EO1 Onboard Cloud Cover Detection Validation Preliminary Report

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Agenda

- Introduction – Dan Mandl & Jerry Miller
- Requirements – Dan Mandl
- Development Effort – Bruce Trout
- Cloud Assessment Procedure – Michael Griffin
- Conclusion – Jerry Miller & Dan Mandl
Intro: Cloud Cover Assessment Concept

- **Rationale:** On board cloud assessment has the potential to considerably reduce the resources on downlink for unwanted scenes.

- **Concept:** Flight validate an onboard cloud cover detection algorithm and determine the performance that is achieved on the Mongoose V

- **Approach:**
  - Formulate and test a cloud cover determination algorithm that is compatible with Hyperion sensor measurements
  - Using MIT / LL provided algorithm, implement and test code to execute on EO-1 platform
  - Uplink and execute code updates onboard EO-1, and evaluate its performance on orbit

- **TRL In = 5**
- **TRL Out = 6**
Intro: Initial Results

- Final onboard cloud cover assessment of an EO-1 8 second (.75 Gbyte) Hyperion scene was expected to take hours but instead took less than 30 minutes

- Streamlined algorithm by:
  - Performing level 0 on all data and then selecting the needed 6 bands
  - Converted level 0 data to radiance (level 1R) one scan line (256 pixels) at a time
  - Performed pixel by pixel cloud assessment

- Can perform onboard cloud assessment faster with the following capabilities:
  - Subsampling of raw data (can get close to same results without processing all data)
  - User defined area of interest within image and only process that portion
  - Direct access to science recorder
  - Cloud assessment algorithm can be expanded since we had more margin than expected

- For 20 test cases on ground, performed cloud assessment within 5% for major test cases
# Intro: Comparison of ESTO On-board Cloud Cover Studies

<table>
<thead>
<tr>
<th></th>
<th>1999</th>
<th>2002/2003</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test type</strong></td>
<td>Simulation</td>
<td>On-orbit</td>
</tr>
<tr>
<td><strong>Instrument</strong></td>
<td>NOAA14 AVHRR multispectral</td>
<td>EO-1 Hyperion hyperspectral</td>
</tr>
<tr>
<td><strong>Bands</strong></td>
<td>.58-.68-.725-1.10-3.55-3.93-10.3-11.3-11.5-12.5</td>
<td>.55-.66-.86-1.25-1.38-1.65</td>
</tr>
<tr>
<td><strong>Processing scenario</strong></td>
<td>Real time</td>
<td>About 1 orbit</td>
</tr>
<tr>
<td><strong>Processor</strong></td>
<td>Commercial Power PC 750, 233 Mhz, 450 MIPS</td>
<td>Rad hard Mongoose V, 12 Mhz, 6-7 MIPS</td>
</tr>
<tr>
<td><strong>Operating System</strong></td>
<td>Linux</td>
<td>VxWorks</td>
</tr>
<tr>
<td><strong>Software Preprocessing</strong></td>
<td>Albedo, radiance and brightness test</td>
<td>Raw data &gt;&gt; L0 &gt;&gt; Level 1b &gt;&gt; reflectance</td>
</tr>
<tr>
<td><strong>Tetsed algorithms</strong></td>
<td>Land, sea, day, night, clouds, ice, snow, sand, sun glint</td>
<td>Differentiate clouds from ice, snow, sand and water</td>
</tr>
</tbody>
</table>
Intro: Spacecraft

- **Two primary Science Instruments**
  - **Advanced Land Imager**
    - 10m resolution
    - Visible imager
    - Questionable if can access data onboard due to onboard format
  - **Hyperion**
    - 30m resolution
    - Hyper spectral imager (220 bands)
    - Data access onboard for cloud detection
  - **Orbit**
    - 705 km Altitude
    - ~15 day Repeat track
    - 98.7 degree inclination
Intro: EO-1 Extended Mission Testbed Activities

