The EO-1 Autonomous Sciencecraft

Steve Chien
ASE on EO-1 Example Mission Scenario

Image taken by Spacecraft
ASE on EO-1 Example Mission Scenario

Image taken by Spacecraft

Onboard Science Analysis

Event Detection

No event Detected: Delete Image

Event Detected

ASE uses state of the art Machine Learning to detect events in the presence of noise

Track a wide range of science events – floods, volcanoes, cryosphere, clouds,…

Key Insight: No need to replicate ground science analysis – just detect activity
\textit{continuous planning} - enables seamless long-duration operations and rapid replanning despite limited onboard CPU.

Onboard planning enables rapid response to detected event.

Autonomous Planning

Retarget for New Observation Goals

Downlink Image and Possibly Re-image Same Area

Feature Detected: Delete Image

Feature Detected

Goal

Goal
ASE on EO-1 Example Mission Scenario

Image taken by Spacecraft

Land Feature Detection

No feature Detected: Delete Image

Feature Detected

Downlink Image and Possibly Re-image Same Area

Event-driven execution of response image

Retarget for New Observation Goals

New Science Images

Autonomous Execution
Challenges for Autonomous Space Agents

- Limited, intermittent communications to the agent.
  - 5 x 10 minute ground contacts per day for Earth Orbiter
  - Once a week or biweekly for deep space cruise
- Limited observability.
  - Limited onboard storage, limited downlink, difficulty in instrumenting spacecraft
- Spacecraft are very complex.
  - Often one of a kind artifacts
- Limited computing power.
  - Low power onboard $\rightarrow$ spacecraft CPUs
    - 25 MIPS & 128 MB RAM typical
    - 4 MIPS & 128MB RAM available on EO-1
- High stakes.
  - EO-1 cost $>$ $100M
  - many years to replace; launch opportunity cost
ASE Flight Software Architecture

- Observation Planner
  - Overflight Times
  - CASPER Planner – response in 10s of minutes
  - SCL – response in seconds with rules, scripts
    - High level S/C State Information
    - Plans of Activities (high level)
  - EO 1 Conventional Flight Software reflexive response
    - Command Signals (very low level)
    - Sensor Telemetry
- Onboard Science
  - Observation Goals
  - Image
- Band Extraction
  - Raw Instrument Data
  - Raw Instrument Data
7 May 2004 ASE monitors Mt. Erebus

- ASE images Erebus (Night)
- ASE initiates band extraction
- ASE runs thermal classifier
- THERMAL TRIGGERED

13:40 GMT
{ } +10 min
{ } +28 min
{ } +29 min
7 May 2004 ASE monitors Mt. Erebus

ASE images Erebus (Night)

ASE initiates band extraction

ASE runs thermal classifier

THERMAL TRIGGERED

Planner selects reaction observation (Stromboli observation replaced)

Thumbnail downlinked (S-band)

13:40 GMT

} +10 min

} +28 min

} +29 min

} +20 min

15:58 GMT

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)

+ 2 hours 18 minutes
7 May 2004 ASE monitors Mt. Erebus

- ASE images Erebus Night
- ASE initiates band extraction
- ASE runs thermal classifier
- THERMAL TRIGGERED
- Planner selects reaction observation (Stromboli observation replaced)
- Thumbnail downlinked (S-band)
- ASE images Erebus again

13:40 GMT
  } +10 min
  } +28 min
  } +29 min
  } +20 min

15:58 GMT

20:10 GMT

+ 2 hours 18 minutes

+ 6 hours 30 minutes
7 May 2004 ASE monitors Mt. Erebus

- ASE images Erebus Night
- ASE initiates band extraction
- ASE runs thermal classifier
- THERMAL TRIGGERED
- Planner selects reaction observation (Stromboli observation replaced)
- Thumbnail downlinked (S-band)
- ASE images Erebus again

- ASE enabled rapid notification of volcanic event
- ASE enabled rapid re-imaging of this event
- Autonomous response as normal operations!
  - Highest leverage for deep space missions
Onboard Science Data Analysis

**Purpose**
To increase science return by determining high priority science data for downlink and identifying dynamic science events

