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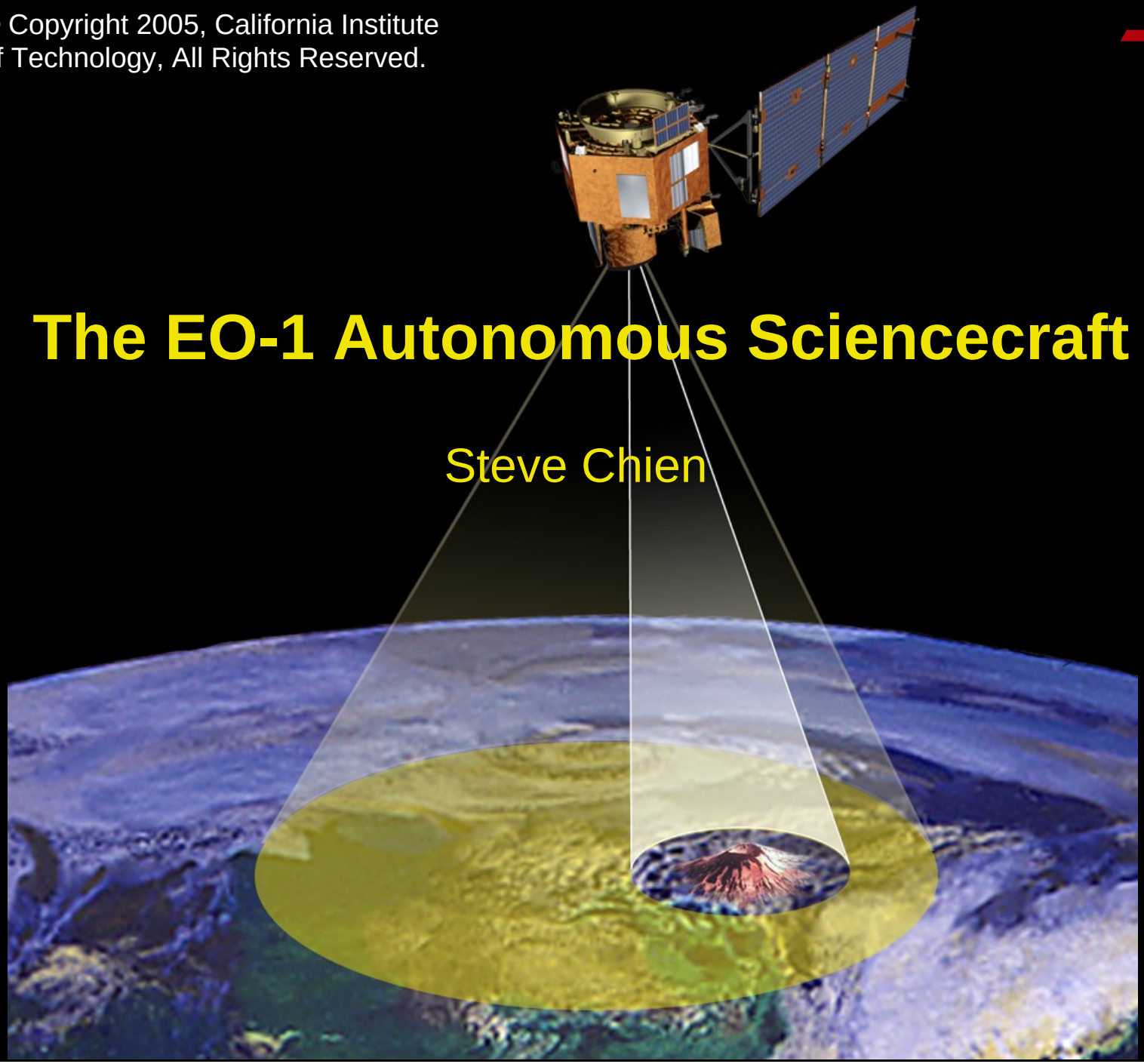
The EO-1 Autonomous Sciencecraft

Steve Chien



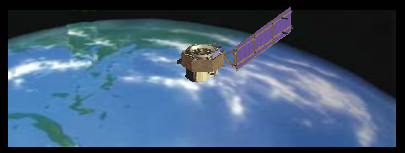
ASE Concept

ASE on EO-1 Example Mission Scenario

Image taken by Spacecraft

ASE on EO-1 Example Mission Scenario

Image taken by Spacecraft

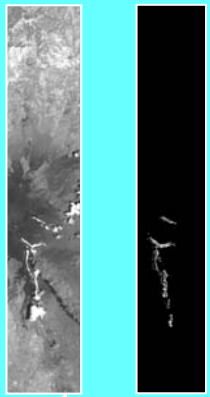


Onboard Science Analysis

Event Detection

No event Detected: Delete Image

Event Detected



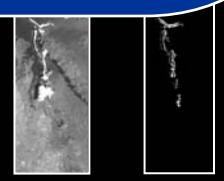
ASE uses state of the art Machine Learning to detect events in the presence of noise

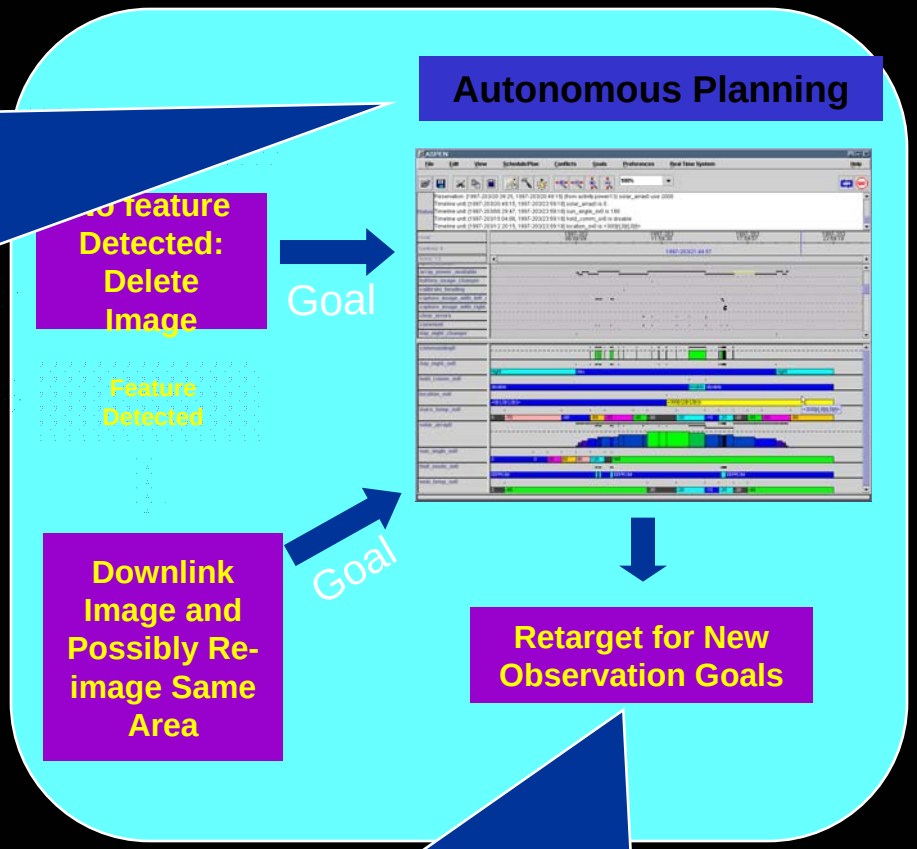
Track a wide range of science events – floods, volcanoes, cryosphere, clouds,…

<u>Key Insight:</u> No need to replicate ground science analysis – just detect activity

ASE on EO-1 Example Mission Scenario

continuous planning - enables seamless long-duration operations and rapid replanning despite limited onboard CPU



