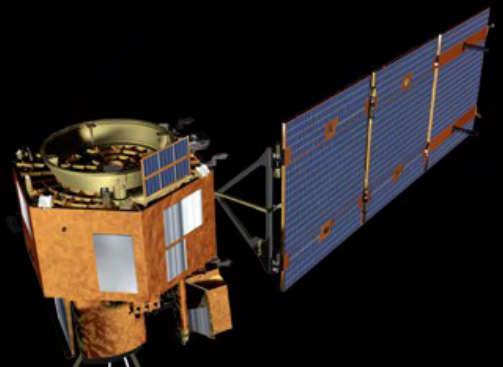


Autonomous Science on EO-1

December 5, 2003

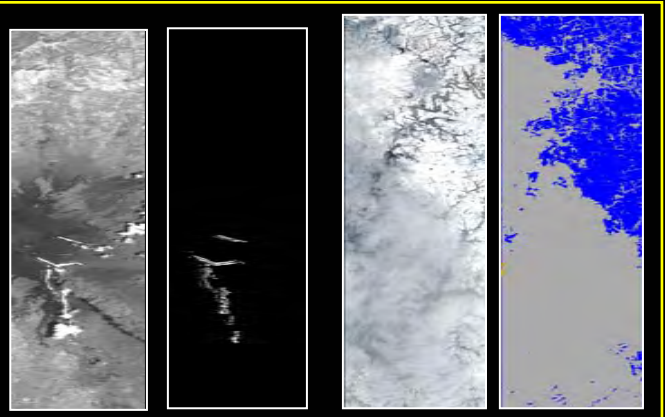
Rob Sherwood

Jet Propulsion Laboratory,
California Institute of Technology

Autonomous Sciencecraft Experiment

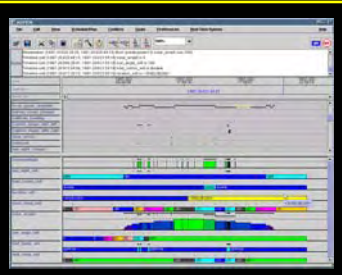
Autonomous Science

- Volcanic activity detection via spectral analysis (lava detection)
- Atmospheric feature (cloud) detection used for onboard data editing
- Feature detection via spectral analysis (land-ice-water-snow)



Autonomous Planning (CASPER)

- CASPER enables onboard development of new plans in response to science events
- CASPER generated plans respect EO1 resource and flight constraints



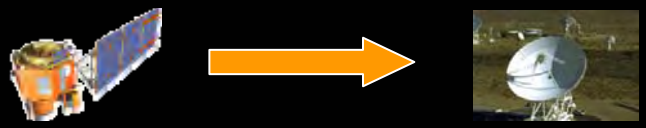
Autonomous Execution Software (Spacecraft Command Language)

- SCL expands CASPER plans into spacecraft commands
- SCL enables robust plans to deal with run-time uncertainties

ASE Scenario

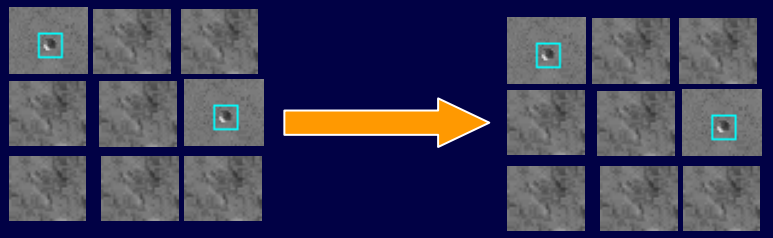
Why fly autonomy software onboard?