**Onboard Processing**

1. **Onboard Cloud Cover Detection Validation**
   - $180K
   - Funded by ESTO

2. **Preliminary EO-1 Autonomy Experiment**
   - Onboard planning
   - Onboard feature detection
   - Dynamic SW Bus
   - $720K
   - Funded by NMP

3. **Dynamic Resource Management**
   - Autonomous scheduling of Ground Station by satellite
   - AIST ESTO NRA Proposal

4. **Intelligent Distributed Spacecraft Technology Testbed**
   - EO-1 image
   - Related activity by NASA JPL

5. **EO-1, Terra, Aqua Sensorweb Demo**
   - Uses MODIS inst center to detect volcanoes
   - Uses ASE to coord image collect autonomously
   - AIST ESTO NRA Proposal

6. **Smart Antenna**
   - Ground phased array
   - Cell tower com to sat
   - AIST ESTO NRA Proposal

**End-to-End Communications**

**Autonomous Coordination**

**Operational Testbed**

**Hyperspectral Compression WG**
- Onboard data mining
- Onboard intelligent image compression
- Working group

**Note:** Numbered boxes are detailed in following slides.
Calculate cloud score onboard (L0, L1 + cloud alg)

If Score < N

Yes

No

Downlink as planned to 1st GS

Screen for clouds onboard

Take Image

Replan alternate image onboard and reschedule S/C activities to accomplish new image

Message GS to cancel old downlink and schedule new contact & receive confirmation

Intro: EO-1 Onboard Cloud Cover Detection With Onboard Replanning

1. Funded by ESTO

2. Funded by NMP

3. Proposed to AIST ESTO NRA

Funded by ESTO

Proposed to AIST

ESTO NRA

Funded by NMP

If Score < N

No

Yes

Take Image

Screen for clouds onboard

Downlink as planned to 1st GS

Replan alternate image onboard and reschedule S/C activities to accomplish new image

Message GS to cancel old downlink and schedule new contact & receive confirmation

Funded by NMP
### Intro: Related Ongoing Feature Detection Efforts

#### Autonomous Change Detection
- **Ice formation/retreat, flooding**
- **Atmospheric Change**
- **Volcanic processes (Lava, mud, plume)**

#### Autonomous Feature Identification
- **Volcanic cinder cones and craters**
- **Impact craters**
- **Sand dunes**

#### Autonomous Discovery
- **Identify features which differ from the background**

- Downlink science products: science events, features - not raw data
- Achieves 2x-100’s x data reduction!
Cloud Cover Assessment Top Level Requirements

- Implement, test, and upload WARP flight software update to perform cloud cover processing on Hyperion SWIR / VNIR image files as requested
- Extract pixel read out values from these files for bands designated for cloud cover assessment use. (Includes both SWIR / VNIR bands)
- Perform radiometric calibration to Level
- Perform cloud cover assessment and telemeter results to the ground
- Provide mechanisms to control cloud cover processing and provide reporting of cloud cover processing status
Level 0 and Level 1 Processing Requirements

- Perform playback of requested SWIR / VNIR image data files stored on WARP
- Synchronize on header for 1st science data packet
- Extract each spatial pixel read out value from this packet for bands designated for cloud cover assessment use
  - VNIR bands - 0.55 (band 20), 0.66 (band 31), 0.86 (band 51)
  - SWIR bands – 1.25 (band 110), 1.38 (band 123), 1.65 (band 150)
  - Read out value extraction involves stripping 12 least significant bits of 2 byte value
- Apply level 1 calibration to each level 0 data sample
Cloud Cover Detection Requirements

- **Perform pixel by pixel testing using reflectance data to determine which pixels are cloud covered.**

- **Cloud coverage for a given pixel will be determined based on results of a series of tests as described in the MIT presentation.** Types of tests will include:
  - **Reflectance Threshold tests.** Tests reflectance value for a given spectral pixel relative to a predefined threshold.
  - **Ratio test.** Tests ratio of reflectance values for 2 different bands for a given pixel relative to a predefined threshold.
  - **Normalized Difference Snow Index (NDSI) test.** Tests differences of 2 bands divided by sum of the 2 bands relative to a predefined threshold value.
  - **Combo test.** Uses results of NDSI and Reflectance threshold tests.