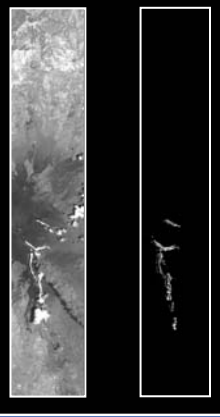


Onboard planning enables rapid response to detected event

ASE on EO-1 Example Mission Scenario

Image taken by Spacecraft

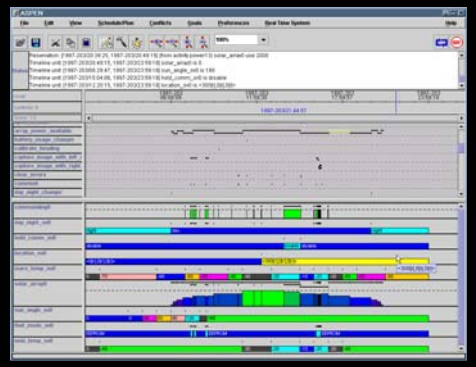
Land Feature Detection



No feature Detected: Delete Image

Feature Detected

Downlink Image and Possibly Re-image Same Area



Retarget for New Observation Goals

New Science Images

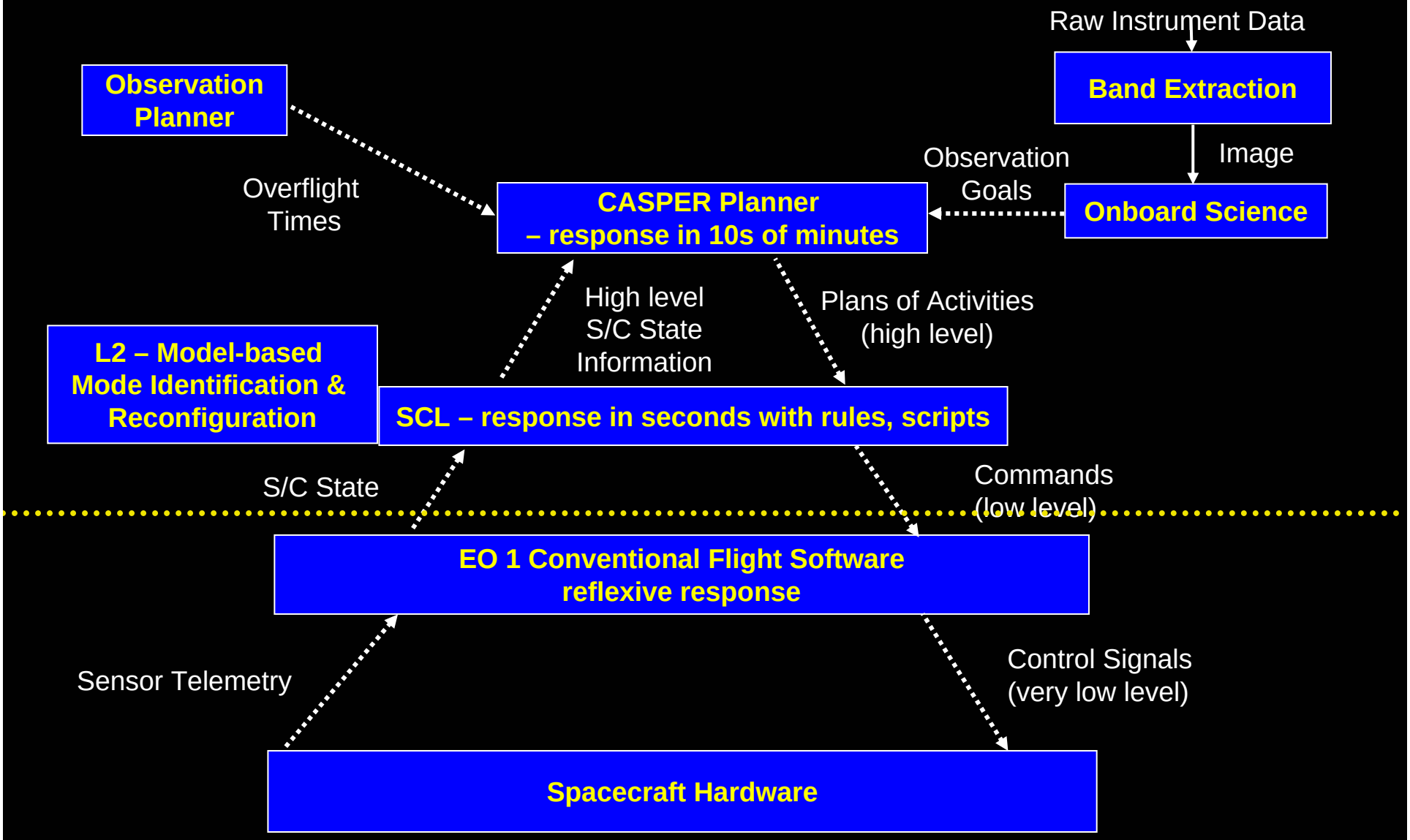
Autonomous Execution

Event-driven execution of response image

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 → 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



7 May 2004 ASE monitors Mt. Erebus

ASE images Erebus (Night) 13:40 GMT

} +10 min

ASE initiates band extraction

} +28 min

ASE runs thermal classifier

} +29 min

THERMAL TRIGGERED

7 May 2004 ASE monitors Mt. Erebus

ASE images Erebus (Night) — 13:40 GMT

} +10 min

ASE initiates band extraction

} +28 min

ASE runs thermal classifier

} +29 min

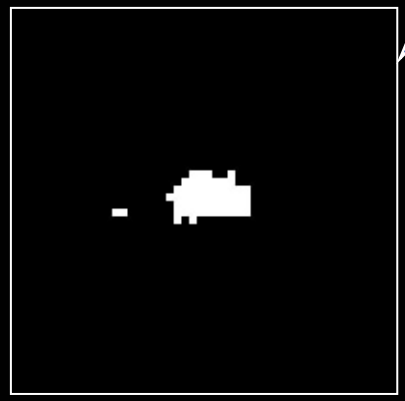
THERMAL TRIGGERED

Planner selects reaction observation (Stromboli observation replaced)

} +20 min

Thumbnail downlinked (S-band) — 15:58 GMT

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



+ 2 hours 18 minutes

7 May 2004 ASE monitors Mt. Erebus

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} +10 min

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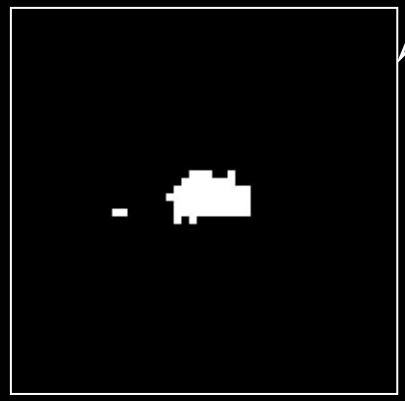
Thumbnail downlinked (S-band) — 15:58 GMT

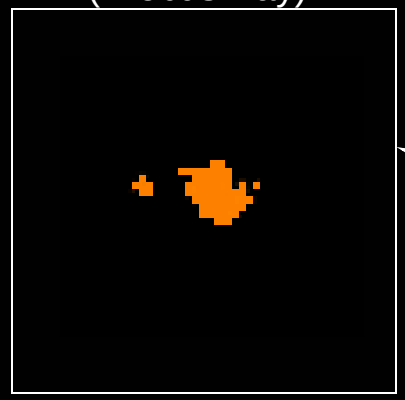
ASE images Erebus again — 20:10 GMT

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



+ 2 hours 18 minutes

ASE Onboard Thermal Classifier (Erebus Day)



+ 6 hours 30 minutes

7 May 2004 ASE monitors Mt. Erebus

ASE images Erebus Night — 13:40 GMT

} +10 min

ASE initiates band extraction

} +28 min

ASE runs thermal classifier

} +29 min

THERMAL TRIGGERED

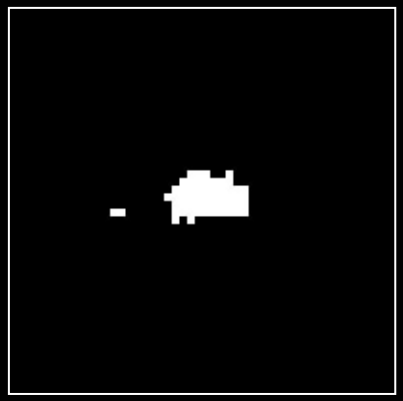
Planner selects reaction observation (Stromboli observation replaced)

} +20 min

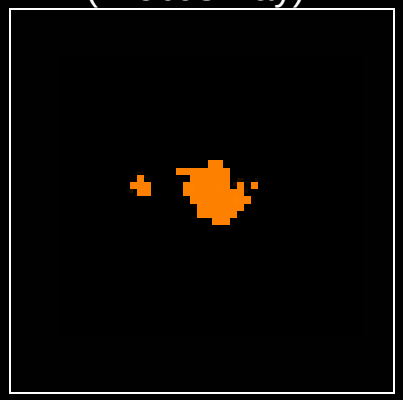
Thumbnail downlinked (S-band) — 15:58 GMT

ASE images Erebus again — 20:10 GMT + 06:30

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



ASE Onboard Thermal Classifier (Erebus Day)