Example criteria for determining important science data

<table>
<thead>
<tr>
<th>Change Detection</th>
<th>Feature Detection</th>
<th>Data Quality Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea ice breakup</td>
<td>Volcanic eruption</td>
<td>Cloudy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cloudy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clear</td>
</tr>
</tbody>
</table>
Detection of a Rare Major Flood on Australia’s Diamantina River using the ASE “Muddy” Floodwater Classifier

<table>
<thead>
<tr>
<th>Pre-flood Dry scene</th>
<th>Flood Advancing 20 Jan 04</th>
<th>Flood Starting to Recede 6 Feb 04</th>
<th>Flood Receding 13 Feb 04</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Jan 04</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cause of flooding: Monsoonal rain

Wavelengths used: 0.86 µm and 0.99 µm

University of Arizona
Cryosphere Classifier
Deadhorse (Prudhoe Bay), Alaska

29 Feb 04
Snow on Sea Ice

20 Jun 04
Sea Ice

27 Jun 04
Water

Wavelengths used in classifier:
0.43, 0.56, 0.66, 0.86 and 1.65 µm

Arizona State University
Planetary Geology Group
Land, Ice, Water, Snow Detection

- **Primary Purpose**
  - Identify areas of land cover (land, ice, water, snow) in a scene

- **Three algorithms:**
  - Scientist manually derived
  - Automatic best ratio
  - Support Vector Machine (SVM)

<table>
<thead>
<tr>
<th>Classifier</th>
<th>Expert Derived</th>
<th>Automated Ratio</th>
<th>SVM</th>
</tr>
</thead>
<tbody>
<tr>
<td>cloud</td>
<td>45.7%</td>
<td>43.7%</td>
<td>58.5%</td>
</tr>
<tr>
<td>ice</td>
<td>60.1%</td>
<td>34.3%</td>
<td>80.4%</td>
</tr>
<tr>
<td>land</td>
<td>93.6%</td>
<td>94.7%</td>
<td>94.0%</td>
</tr>
<tr>
<td>snow</td>
<td>63.5%</td>
<td>90.4%</td>
<td>71.6%</td>
</tr>
<tr>
<td>water</td>
<td>84.2%</td>
<td>74.3%</td>
<td>89.1%</td>
</tr>
<tr>
<td>unclassified</td>
<td>45.7%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Support Vector Machines (SVM)

- Creates classifier that separates two distinct classes
- Maps the data into a high dimensional space and finds a hyperplane that separates data from two classes
- The optimal hyperplane maximizes the margin (the distance between the hyperplane and nearest points from the two classes)
- Kernels used:
  - linear
  - Gaussian radial basis function (rbf)
  - normalized polynomial (npoly)

The turquoise lines represent the optimal hyperplane and its corresponding margin for these data. White lines are non-optimal hyperplanes.
Automated Mission Planning
Onboard Replanning

Goals:
- science requests
- downlink requests
- maneuver requests

Constraints:
- memory
- power

Activity Plan:

2003:233:16:49:57 CMD ACSETWHLBIAS(INERTIAL,X=0.341589,Y=1.1749,Z=-0.118046);
2003:233:17:56:57 CMD ACGOTOMANEUVER(ORBITAL,TIME=900,XLIMDEG=0.02,YLIMDEG=0.062699,…);
2003:233:18:07:06 CMD I_SETFPEPOWER(Power_MASK=5);
2003:233:18:07:06 CMD YHEASTBY;
2003:233:18:07:16 CMD YHEASETWNIR(GAINA=1,GAINB=1,GAINC=1,GIND=1,…);
2003:233:18:07:26 CMD YHEASETVNIR(VNIRALV8,VNIRBLV8,VNIRCLV8,VNIRDLV8);
2003:233:18:11:06 CMD I_CONFIGFPE(CONFIG_COMMAND=16908); …
2003:233:18:17:06 CMD BCMMODESCRS422;
2003:233:18:17:16 CMD WRMSREC(IDWS=65535,IDWV=65535,…);
2003:233:18:17:54 CMD I_SET_FPE_DG(DURATION=-1);
…
<table>
<thead>
<tr>
<th>Resources</th>
<th>uses 30 W power; uses &lt;variable&gt; memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>State Constraints</td>
<td>requires ACS state to be “Fixed Attitude”</td>
</tr>
<tr>
<td>Required Activities</td>
<td>Decompositions</td>
</tr>
<tr>
<td></td>
<td>dark calibration image before</td>
</tr>
<tr>
<td></td>
<td>dark calibration image after</td>
</tr>
</tbody>
</table>