- **Statistics to be provided which provide total tested and cloudy pixels, and percentage cloudy.**
Dev Effort – SW Environment

◆ Two Mongoose 5 (M5) Processors:
  – C&DH, WARP
  – 12MHz, ~6 MIPS, 256 MB RAM on each M5
◆ Both M5’s running VxWorks 5.3.1
◆ WARP M5 unused except for collection, S-band downlink events
◆ WARP M5 has access to spacecraft bus for telemetry, commanding
Dev Effort: EO-1 Data Architecture
Dev Effort: WARP Data Flow

Diagram:
- ACDS
  - S-Band RF
    - S-Band Downlink
    - S-Band Data 4 Mbps
  - MIL-STD-1773
    - CMD & TLM point-to-point interfaces

- HSI VNIR SWIR
  - RS-422 68 Mbps
  - RS-422 165 Mbps
  - 4 Ch. RS-422 ~ 500 Mbps

- ALI MS/PAN
  - RS-422 102 Mbps

- AC
  - RS-422 192 Mbps

- WARP
  - X-Band Downlink
  - X-Band Data 105 Mbps

- MIL-STD-1773 (to/from ACDS)

- Reset (from ACDS)
Dev Effort: WARP Block Diagram
Dev Effort: Existing WARP FSW Architecture

Software Bus (SB)

VxWorks / Tornado (OS)

- Memory Scrub Task (MS)
- Health & Safety Task (HS)
- MSSP I/F Task (MP)
- PM I/F Task (PM)
- Memory Dwell Task (MD)
- Checksum Task (CS)
- Software Manager Task (SM)

- 1773 RT Task (RT)
- MSSP Driver
- PM Driver

- Recorder Management Task (RM)

- Interrupt-Driven Device Driver
- Newly Developed Task for EO-1 WARP
- Re-Used Task from MIDEX/MAP
Dev Effort: Cloud Cover Patch Concept

- Will run as part of memory dwell, when not dwelling MD currently does nothing except wait for messages on the software bus.
- Memory Dwell is lowest priority task except idle.
- S-Band playback control flow messages will be re-routed to and from the MP task to the MD task by patching the software bus routing tables.
- CC Code will run whenever data ready message is sent from RM.
- MD will utilize all spare CPU in system.
- Health and safety CPU hogging check will be patched out with NOPs.
Dev Effort: Cloud Cover Detection Software Memory Usage

- **Cloud cover SW patches fit between tasks (Gaps ~100kBytes)**

<table>
<thead>
<tr>
<th>Data Value</th>
<th>Data Type</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warp File IDs</td>
<td>ground uplink</td>
<td>8 bytes</td>
</tr>
<tr>
<td>Solar Zenith Angle &amp; Julian Day</td>
<td>ground uplink</td>
<td>24 bytes</td>
</tr>
<tr>
<td>Dark Noise Offset values (6 bands * 256 pixels * 2 bytes)</td>
<td>calculated</td>
<td>~3 Kbytes</td>
</tr>
<tr>
<td>Calibration factors (6 bands * 256 pixels)</td>
<td>stored</td>
<td>~6 Kbytes</td>
</tr>
<tr>
<td>Solar flux values (6 bands)</td>
<td>stored</td>
<td>24 bytes</td>
</tr>
<tr>
<td>S-Band data local buffer</td>
<td>recorded data</td>
<td>~929k (existing buffer)</td>
</tr>
<tr>
<td>Image level 0 data</td>
<td>generated</td>
<td>8 Mbytes (for 12s image)</td>
</tr>
<tr>
<td>Cloud Cover Test Thresholds (&lt;10)</td>
<td>stored</td>
<td>40 bytes</td>
</tr>
<tr>
<td>Cloud Cover Statistics and Telemetry</td>
<td>generated</td>
<td>&lt; 1k bytes</td>
</tr>
</tbody>
</table>
Dev Effort: SW Test Approach