- **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**

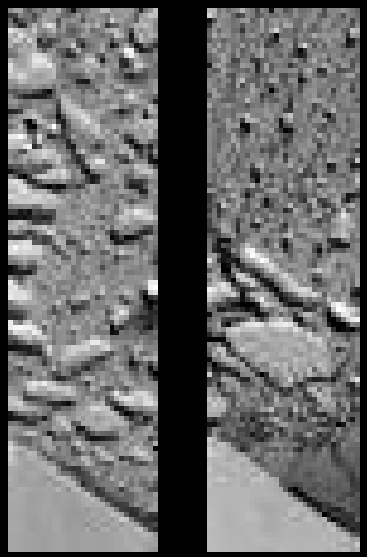
Onboard Science Data Analysis

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

Change Detection



Sea ice breakup

Feature Detection

Volcanic eruption

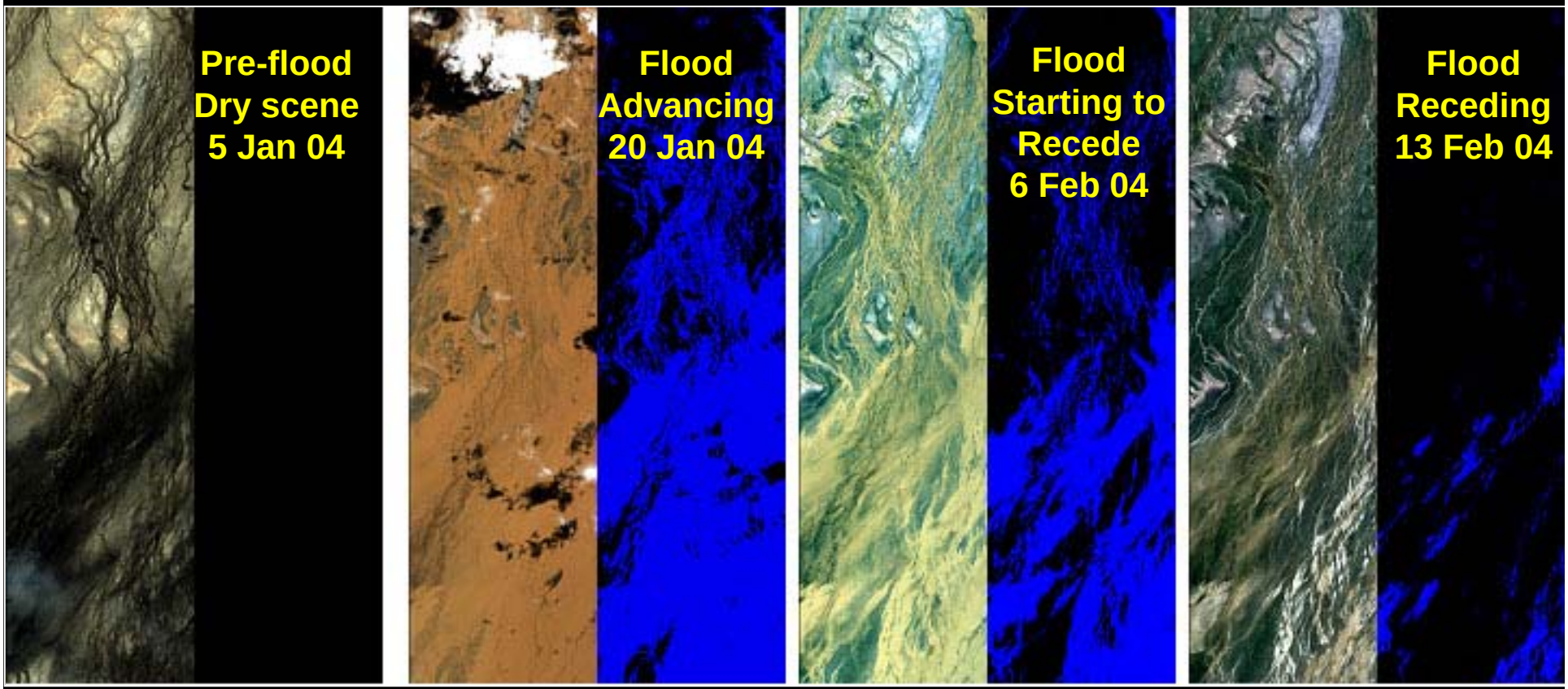
Data Quality Control

Cloudy

Cloudy

Clear

Detection of a Rare Major Flood on Australia's Diamantina River using the ASE "Muddy" Floodwater Classifier



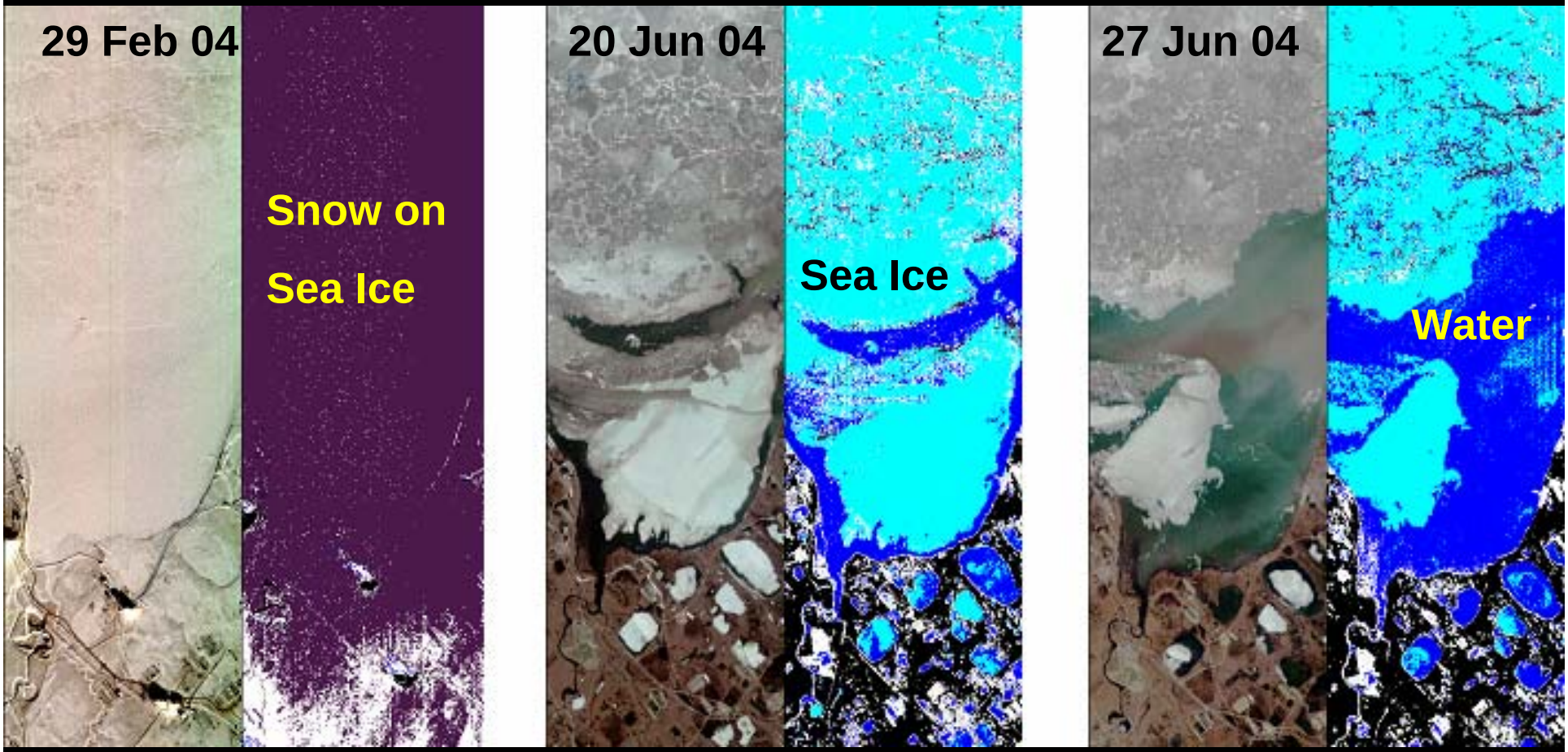
Cause of flooding: Monsoonal rain

Wavelengths used: 0.86 µm and 0.99 µm

University of Arizona

Cryosphere Classifier

Deadhorse (Prudhoe Bay), Alaska



- Snow
- Water
- Ice
- Land
- Unclassified

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

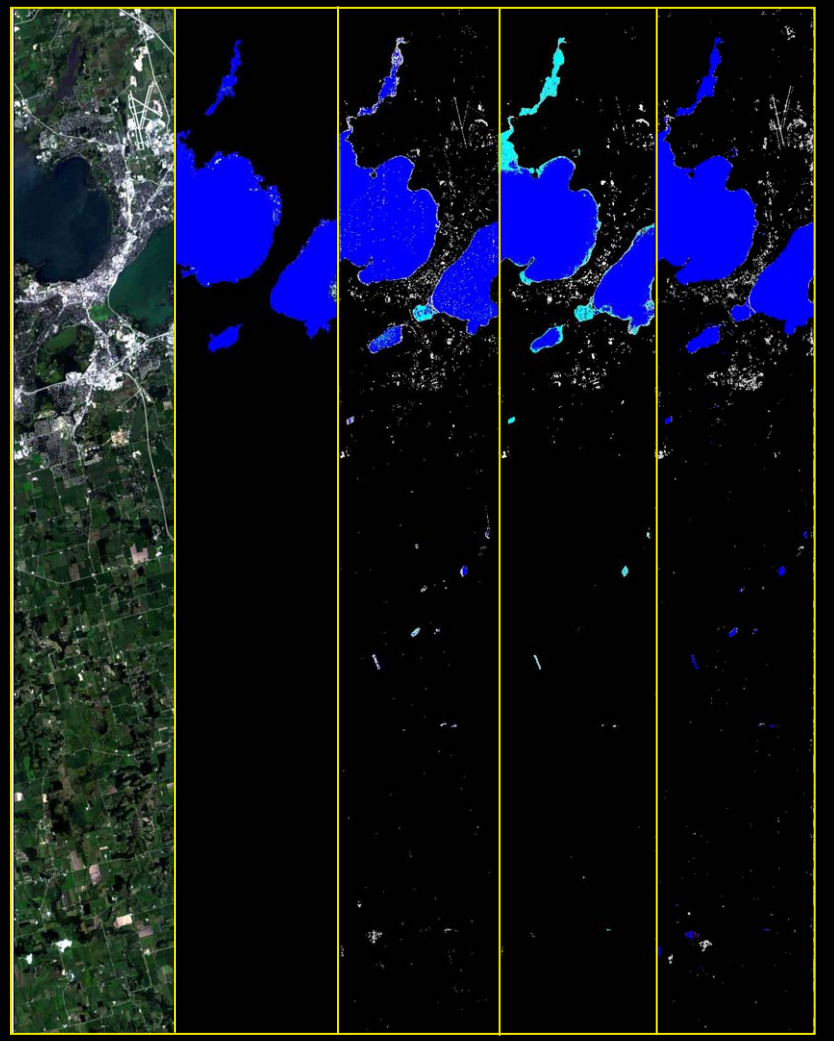
Arizona State University
Planetary Geology Group