- To utilize limited downlink resource
- To capture dynamic science



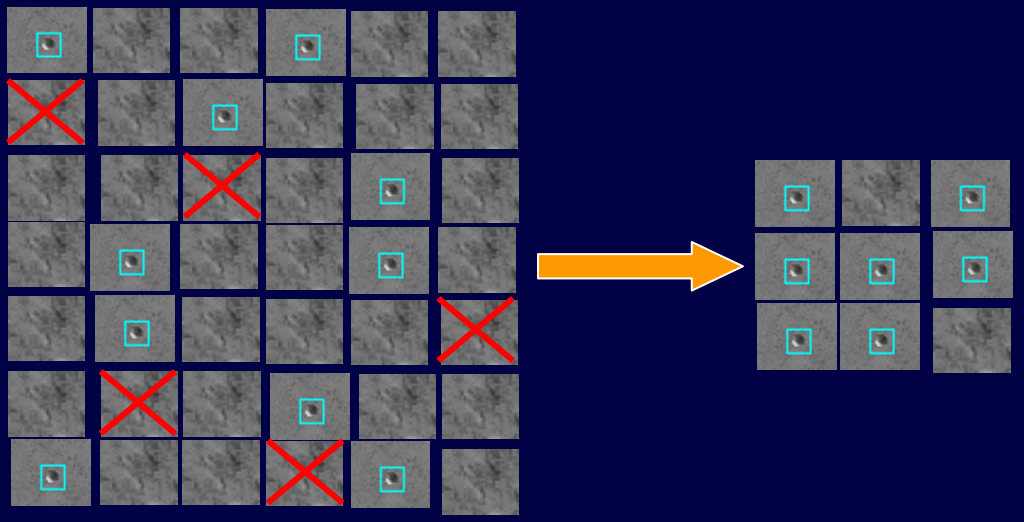
Old Way:

- Take 200 Images
- Downlink 200 images



New Way:

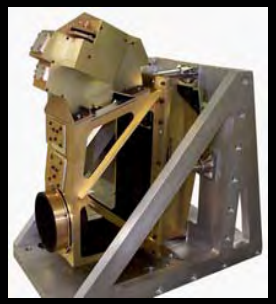
- Take 2000 Images
- Downlink best 200 images
  - Only most scientifically interesting portions
  - Could be cloud free images



Technology Carrier: EO1 Mission

- ASE is a technology experiment
  - Part of New Millennium ST6 Project
  - Subsystem demonstration
  - Funded to flight demonstrate autonomy software technology for future mission adoption
  - Uses Hyperion payload (hyper-spectral, 220 bands, 30 m resolution)

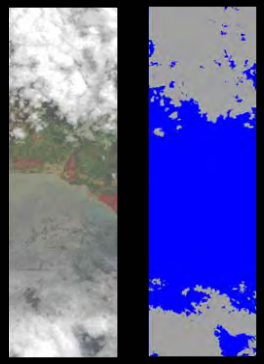
- CDS: Two Mongoose V CPU's
  - Mongoose V @ 8 MIPS and 256 MB RAM
  - Flight control software on CDH CPU
  - Autonomy software on WARP CPU
    Wideband Advanced Recorder and Processor



ASE on EO1 Mission Scenario

Autonomous Science

Cloud Detection



Clouds Sparse

Downlink Image

Extensive Cloud Cover

Autonomous Planning

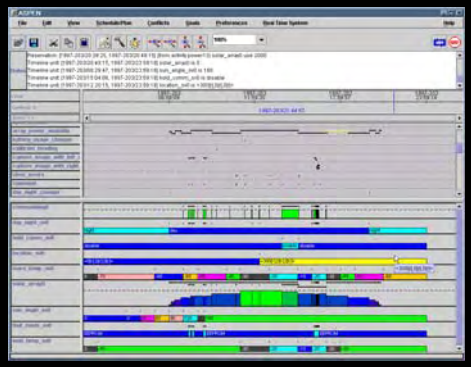
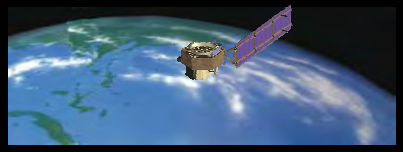
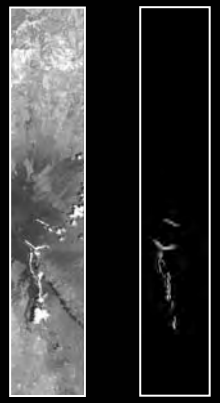