- **Algorithms were integrated and tested first on a PC based simulation system using files for input test data - 9/02**

- **Patch test – 8/02**
  - *Prove that we can patch the WARP Mongoose V without a full fidelity test bed*
  - *Patched No-op*

- **Level 0 bandstripping test – 11/02, 12/02 and 1/03**
  - *Test of full kernel load needed for later loading of CASPER*
  - *Test capture of playback data from WARP to Mongoose*
  - *Test level 0 bandstripping of data*

- **Level 1 and onboard cloud assessment 3/10/03**
  - *Test conversion to level 1*
  - *Test cloud algorithm*
  - *Measure performance*
Dev Effort: Development Challenges

◆ **WARP test bed limitations**
  
  – **WARP Wide Band Recorder and associated interfaces do not exist**
  
  – **WARP M5 Available Memory limited to 32 Mbytes versus the onboard memory which has 256 Mbytes**

◆ **Revised load process and checksum process**
Cloud Cover Estimation Procedure

From calibrated Hyperion radiance data, convert to top-of-atmosphere (TOA) reflectance and estimate on a pixel-by-pixel basis the extent of cloud cover in a scene.

1. Convert radiance data to TOA reflectance

   Use pre-computed band solar flux values, earth-sun distance ratio, and the solar zenith angle

2. Process each frame (or line) of data

   Determine which pixels are cloud-covered
   Distinguish land, water, snow or ice from clouds

3. Produce cloud cover statistics for the scene
1. Radiance to TOA Reflectance - Procedure -

◆ Obtain calibrated level 1B radiance data
  – Large part of cloud cover effort is focused on this task
  – 1 frame (256 samples by 6 bands) at a time

◆ Obtain from telemetry or other means for the Hyperion scene
  – Earth-sun distance ratio \( d_{e-s} \)
  – Cosine of the solar zenith angle \( \mu_0 \)
  – Band Solar Flux values \( S_{0,i} \)

◆ For each band \( i \) use the following formula to convert the calibrated Hyperion radiance \( L_i \) to reflectance \( \rho_i \)

◆ Final product is one TOA reflectance value for each band at each pixel
  – \( \rho(256,6) \) for a single Hyperion frame

\[
\rho_i = \frac{\pi}{\mu_0 S_{0,i} / d_{e-s}^2} L_i
\]
2. Cloud Cover Algorithm
- Basic Tests -

- The cloud cover algorithm uses only 6 bands of Hyperion data

  - 0.56, 0.66, 0.86, 1.25, 1.38, 1.65 μm
  - 0.56 μm: used w/ 1.65 μm to compute the snow index
  - 0.66 μm: basic cloud reflectance test channel
  - 0.86 μm: used w/ 0.66 μm in NDVI-like ratio test
  - 1.25 μm: desert/sand discrimination
  - 1.38 μm: high cloud test channel
  - 1.65 μm: used w/ 0.56 μm to compute the snow index

- On-board processing limitations requires small number of bands
- Each test utilizes TOA reflectance data
- 20 Hyperion scenes of varying surface and cloud features were used to define test thresholds
Spectral Band Locations With Sample Reflectance Curves

Bands 1 2 3 4 5 6

Reflectance vs. Wavelength (μm)

- Snow
- Cloud
- Grass
- Water
Cloud Cover Detection Algorithm

6 channels used
0.56, 0.66, 0.86, 1.25, 1.38, 1.65 μm

ρ_{1.38} > ρ_{T_1}
ρ_{0.66} ≥ ρ_{T_2}
ρ_{0.66} ≥ ρ_{T_3}
DSI > T_5
T_6 > NDSI ≥ T_7