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)

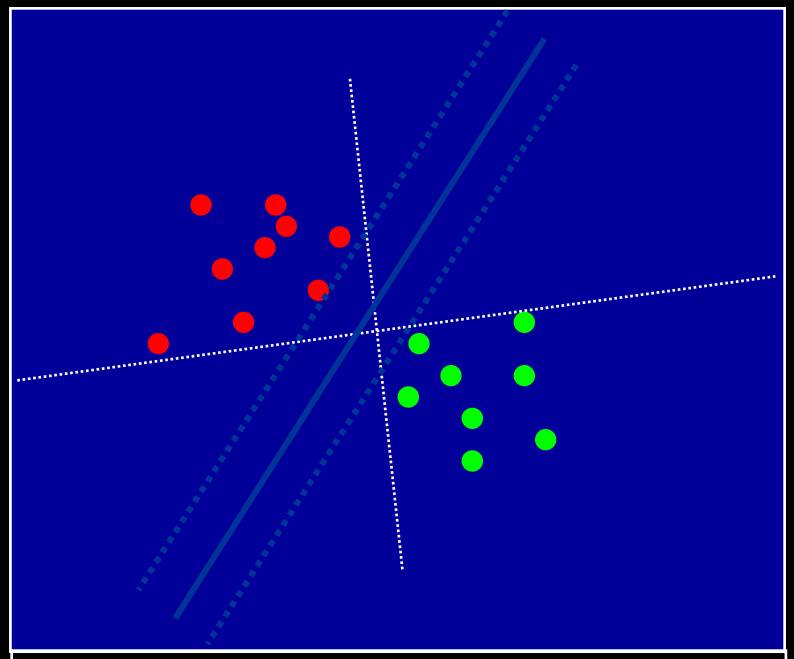
Classifier	Expert Derived	Automated Ratio	SVM
cloud	45.7%	43.7%	58.5%
ice	60.1%	34.3%	80.4%
land	93.6%	94.7%	94.0%
snow	63.5%	90.4%	71.6%
water	84.2%	74.3%	89.1%
unclassified	45.7%		

Lake Mendota, Wisconsin



Visible Image | Expert Labeled | Expert Derived | Automated Ratio | SVM

Support Vector Machines (SVM)



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

- 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)

Automated Mission Planning

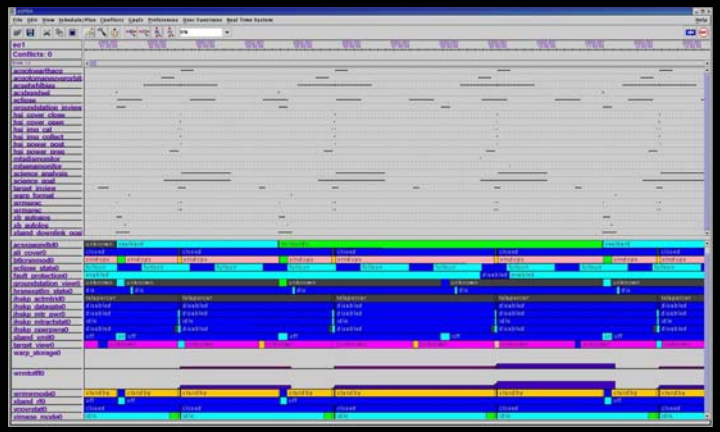
Onboard Replanning

Goals:

science requests,
downlink requests,
maneuver requests

Constraints:

memory,
power



Activity Plan:

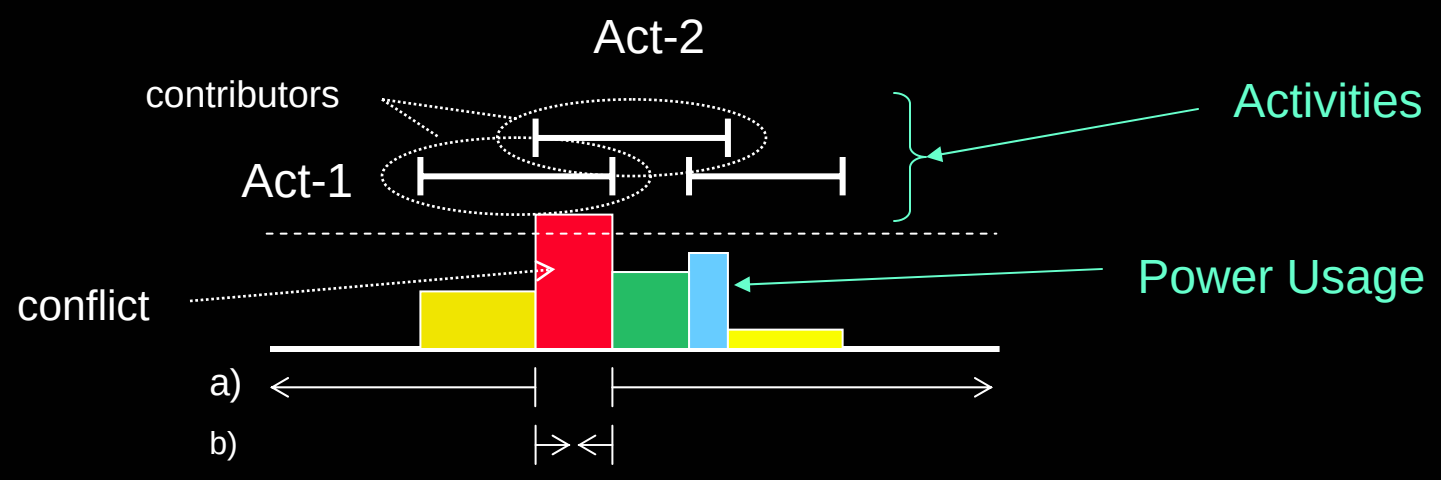
```
2003:233:16:49:57 CMD ACSETWHLBIAS(INERTIAL,X=0.341589,Y=1.1749,Z=-0.118046);
2003:233:17:56:57 CMD ACGOTOMANEUVER(ORBITAL,TIME=900,XLIMDEG=0.02,YLIMDEG=0.062699,…);
2003:233:18:07:06 CMD I_SETFPEPOWER(POWER_MASK=5);
2003:233:18:07:06 CMD YHEASTBY;
2003:233:18:07:16 CMD YHEASETSWIR(GAINA=1,GAINB=1,GAINC=1,GAIND=1,…);
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);
                ...
```

CASPER Uses Model of Activities

Science Data Collect Activity	
Resources	uses 30 W power; uses <variable> memory
State Constraints	requires ACS state to be “Fixed Attitude”
Required Activities	Decompositions dark calibration image before dark calibration image after