Image taken by Spacecraft (hyperion) & appropriate bands extracted



Land Feature Detection



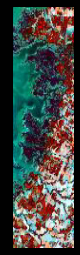
No feature Detected

Feature Detected

Downlink Image

Retarget for New Observation Goals

New Science Images



Autonomous Execution

Autonomous Science

- Utilize onboard science analysis to summarize, retarget, or rapidly respond to science events to increase science return

- Onboard Science Components
  - Cloud detection
  - Thermal anomaly detection
  - Land, Ice, Water, Snow, Vegetation Recognition
  - Change detection
  - Feature recognition software (looking for specific patterns)

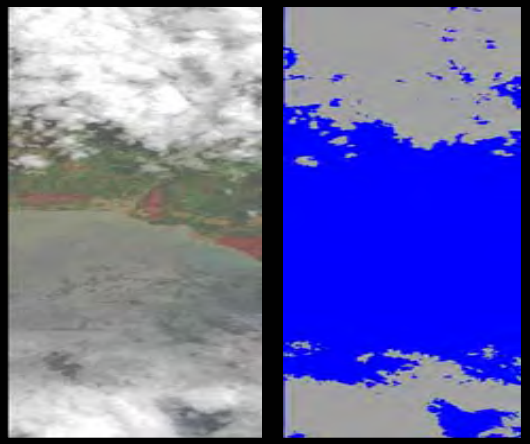
- Algorithms are valid for multiple features and processes: we are not limited to specific types of science targets

- The science analysis algorithms can be used for several imaging datasets (visible, IR, UV, radar, etc.) although we are taking advantage of the multi-spectral capabilities of Hyperion

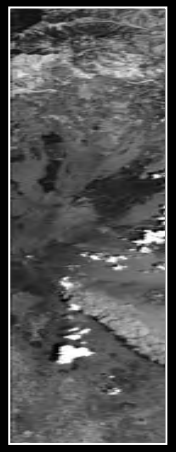
- Onboard ASE Science Classifiers utilize up to 12 bands of L0.5 Hyperion data (including 6 used by cloud detection algorithm)

Cloud Detection & Thermal Anomaly Detection

- Cloud detection
  - Developed by MIT/Lincoln Labs
  - Uses intensities at six different spectra and thresholds to identify likely clouds in scenes
  - Leverages key spectra for high accuracy with simple approach
  - Discard scenes that are mostly clouds
  - Cloud detection algorithm good analogue for Code S atmospheric feature applications (such as Mars dust storm detection)