CASPER uses these activity models to determine how activities will affect spacecraft state and resources.
### Activities, Constraints, Repairs

#### Contributors
- Act-1
- Act-2

#### Activities

- Act-1
- Act-2

#### Power Usage
- a)
- b)

---

<table>
<thead>
<tr>
<th>General Property</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constraint</strong></td>
<td>Property that must hold for plan to be valid</td>
</tr>
<tr>
<td></td>
<td>Must always use less power than available</td>
</tr>
<tr>
<td><strong>Conflict</strong></td>
<td>Violation of a constraint</td>
</tr>
<tr>
<td></td>
<td>Current plan uses more power than available over (b)</td>
</tr>
<tr>
<td><strong>Repair Method</strong></td>
<td>Modification to plan that may remove conflict</td>
</tr>
<tr>
<td></td>
<td>Delete activity using power during conflict (b)</td>
</tr>
<tr>
<td><strong>Repair Choice</strong></td>
<td>Which activity to delete</td>
</tr>
<tr>
<td></td>
<td>Delete largest user?</td>
</tr>
</tbody>
</table>
Repair Algorithm

Start
(if conflicts exist and user time-limit not exceeded)

Select a conflict
... 
Select a repair method
move
Select an activity
... 
Select a start time
... 
Perform the action, collect the new conflicts, and repeat
Portfolio of Stochastic Portfolios of Heuristics

Strategy Selection

One Strategy

Choice points:
- Which conflict should I repair? (conflict_i)
- How should I repair conflict ci? (action_i)
- Which activity should I add? (activity_i)
- Where should its new start time be? (Start_time_i)

Strategy:
- 95
- 5
- 50
- 50
- 5
- 5
- 90
- 40
- 60
- 30
- 30
- 40

Heuristics:
- conflict_i
- action_i
- activity_i
- Start_time_i
Warp mode

HypState

Night collect

Day collect

Downlink

Hyperion Preparation

Target in view

X-band Ground Station

SSR file count

SSR data volume
Onboard Replanning

- CASPER uses continuous planning techniques to improve response time
Continuous Planning on EO-1

- Deleted Past Activities
  - Lake Michigan
  - Increased detail

- Near-term detailed planning window
  - Current time

- Long-term abstract planning window
  - Current time + 6 hours
  - Dallas Overlap
  - Winnibigoshish Leech Lakes
  - Abstract science goal

- Rio Grande

Activities:
- Increased detail

Locations:
- Lake Michigan
- Rio Grande
- Winnibigoshish Leech Lakes
Impact of Continuous Planning on EO-1

• 1 week EO-1 ops = ~100 science observations
  + 50 S-Band/X-Band contacts
  = 7800 activities*
  = ~224 MB Heap Space

• CASPER is limited to a 32 MB of heap space

• ASE performs detailed planning ~6 hours in advance
  = ~16MB Heap Space

* - just for observations, not including the downlink and momentum management activities
ASE Windows

- Delete Activities (f=90m)
- Commit Activities (f=5s)
- Repair Conflicts (f=5s)
- Save Activities (f=20m)
- Filter Goals (f=0)
- Satisfy Goals (f=2m)
- Re-Satisfy Goals (f=10m)
- Filter Updates

Timeline:
- 10m a b 10m
- 10m Filter Updates

Goal:
- 10m
- 1m Filter deletePastActivities
EO-1 Scene Prioritization

- Scenes carry priority of 0-999 (including onboard reactions)
- Lower priority # = higher priority
- Implemented by search heuristics
  - Heuristics prefer deletions of lower priority scenes
- Conscious decision to not use CASPER optimization capability [Rabideau et al. 2000]
  - Not core ASPEN
  - Difficulty in using with CASPER (windows)
Modeling File System

- Can model directly using Generalized Timelines (GTL)
- Decision to NOT fly GTL based on risk (only core ASPEN)
- Work-around model via single state requiring processing of last image or exception activity link