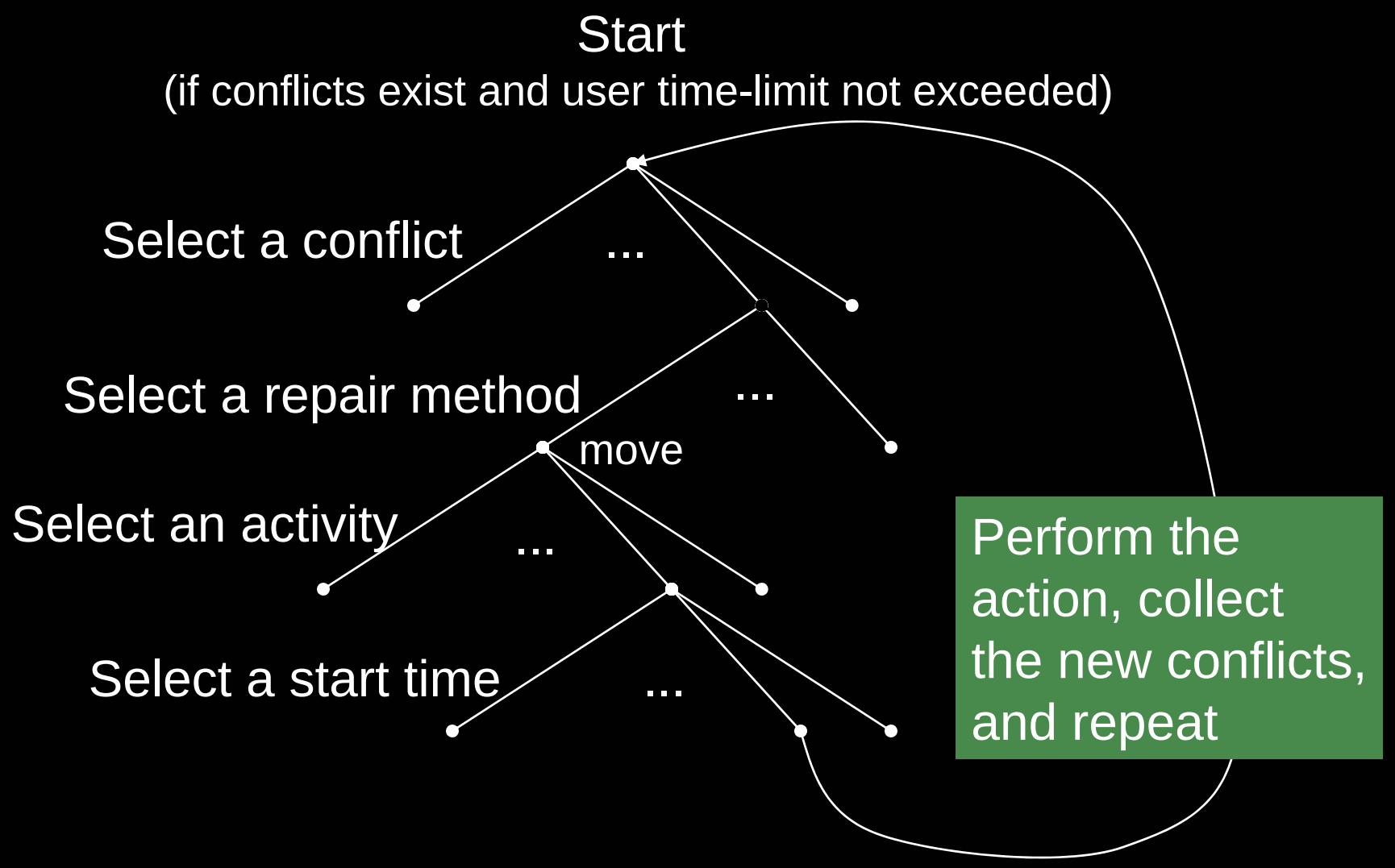
CASPER uses these activity models to determine how activities will affect spacecraft state and resources

Activities, Constraints, Repairs

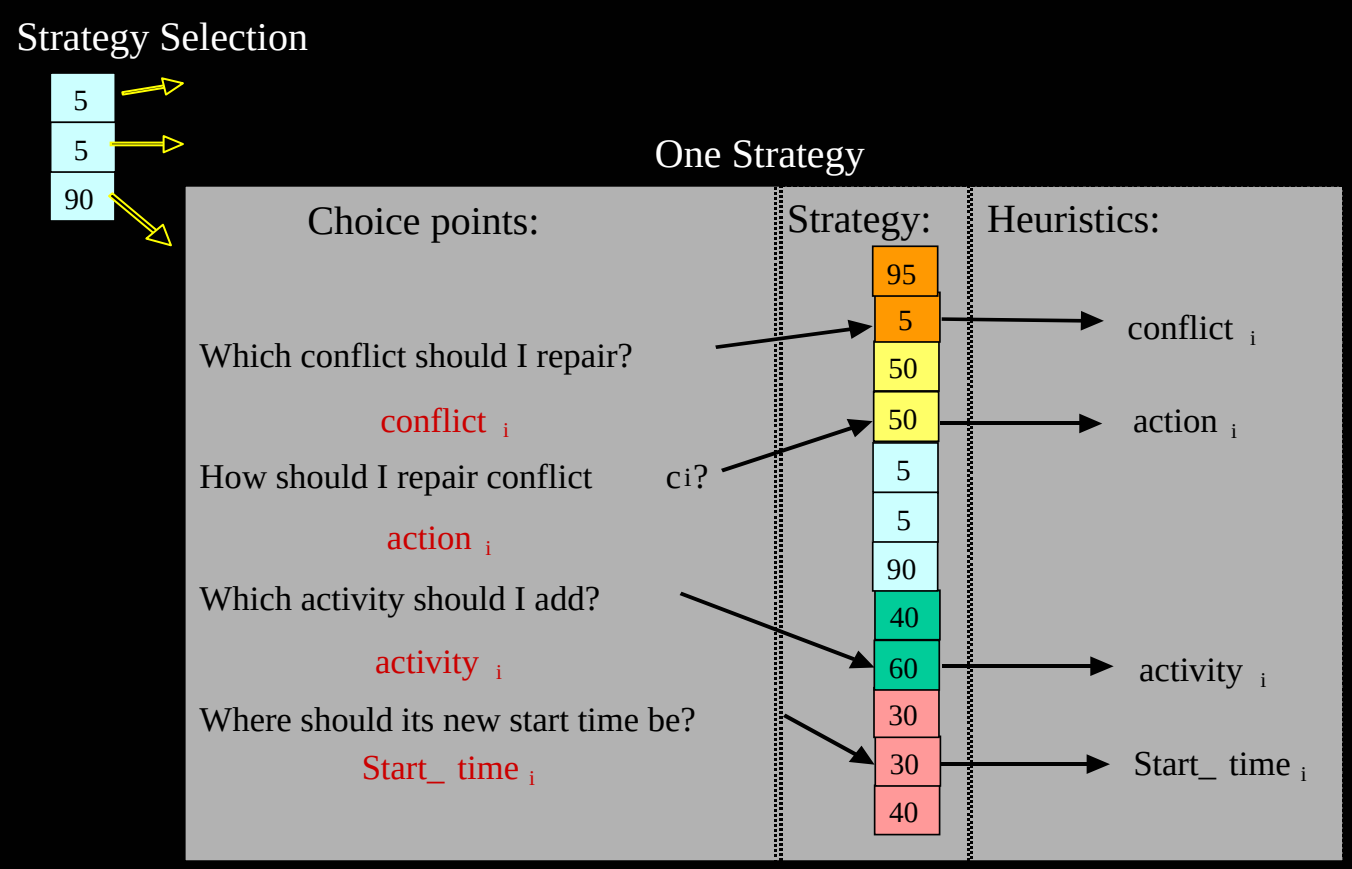


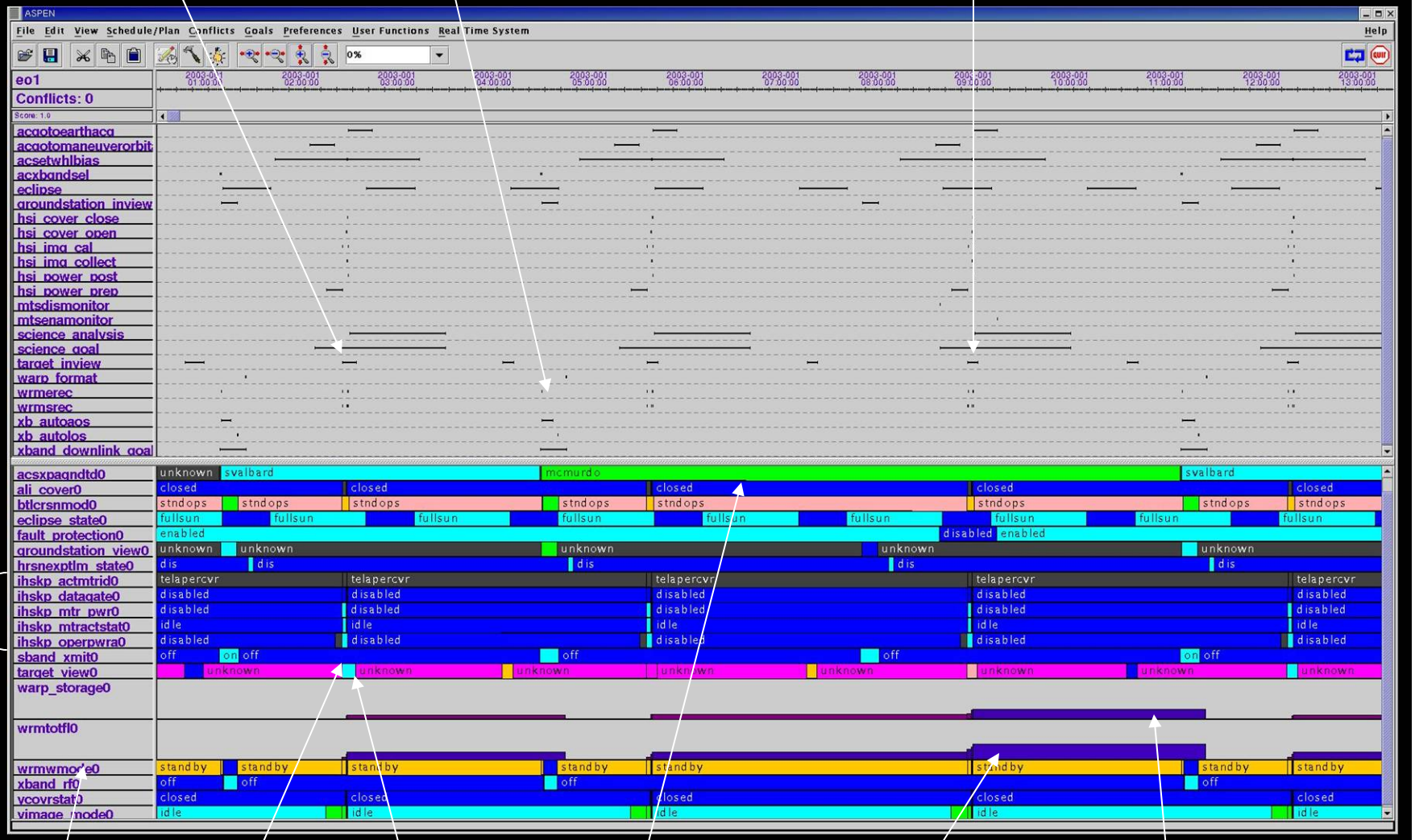
	General Property	Example
Constraint	Property that must hold for plan to be valid	Must always use less power than available
Conflict	Violation of a constraint	Current plan uses more power than available over (b)
Repair Method	Modification to plan that may remove conflict	Delete activity using power during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

