
</tr>
<tr>
<td>applied</td>
<td>SCALA</td>
<td>DFG</td>
<td>HALO Earth Observation Programme</td>
</tr>
<tr>
<td>ongoing</td>
<td>Algorithm Development</td>
<td>SNSF</td>
<td>Science Applications</td>
</tr>
<tr>
<td>ongoing</td>
<td>Spectral Signatures</td>
<td>armasuisse</td>
<td>Special Applications</td>
</tr>
</tbody>
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