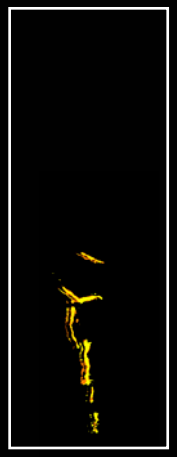


Original Image Detected Clouds



Visual Spectra

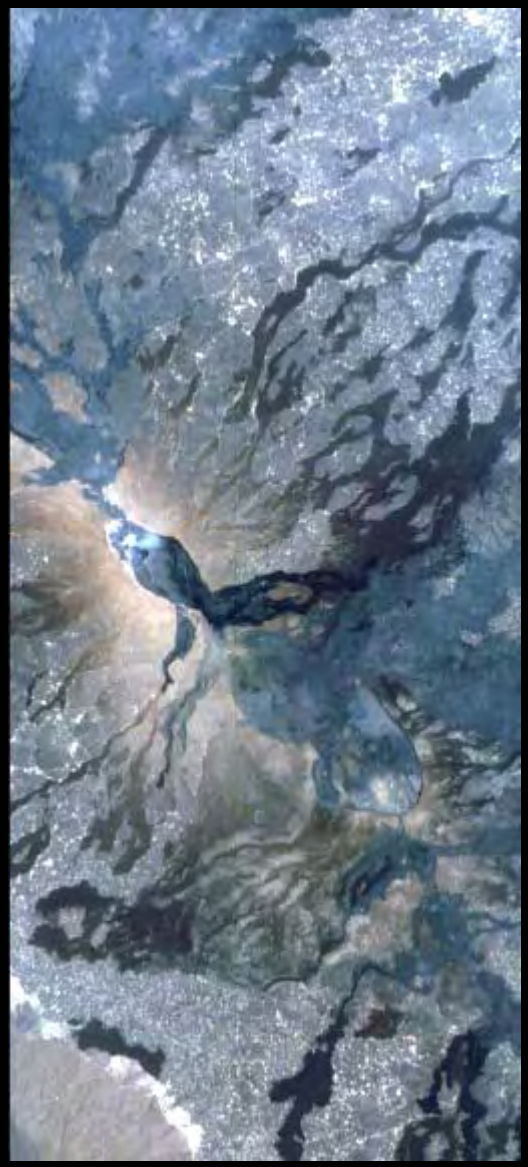
Infra-red Spectra



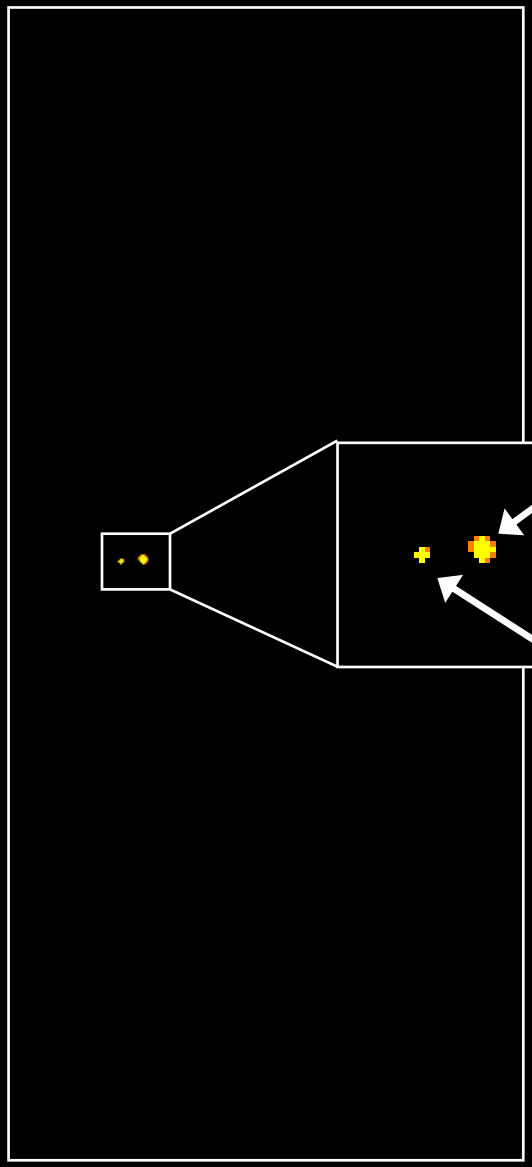
Detected Lava

- Thermal anomaly detection
  - Uses infrared spectra characteristics to detect lava flows & other volcanic activity
  - Has been tested successfully on ground using mission data
  - Good analogue for Code S thermal anomaly detectors (such as Mars Odyssey & Io missions)