- Image Reventador
- File of Raw Hyp Data on WARP
- RAM Buffer
- Classification Result/trigger
- Debug Classification Image
- Image Rio Tacquari
- Science Process Reventador
- Band Strip Reventador
- Potential Downlink and WARP Format
CASPER RAM Reduction

- Original size
- Remove unused modules
- Remove code inefficiencies
- Compiler optimization
- Final size after compression

Graph showing RAM reduction with bar heights indicating the size in MB.
## ASE Validation

<table>
<thead>
<tr>
<th></th>
<th>Instruments overheat from being left on too long</th>
<th>Instruments exposed to sun</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operations</strong></td>
<td>For each turn on command, look for the following turn off command. Verify that they are within the maximum separation.</td>
<td>Verify orientation of spacecraft during periods when instrument covers are open.</td>
</tr>
<tr>
<td><strong>CASPER</strong></td>
<td>High-level activity decomposes into turn on and turn off activities that are with the maximum separation.</td>
<td>Maneuvers must be planned at times when the covers are closed (otherwise, instruments are pointing at the earth)</td>
</tr>
<tr>
<td><strong>SCL</strong></td>
<td>Rules monitor the “on” time and issue a turn off command if left on too long.</td>
<td>Constraints prevent maneuver scripts from executing if covers are open.</td>
</tr>
<tr>
<td><strong>FSS</strong></td>
<td>Fault protection software will shut down the instrument if left on too long.</td>
<td>Fault protection will safe the spacecraft if covers are open and pointing near the sun.</td>
</tr>
</tbody>
</table>
ASE Current Status

• Current count > 2400+ autonomous data collects; 1st flights in Fall 2003

• ASE Software so successful it is now in use as baseline operations for the remainder of the mission.
  • Enabled > 100x increase in science return
    • Measured as: # events captured / MB downlink
  • Enabled a reduction in net operations costs $2.5M/year → $1.0M/yr

• ASE/EO-1 Operations expected to continue through at least December 2005
Sensorweb

Triggers so far: Wildfires, Floods, Volcanoes (thermal, ash), Ice/Snow, in-situ sensors, modified by cloud cover
## Sensorweb Applications

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Source</th>
<th>Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanos</td>
<td>MODIS (Terra, Aqua)</td>
<td>MODVOLC, U Hawaii</td>
</tr>
<tr>
<td></td>
<td>GOES</td>
<td>GOESVolc</td>
</tr>
<tr>
<td></td>
<td>POES</td>
<td>AVHRR - Volcano</td>
</tr>
<tr>
<td></td>
<td>Air Force Weather Advisory</td>
<td>Volcanic Ash Alerts</td>
</tr>
<tr>
<td></td>
<td>International FAA</td>
<td>Volcanic Ash Advisories</td>
</tr>
<tr>
<td></td>
<td>Tungurahua, Reventador</td>
<td>In-situ instruments, Harvard, UNH</td>
</tr>
<tr>
<td>Hawaiian Volcano</td>
<td>Hawaiian Volcano Observatory, Erebus</td>
<td>Sensor alerts</td>
</tr>
<tr>
<td></td>
<td>Volcano Observatory, Rabaul Volcano</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Observatory, ...</td>
<td></td>
</tr>
<tr>
<td>Floods</td>
<td>QuikSCAT</td>
<td>Dartmouth Flood Observatory</td>
</tr>
<tr>
<td></td>
<td>MODIS</td>
<td>Dartmouth Flood Observatory</td>
</tr>
<tr>
<td></td>
<td>AMSR</td>
<td>Dartmouth Flood Observatory</td>
</tr>
<tr>
<td>Cryosphere</td>
<td>QuikSCAT (Nghiem)</td>
<td>Snow/Ice, JPL/Nghiem</td>
</tr>
<tr>
<td></td>
<td>Wisconsin Lake Buoys</td>
<td>UW Dept. Limnology</td>
</tr>
<tr>
<td>Forest fires</td>
<td>MODIS (Terra, Aqua)</td>
<td>RAPIDFIRE, U. MD, MODIS Rapid Response</td>
</tr>
<tr>
<td>Dust Storms</td>
<td>MODIS (Terra, Aqua)</td>
<td>Naval research Laboratory, Monterey</td>
</tr>
<tr>
<td>Clouds</td>
<td>EPOS</td>
<td>DoD</td>
</tr>
</tbody>
</table>
Wildfire Sensorweb