Repair Algorithm



Portfolio of Stochastic Portfolios of Heuristics





Day collect

Downlink

Night collect

Hyp State

Warp mode

Hyperion Preparation

Target in view

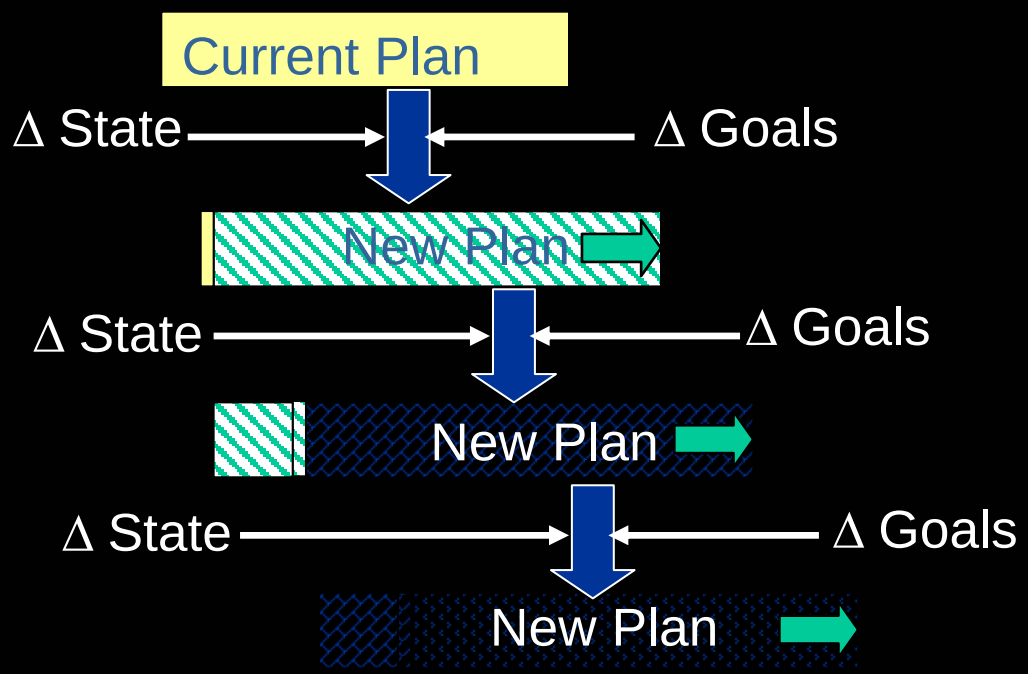
X-band Ground Station

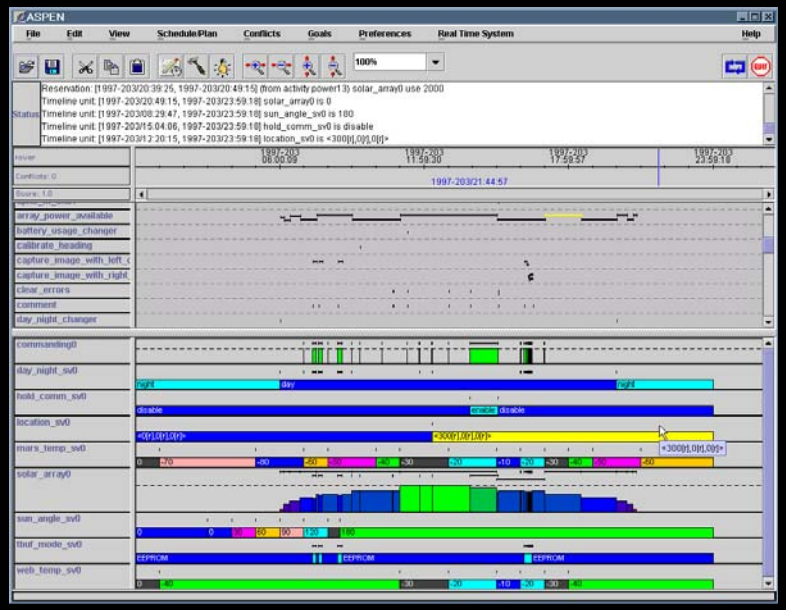
SSR file count

SSR data volume

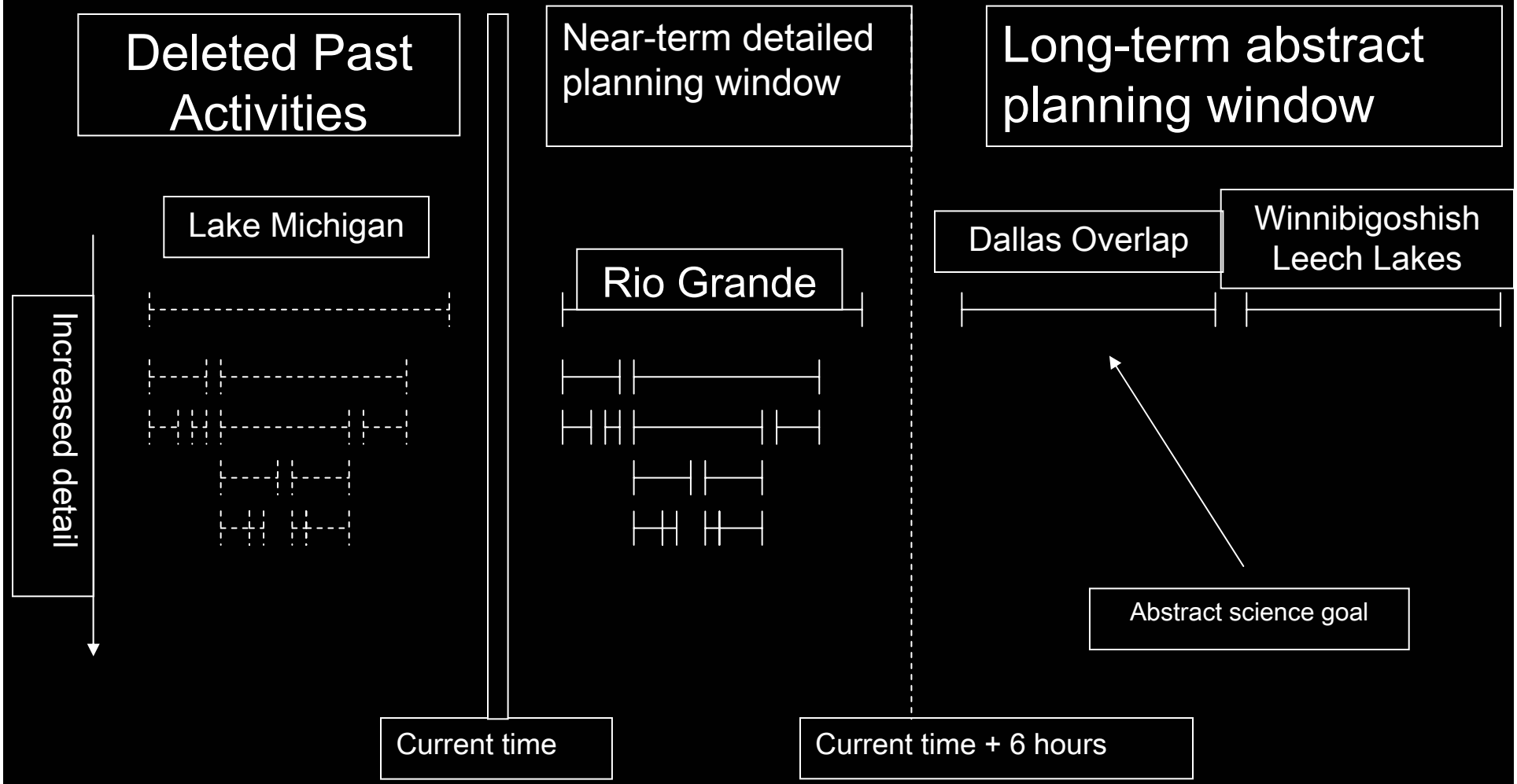
Onboard Replanning

- CASPER uses continuous planning techniques to improve response time





Continuous Planning on EO-1



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

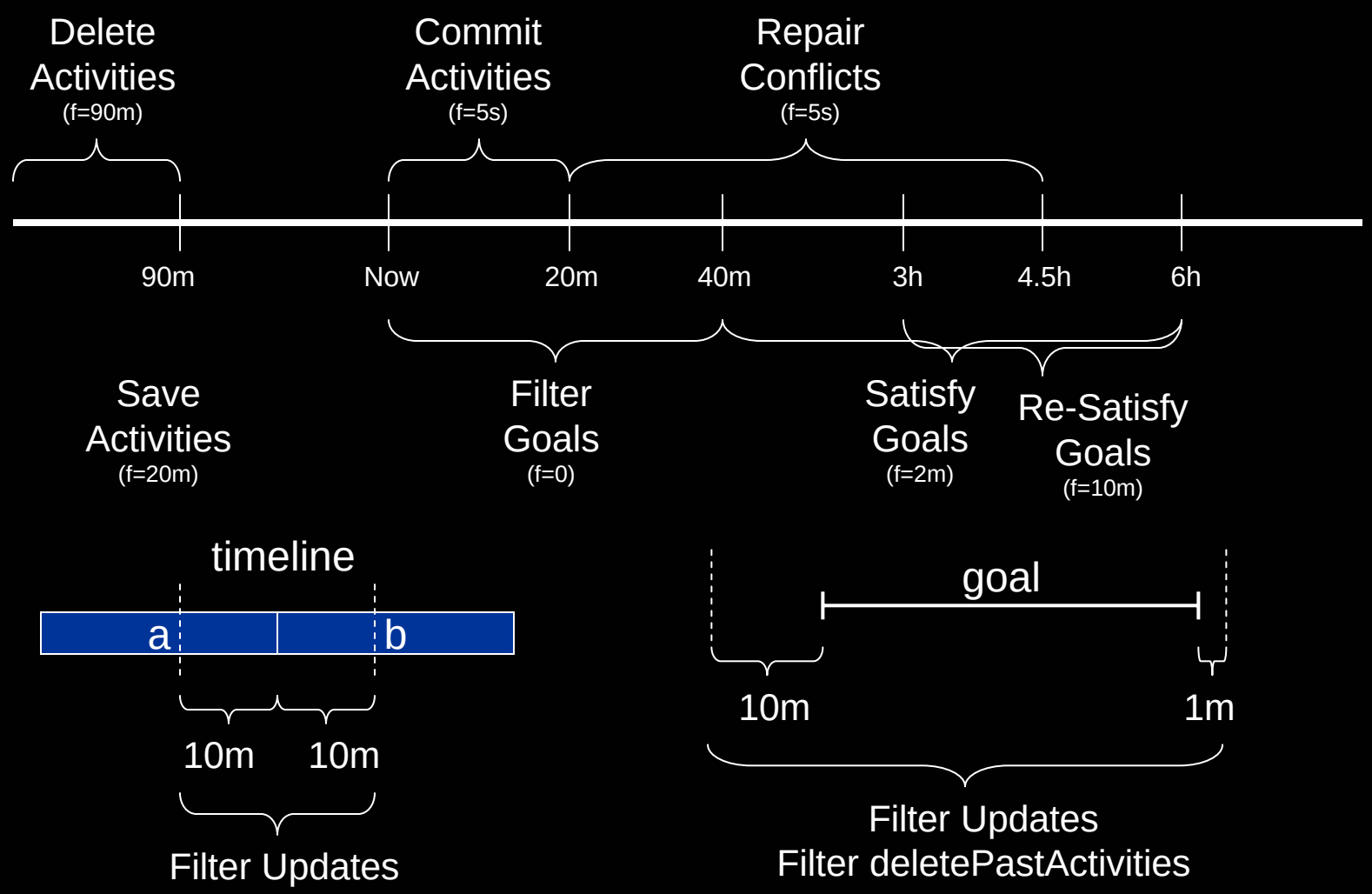
- CASPER is limited to a 32 MB of heap space