Active Volcanism Detection



VIS data



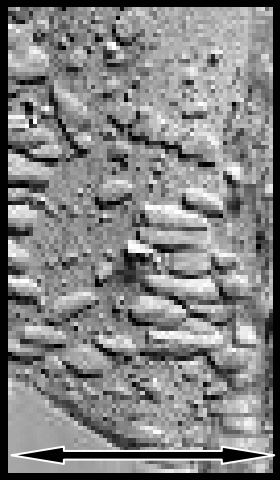
Thermal classifier output

Erta'Ale, Ethiopia
14 May 2001

Land-Ice-Water Classification

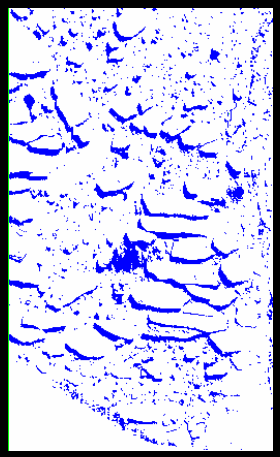
- Land-Ice-Water-Snow Detection
  - Developed at JPL
  - Uses multiple spectra to identify areas of image with land, ice, water, and snow
  - Observation process:
    - Classify pixels, count pixels of water-ice-snow-land
    - Compare with previous observation for new water or ice
    - If change is detected, trigger re-observation to monitor the rate of ice formation or break-up
    - Downlink entire new dataset

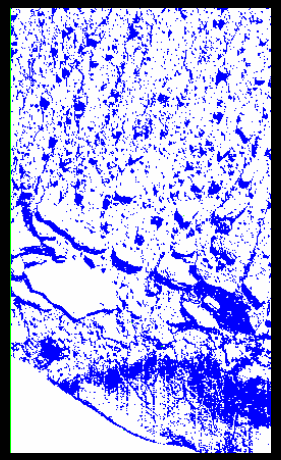
4/6/2002



7 km

4/13/2002



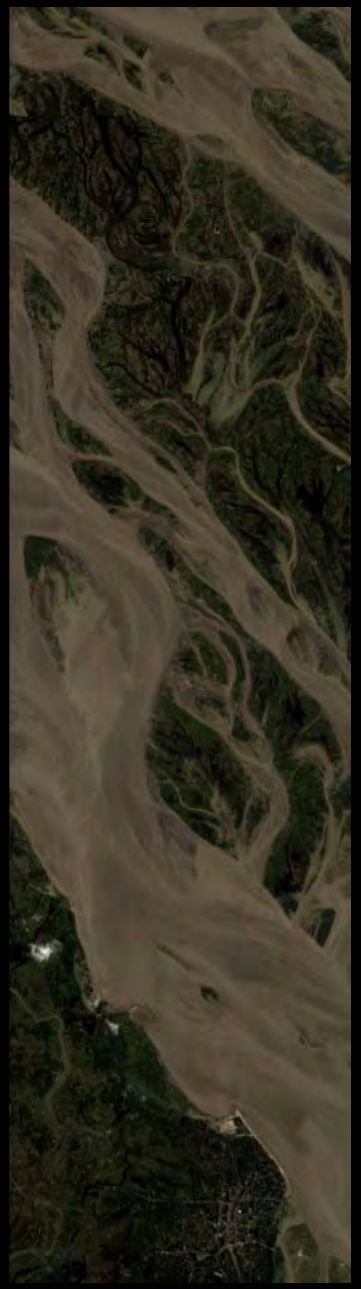


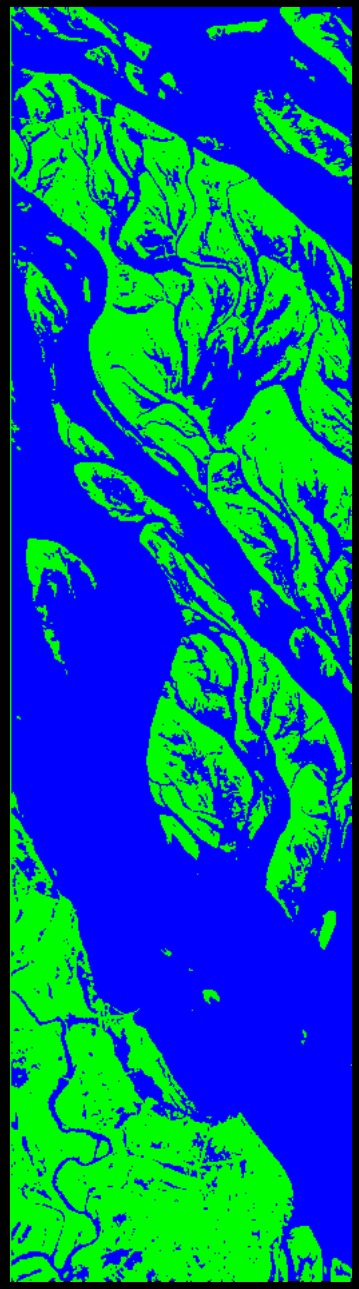
Location: Larsen Ice Shelf, Antarctica
Process: Break-up of ice shelf
Trigger: Change Detection