ρ_{1.38} < ρ_{T_1}
ρ_{0.66} < ρ_{T_3}
T_5 > NDSI ≥ T_6

ρ_{1.25} > ρ_{T_4}
NDSI < T_7
NDSI > T_8

ρ_{T_1} – ρ_{T_4} are reflectance thresholds
T_5 – T_8 are index thresholds

NDSI: Normalized Difference Snow Index, DSI: Desert/Sand Index
Cloud Cover Algorithm
- NIR Absorption Band Tests -

Test 1: High/mid cloud reflectance threshold
\[ \rho_{1.38 \mu m} > \sim 0.1 \]

- Only high clouds are typically observed in this channel
- Strong water vapor absorption masks most low level/surface features
- Under dry conditions, surface features such as ice and snow can be observed and mistaken for clouds
- Further vegetation and snow/ice discrimination tests are necessary to isolate clouds

Cheyenne, Wyoming

Cloud-free, Low/Mid cloud, Mid/High cloud

<table>
<thead>
<tr>
<th>All others</th>
<th>High/Mid Clouds</th>
</tr>
</thead>
<tbody>
<tr>
<td>No (N)</td>
<td>Yes (Y)</td>
</tr>
</tbody>
</table>

To Test 2
2. Cloud Cover Algorithm
- Visible Reflectance Test -

Test 2: Red channel reflectance threshold

\[ \rho_{0.66 \mu m} > \sim 0.3 \]

- Assumes low reflectance of most vegetation, soil and water surfaces in the red region of the spectrum
- Snow, Ice, bright desert/sand surfaces and clouds should pass this test

![Wavelength vs. Reflectance Graph]

<table>
<thead>
<tr>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

- Cloud-free
- Low/Mid cloud

Cloud-Free

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Soil</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow / Ice</td>
<td>Desert / Sand</td>
<td>Some Vegetation</td>
</tr>
</tbody>
</table>

To Test 3

![Kokee Hawaii Image]
2. Cloud Cover Algorithm
- Visible/NIR Ratio Test -

Test 3: VIS/NIR ratio test

\[
\frac{\rho_{0.66\,\mu m}}{\rho_{0.86\,\mu m}} > \sim 0.7
\]

- Discriminates vegetative surfaces whose reflectance varies strongly from Visible to NIR
- Vegetative and soil surfaces exhibit small ratio values.
- Clouds, desert/sand, snow and ice surfaces have high ratio values.

Kokee Hawaii

Cloud-free

Low/Mid cloud

No (N) | Yes (Y)
---|---
Vegetation | Snow / Ice
Desert / Sand | Clouds

To Test 4
Test 4: Desert Sand Index (DSI)

\[ DSI = \frac{\rho_{1.25} - \rho_{1.65}}{\rho_{1.25} + \rho_{1.65}} > -0.01 \]

- Discriminates bright soil and sand surfaces whose reflectance increases slightly from 1.25 to 1.65 μm
- Clouds, snow and ice reflectance tends to decrease over this range

Cloud-free

To Test 5
Test 5: Normalized Difference Snow Index (NDSI)

\[ \text{NDSI} = \frac{\rho_{0.56\,\mu m} - \rho_{1.65\,\mu m}}{\rho_{0.56\,\mu m} + \rho_{1.65\,\mu m}} \]

- Some sparse or shadowed snow (in mountains) can pass test
- Cloud-free snow generally displays

To Test 6
Cloud Cover Algorithm
- SWIR Reflectance Tests -

**SWIR Reflectance Tests**

- **Test 6**  \[ \rho_{1.25 \mu m} > \sim 0.35 \]
- **Test 7**  \[ \rho_{1.38 \mu m} < \sim 0.1 \]
- *Eliminates most snow/ice*
- *Low/Mid clouds should pass tests*

![Reflectance Graph](image)