Utilizes MODIS Land Rapid Response Active Fire Mapping:

Wildfires

- Use MODIS active fire alerts
  - MODIS morning and afternoon daytime overflights
- Uses data from GSFC Distributed Active Archive Center (DAAC)
  ~ 3-6 hours from acquisition, uses predicted ephemeris
Wildfire Detection

- Detects hotspots using
  - absolute threshold
    - $T_4 > 360K$, $330K$ (night) or
    - $T_4 > 330K$, $315K$ (night)
    - and $T_4 - T_{11} > 25K$ ($10K$ @ night)
  - and relative threshold
    - $T_4 > \text{mean}(T_4) + 3 \text{stddev}(T_4)$
    - and $T_4 - T_{11} > \text{median}(T_4 - T_{11}) + 3 \text{stddev}(T_4 - T_{11})$

Looks for areas significantly hotter than surrounding area (requires 6 surrounding pixels cloud, water, fire free $\rightarrow 21 \times 21$)
Wildfire Science Trigger

- Trigger uses intersection of
  - NIFC major fires
  - Rapidfire active fires detection
  - User-defined area of interest
- Science Goal Monitor (Jones et al., GSFC)
  - Computes largest weight (activity) centroid of hotspots in the above intersection
Status – Wildfire Sensor Web

• Preliminary demonstrations
  – Robert Fire, August 2003, Montana
  – Simi/Val Verde Fire, October 2003, Southern CA
  – Old Fire, October 2003, Southern CA
• Currently working on incorporating cloud cover data into tasking
• Impact:
  – More high resolution data for use in rehabilitation
MODIS Rapid Response
Active Fire Detections

Robert Fire Demonstration
August 2003

EO-1 Advanced Land Imager
Burn Scar Image

POC: C. Justice, R. Sohlberg et al.
On 11-2-03, the NASA Wildfire SensorWeb was employed to collect data on the burn scars resulting from the Simi Valley, Val Verde and Piru fires in Southern California. MODIS active fire detections for the duration of the event were used to target an acquisition by the ALI and Hyperion instruments onboard EO-1. Such data are employed by the USDA Forest Service for Burned Area Emergency Rehabilitation mapping. BAER maps are used to target high risk areas for erosion control treatments. In this image, burned areas appear red while the unburned areas appear green. The blue burn perimeter vector is based on ground data.

POC:
C. Justice,
R. Sohlberg et al.
Flood Sensorweb

Uses Dartmouth Flood Observatory QUIKScat Global Flood Atlas:
Floods

- Leverage Dartmouth Flood Observatory global flood atlas activities
- Identify floods in remote locations automatically based on satellite data
- MODIS, QuikSCAT, AMSR-E possible
  - QuikSCAT used to avoid cloud issues - more amenable to automation
- Active flooding triggers EO-1 observations at gauging reaches
Dartmouth-Flood Observatory QuikSCAT

- The DFO in collaboration with JPL/QuikSCAT processes QuikSCAT Scatterometer data to assess surface water conditions.
- VV/HH ratio is used to assess surface water properties of the areas in 0.25 lat/lon degree bins.
- The 7 day running mean is used to dampen effects of short-duration rainfall over urban areas.
- This data is then compared to the seasonal (90 day) average of the previous year to screen out wetlands.

POC:
Brakenridge/DFO
Ngiem/JPL
Sample Detections - China

- Blue and Yellow indicate increased and decreased surface water extent compared to September-October, 2002.

POC:
Brakenridge/DFO
Ngiem/JPL
Flood alerts are then used to retask EO-1.

**EO-1 Hyperion Image Brahmaputra Aug 6, 2003**

**MODIS Image Brahmaputra, India Aug 6, 2003**

250M resolution  
(10M ALI Pan band possible)  
30M resolution
Impact

Higher resolution data is acquired of:

• **key locations** (pre-determined satellite gauging reaches) and
• **times** (active flooding regions)

With the end result of improved flood science.
And the Future…

- Use timely event detection and knowledge of topography to track event progression

proposed 4-week imaging campaign for the lower Zambesi river in Mozambique
Volcano Sensorweb

Uses University of Hawaii, Hawaii Institute for Geophysics & Planetology detectors:

Ongoing Extensions
Dust Storms

- Large scale dust storms detectable in MODIS imagery
- Working with Naval Research Laboratory Monterey to utilize their MODIS & GOES-based systems to track large-scale dust storms
- EO-1 triggered to image dust storms
- Great Mars analogue

POC: S. Miller, NRL Monterey.