Classifier Output:
Water is blue, Ice is White

Flood Detection

- Flood Detection
  - To monitor regions that seasonally flood, demonstrating ASE change detection.
  - Observation process:
    - As with ice: classify observation and count water pixels as basis for comparison
    - If sufficient number of changed pixels (a large enough area of change detected), then download data and retask spacecraft to obtain more data

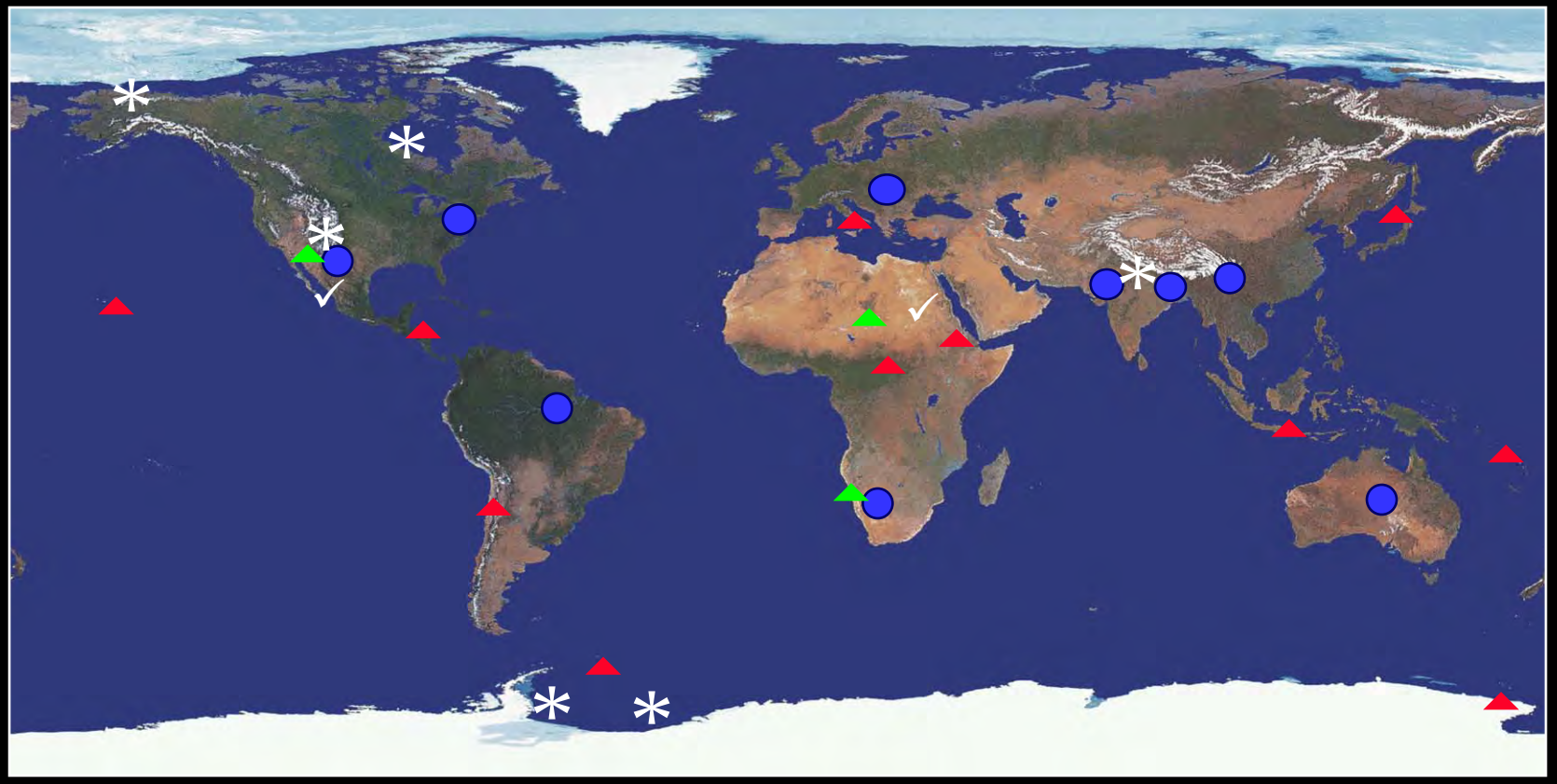




Brahmaputra River, India
Hyperion data, Aug 2003

Classifier Output:
Water is blue, Land is Green

Initial ASE Targets: 2003-2004



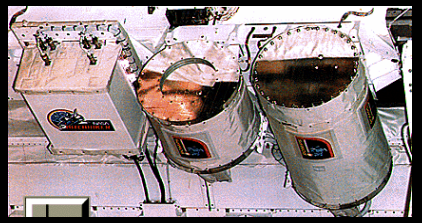
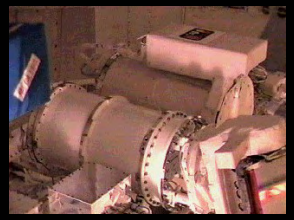
▲ = volcanoes
▲ = dunes
✓ = aeolian
✳ = ice formation/breakup
● = flooding

Autonomous Planning

- CASPER is the Continuous Activity Scheduling Planning Execution & Replanning software
- CASPER use a model of spacecraft activities to construct a mission plan to achieve mission goals while respecting spacecraft operations constraints
  - Example goals: science requests, downlink requests, maneuver requests
  - Example constraints: memory, power, propellant, etc.
- CASPER uses continuous planning techniques to achieve a quick response time