<table>
<thead>
<tr>
<th>Wavelength ((\mu m))</th>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.20</td>
<td>1.0</td>
</tr>
<tr>
<td>1.25</td>
<td>0.9</td>
</tr>
<tr>
<td>1.30</td>
<td>0.8</td>
</tr>
<tr>
<td>1.35</td>
<td>0.7</td>
</tr>
<tr>
<td>1.40</td>
<td>0.6</td>
</tr>
<tr>
<td>1.45</td>
<td>0.5</td>
</tr>
<tr>
<td>1.50</td>
<td>0.4</td>
</tr>
</tbody>
</table>

**Cloud-free**  
**Low/Mid cloud**

<table>
<thead>
<tr>
<th>Snow / Ice</th>
<th>Low / Mid Clouds</th>
</tr>
</thead>
<tbody>
<tr>
<td>No (N)</td>
<td>Yes (Y)</td>
</tr>
</tbody>
</table>
Cloud Cover Algorithm
- Test Case Results -

- The following slides show results from the cloud cover algorithm for a selection of Hyperion scenes
- One or two segments (1000 lines each) of the overall Hyperion scene are displayed
- Cloud cover estimates (percent of displayed scene covered by all clouds) is shown at the bottom
- Examples are meant to highlight successes and failures of algorithm

Colors
- Cloud-free
- Low/Mid cloud
- Mid/High cloud
Kokee Hawaii

Lines 1700 - 2700

Total Cloud: 41.3 %

Success – Discriminates land/cloud, land/water

Failure – Misses some darker cloud over water

Lines 3200 - 4200

Total Cloud: 6.8 %
Cheyenne Wyoming

Lines 500 - 1500

Lines 2000 - 3000

Total Cloud: 58.9 %

Total Cloud: 27.0 %

<table>
<thead>
<tr>
<th>Success</th>
<th>Snow/cloud, ice cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure</td>
<td>Difficulty with shadowed snow cover</td>
</tr>
</tbody>
</table>
Kansas City

Lines 0 - 1000

Lines 2100 - 3100

Total Cloud: 72.6 %

Total Cloud: 18.6 %

<table>
<thead>
<tr>
<th>Success</th>
<th>Bright Snow/cloud discrimination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure</td>
<td>Some snow cover flagged as cloud</td>
</tr>
</tbody>
</table>
Chiefs Island

Total Cloud: 68.9%

Lake Pontchartrain

Total Cloud: 48.6%

<table>
<thead>
<tr>
<th>Success</th>
<th>Detects Cirrus, Cumulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure</td>
<td>Cloud Cover underestimated</td>
</tr>
<tr>
<td></td>
<td>Bering Sea</td>
</tr>
<tr>
<td>----------------</td>
<td>------------</td>
</tr>
<tr>
<td>Total Cloud</td>
<td>0.7 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Success</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bright Ice, snow all flagged clear</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small amount of dark snow features</td>
</tr>
</tbody>
</table>
Suez Canal

Total Cloud: 0.3 %

Chernobyl

Total Cloud: 0.0 %

<table>
<thead>
<tr>
<th>Success</th>
<th>Bright sand, soil all flagged clear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure</td>
<td>Small amount of bright soil</td>
</tr>
</tbody>
</table>
Summary of Cloud Cover Algorithm Performance

- **Algorithm results are encouraging**
- **On-board cloud cover detection accuracy requirements are not stringent (10-15%)**
  - Only need to know if scene is clear enough for user
  - Simple algorithms with limited # of bands sufficient
- **Algorithm does a good job not classifying bright surface features (snow, ice, sand) as clouds**
- **Difficulties with dark snow and dark/shadowed features**
  - Adjustment of thresholds (e.g., geographical, seasonal) may improve results
- **Areas for future enhancements/improvements**
  - More sophisticated algorithms
  - More bands
  - More precise validation of actual cloud cover

Schedule calls for first on-board test in December 2002
Conclusion

- Discovered many methods to streamline onboard cloud assessment
- Big driver to onboard cloud assessment is precision required
  - For many applications, accuracy within a 5% is adequate thereby allowing shortcuts