Ice Breakup

Larsen Ice Shelf, Antarctica
– analogue to Europa – Ice breakup triggers imaging

Eighteen (18) of MODIS imagery  Dec 17, 2001- Jan 4, 2002
Courtesy MODIS Land Rapid Response Jacques Descloitres, GSFC.
In-situ Instrumentation

- Sometimes available to trigger or corroborate remote sensing detection
- Currently investigating use of such instruments for
  - Volcanoes – Kilauea, HI; Etna, Italy
  - Flooding – Avra Valley, AZ
  - Dust Storms – Soda Lake, CA; Jornada, NM
  - Lake Freeze/thaw – Sparkling Lake & Trout Lake, WI
HVO instrumentation: tiltmeter net

Kilauea Caldera
April 5, 2002 event

24 hrs from trigger to surface eruption:
New flows detectable by EO-1 on order of days

Events on this scale occur ~ every 6 months. No false positives so far. The next event? ~Oct 2003-Jan 2004.

POC: P. Cervelli/HVO

Photograph by J. Kauahikaua
Lake Buoys

U. Wisconsin Center for Limnology

**Sparkling Lake Buoy:** vertical temperature, surface meteorological data

**Gas Flux (Metabolism) Buoys:** dissolved oxygen, dissolved carbon dioxide, temperature and conductivity, surface meteorological data

**Trout Lake Buoy:** vertical profiling buoy, dissolved oxygen, temperature, conductivity, chlorophyll, light, transmissivity, pH, and total dissolved gas, coupled with meteorological data from the surface.

- Using in-situ buoys detection of lake freezing to trigger remote observations

Analogue to:
Martian Ice Cap tracking, Europa Ice Cap Tracking.

POC: Hanson et al. / UW-Madison

Images courtesy UW Center for Limnology
Sensorwebs: The Future

• Sensorweb triggers all “static architecture” (e.g. pre-defined trigger, response)

• The future:

• Agents “discover” each other and dynamically team to provide science products on demand!
Future Applications
Mars Polar Volatiles - Odyssey

- Develop means for automatically tracking CO₂ ice cap formation and retreat onboard Odyssey using THEMIS;

- THEMIS PI (Christensen) requested onboard science capabilities for ODY 2nd extended mission: dust storms, clouds, thermal anomalies, polar volatiles

K. Wagstaff, R. Castano
Martian Aeolian Features

Wind Streaks and Dune Caps

Dark Slope Streaks
Dust Devil tracks in THEMIS/Odyssey Imagery

Dust Devil as captured by Pathfinder
Mars Exploration Rovers

• ASE technology software is being infused into the Mars Exploration Rovers Mission to detect and summarize imagery containing clouds and dust devils
  – Planned upload in January 2006

Clouds

Dust Devils
Spirit Navcam –
Sol 433 (March 21, 2005)

S. Chien, R. Castano
Martian Dust Storms

Detection using low res instruments (TES)

Image edges or formation using high res or complementary instruments?

Similar effort being performed using MODIS and EO-1 Hyperion in collaboration with Naval Research Laboratory - Monterey

Martian Dust Storm Activity

OCT 01, 2001

Thermal Emission Spectrometer

Courtesy TES team, ASU
Tracking Magnetospheric Events

Aurora as seen by IMAGE FUV instrument
Space Weather

Sun-pointed instruments detect solar activity such as Coronal Mass Ejection (CME)

Earth orbiting Magnetospheric Observers automatically respond by reconfiguring to acquire best data
Change Detection on Io

- Global, regional, and local change takes place on Io: scales range from 1000 km to < 10 m
- FID: No craters yet seen; plumes, deposits, IR signatures on inbound allow fast retargeting
- Change detection in IR as well as visible

Changes at Pele and Pillan, 1997-1999 (visible)