- EO1 will utilize the CASPER continuous planning system onboard to replan to achieve newly derived science goals

Autonomous Execution

- Uses Spacecraft Command Language (SCL) developed by Interface and Control Systems
- SCL integrates procedural programming with a forward-chaining, rule-based system for event-driven real-time processing
- In the ASE concept, SCL scripts are planned and scheduled by the CASPER onboard planner
- SCL to also be used in ground control of EO1
- SCL is a mature software product used on many mission including several flights: Clementine I, ROMPS, DATA-CHASER, ICM for ISS, FUSE,…

Possible Future Applications: Mars

(Proposed Mars Odyssey Mission Scenario)

Ground generates sequence with additional imaging commands

THEMIS Image taken by Odyssey between mapping image data takes

Image is analyzed onboard

Nothing Detected: Delete Image

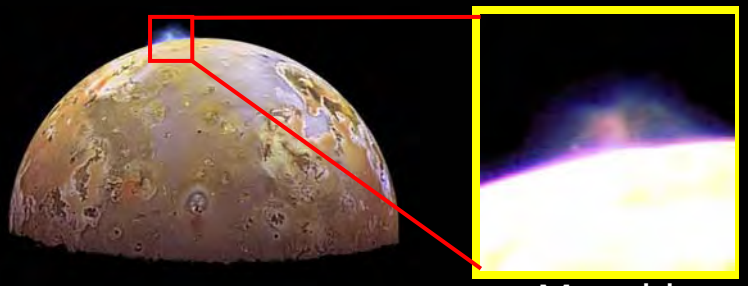
Feature Detected: save image for possible downlink

Ground is notified via engineering telemetry that an image is available, location, and type of detection.

The Mars Odyssey THEMIS imager used about 5% of the time for mapping mission due to limited downlink. ASE science analysis could run during part or all of other 95%.