- ASE performs detailed planning ~6 hours in advance

  = ~16MB Heap Space

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

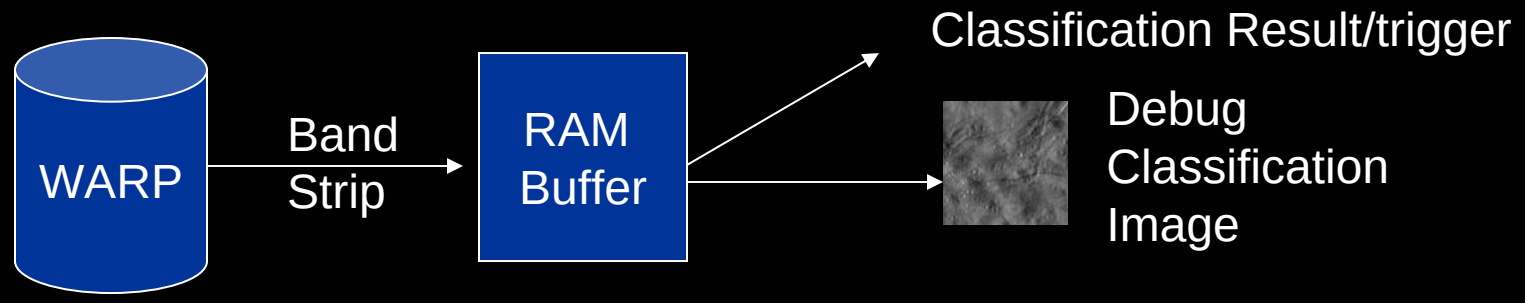
ASE Windows


Delete Activities
(f=90m)
Commit Activities
(f=5s)
Repair Conflicts
(f=5s)
90m
Now
20m
40m
3h
4.5h
6h
Save Activities
(f=20m)
Filter Goals
(f=0)
Satisfy Goals
(f=2m)
Re-Satisfy Goals
(f=10m)
timeline
a
b
10m
10m
Filter Updates
goal
10m
1m
Filter Updates
Filter deletePastActivities

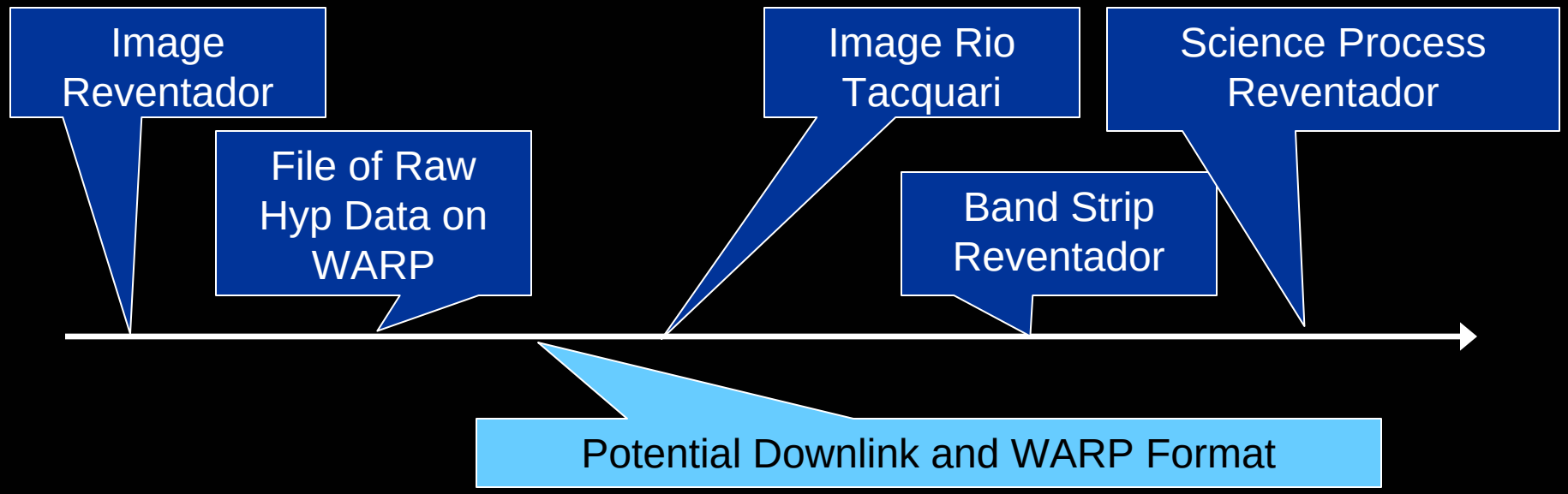
EO-1 Scene Prioritization

- 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)