Emplacement of lava flows, Prometheus, 1999-2000
Change Detection on Io - 2

1. G7 April 1997 Galileo SSI
2. C10 September 1997
3. C21 July 1999

Changes 1-2
Changes 2-3
Changes 1-3
Feature Identification: Plume detection

Change detection also works in the infrared (4.8 microns)
Tracking Jovian Atmospheric Features
Tracking Jovian Lightning
Tracking Europan Surface Changes

- Extract and track segmentation of boundaries
- Extract and track region boundaries
- Use to identify areas of change
- Use to determine science priority or compress
Titan Aerobot
Europa Cryobot - A Motivating Example
Unknowns and Impact on Operations – Europa Cryobot

- Thickness and composition of ice-cap
  - energy expended to penetrate surface
  - data volume and type collected
  - ability to communicate while below cap (reliability, rate)
  - effectiveness of melting strategies (fast v. slow)
- Properties of underground ocean
  - energy and time cost to move/explore
  - effectiveness of sensors (reliability, range, discriminability)
  - ability to communicate
  - predictability of above
Comet Lander

Examples of Unknowns and Impact on Planning

- Hardness of surface
  - time to drill to specified depth
  - power consumption of drilling activities
- Outgassing properties of comet under solar illumination
  - affects lighting for pictures
  - may affect communications links
Mars Robotic Outpost

Adaptive, self-organizing Exploration Agents
• conduct extended (decades long) environmental and geological Martian survey

• Long-term environmental changes (general warming trend)
• Medium-term environmental changes (seasons)
• Shorter-term environmental changes (storms)
• Hardware degradation
• Communications performance
• Mobility
• Sensor effectiveness
...
Challenges for AI from Space Applications

• Research
  – What sort of agent architectures make sense?
  – How to have reliable, predictable multi-agent systems?
  – How to represent tradeoffs in decisions (decision theory?)?
  – How to interface to an embedded agent?
  – How to validate autonomous agents?
    • Given the challenges of validating current operations!
  – How to enable automated planning to change as the mission changes?

• Engineering
  – How to perform “validated” knowledge engineering
  – How to integrate complex systems better?
  – How to bring AI to embedded systems with less pain?
Conclusions

- AI for Spacecraft Autonomy technology is here and now at NASA!

- Onboard autonomy can
  - Enable returning the most important science data
  - Enable rapid response to short-lived science events

- Multiple assets can be linked with autonomy to further advantage

- Techniques apply to a wide range of sensors and event types – space, air, and ground

*AI will revolutionize future NASA Missions!*
ASE Information/Acknowledgements

- Web Site:  ase.jpl.nasa.gov
- Team:
  - Steve Chien (Principal Investigator), Rob Sherwood (Experiment Mgr)
  - JPL: Danny Tran (Software Lead), Rebecca Castano (Onboard Science Lead), Ashley Davies (Science Lead), Gregg Rabideau, Ben Cichy, Nghia Tang
  - ICS: Darrell Boyer, Jim Van Gaasbeck
  - Univ. of AZ: Victor Baker, Felipe Ip, James Dohm
  - ASU: Ronald Greeley, Thomas Doggett
  - GSFC: Dan Mandl (Mission Director), Stu Frye (Systems Engineer, Mitretek), Jerry Hengemihle, Scott Walling & Bruce Trout (Microtel), Jeff D’Agostino (Hammers), Seth Shulman (Operations Lead, CSC), Lawrence Ong (SSAI), Stephen Ungar (EO-1 Scientist), Thomas Brakke
  - MIT LL: Michael Griffin, Hsiao-hua Burke, Carolyn Upham
- ASE Sponsor:
  - New Millennium Program, ST-6 Project
- Technology Development:
  - Intelligent Systems Program
  - CETDP, Thinking Systems Thrust
  - Interplanetary Network Technology Program
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Momentum Management

• EO-1 uses reaction wheels to point spacecraft
  – Equal and opposite reaction
• EO-1 has only 3 wheels, limits on wheel speeds, means desaturation an issue
• Magnetic Torquer Bars to desaturate wheels “zero bias”
• Each observation now is dependent on prior ones through wheel momentum
• CASPER models “zero state” ness of wheels
• Ground-based automation to upload tables for wheel bias combinations for “potential scenes”