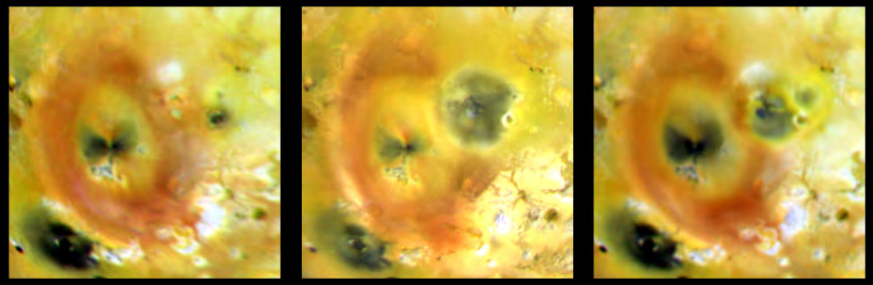
Possible Future Applications: Io

Feature identification: Volcanic plume detection



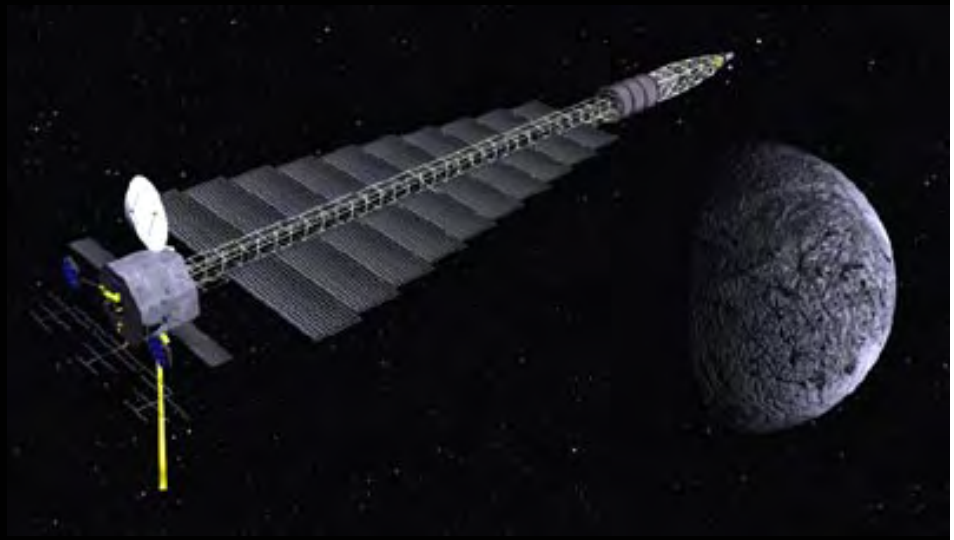
Masubi

Change detection: Emplacement of pyroclastics and lava flows at Io (Galileo data)



Pele and Pillan Patera, 1997-1999

JPL's proposed **JIMO** mission: **J**upiter **I**cy **M**oons **O**rbiter



High spectral, spatial and temporal monitoring of Jupiter and the Galilean satellites will be possible with JIMO

ASE Status

- We have run several experiments with the CASPER planning software and SCL execution software
  - CASPER has autonomously commanded instrument dark calibrations, cover open/closes, and downlinks
  - Ground development, refinement, and testing of the science algorithms using hyperion data is continuing
- We expect to start testing the full ASE software including science in early 2004 (February)
- We will continue to run experiments until the end of fiscal 2004 or until the end of deorbit if that occurs first

Summary

- Using on-board software for planning, science data analysis, and execution will increase mission value and reduce mission cost by:
  - Returning only the most important science data
  - Allowing quick response to opportunistic and dynamic science events
  - Side benefits of ASE:
    - Allowing the spacecraft to be commanded with high-level goals
    - Moving the labor-intensive spacecraft and science data analysis functions onboard the spacecraft
    - Allowing onboard response to faults

Upcoming missions will benefit from the ASE demonstration of integrated onboard autonomy

Acknowledgements

- Web Site: http://ase.jpl.nasa.gov
- ASE Team:

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