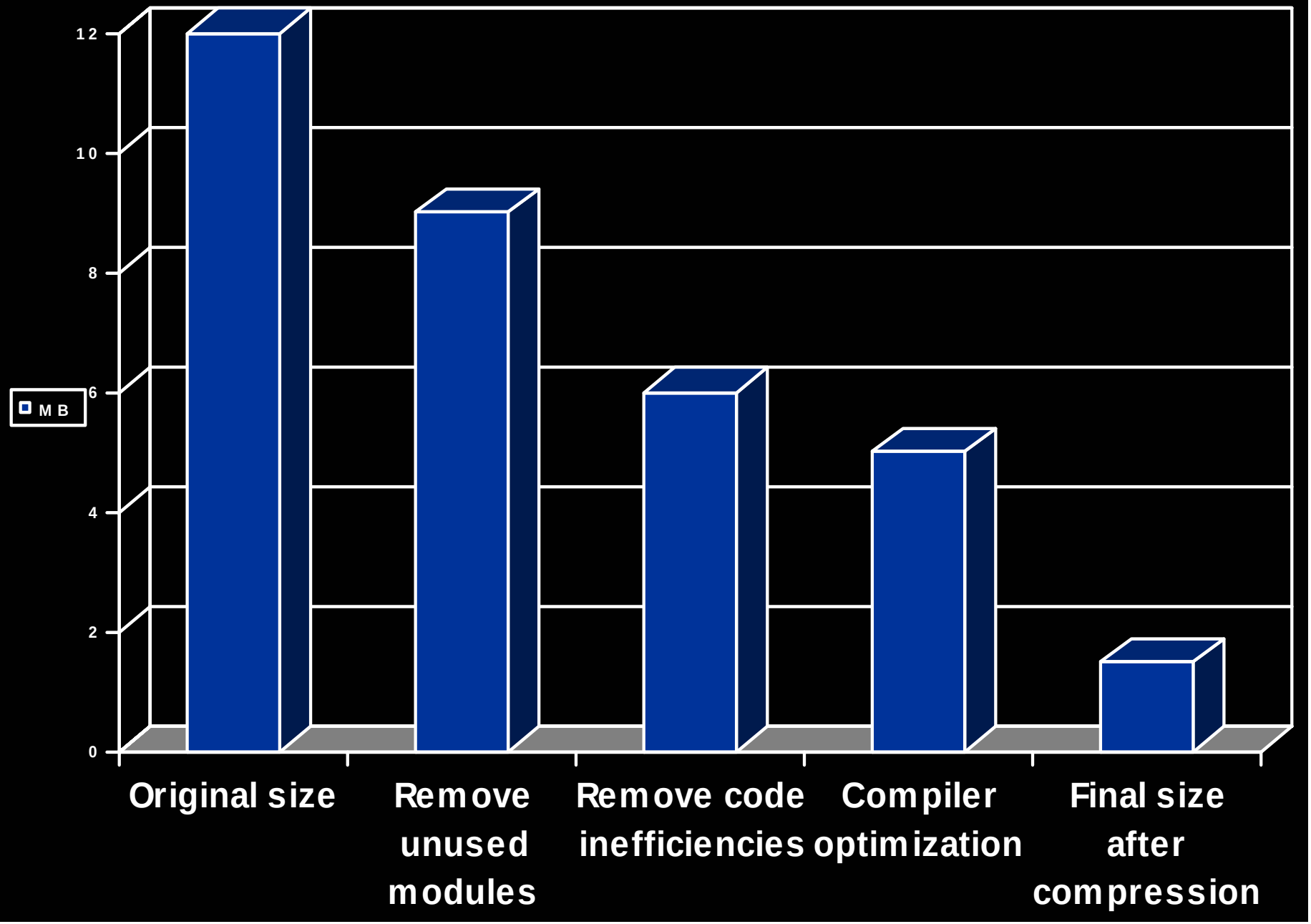
Modeling File System



- 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



CASPER RAM Reduction



ASE Validation

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

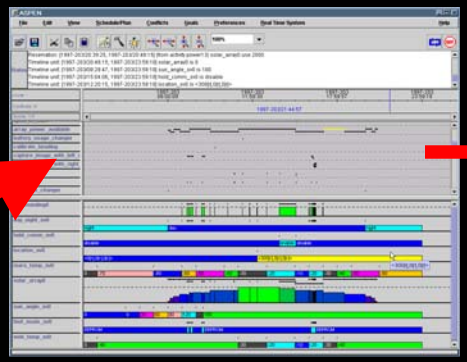
ASE Current Status

- 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

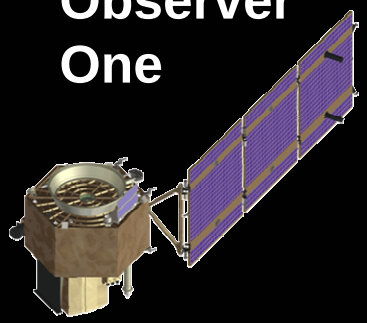
Sensorweb

Sensorweb

Re-tasking



Earth Observer One



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

Sensorweb Applications

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

Wildfire Sensorweb

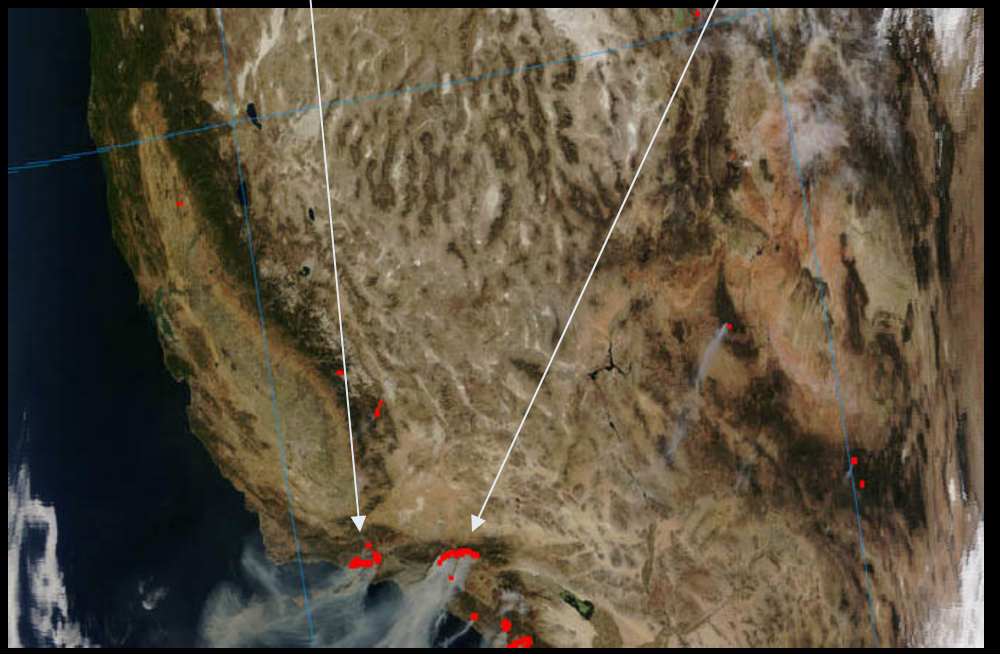
Utilizes MODIS Land Rapid Response Active Fire Mapping:

Justice, Giglio, et al., *(2002)* The MODIS fire products, Remote Sensing of Environment 83 (2002) 244–262

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

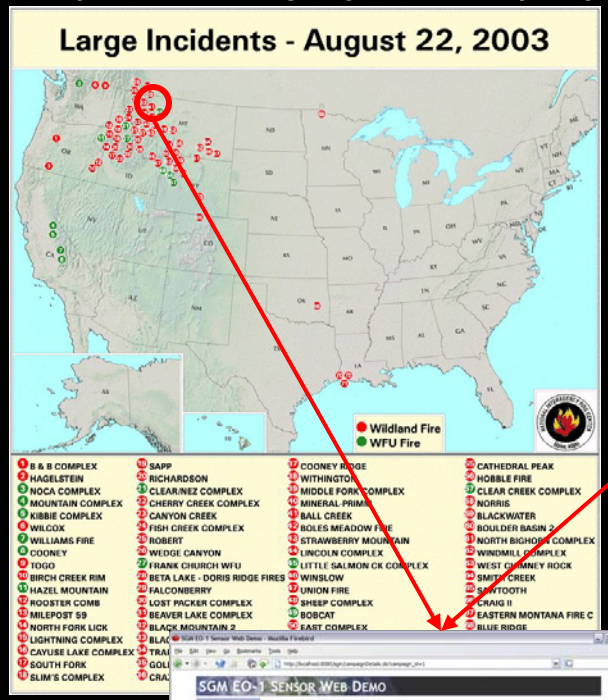
- Detects hotspots using
  - absolute threshold
    - T_4>360K, 330K(night) or
    - T_4>330K, 315K(night) and T_4-T_{11}>25K(10K @ night)
  - and relative threshold
    - T_4 > mean(T_4)+ 3stddev(T_4) and T_4 - T_{11} > median(T_4-T_{11})+ 3stddev(T_4-T_{11})

Looks for areas significantly hotter than surrounding area (requires 6 surrounding pixels cloud, water, fire free → 21x21)

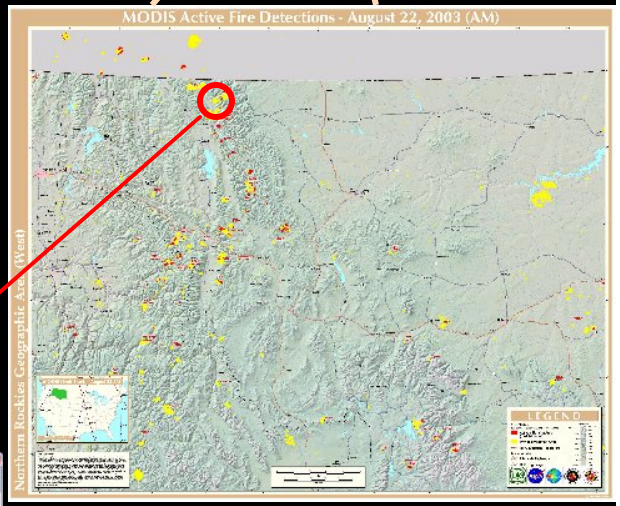
Wildfire Science Trigger

- 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

Large wild fires tracked by National Interagency Fire Center (NIFC)



MODIS Instrument on Terra or Aqua



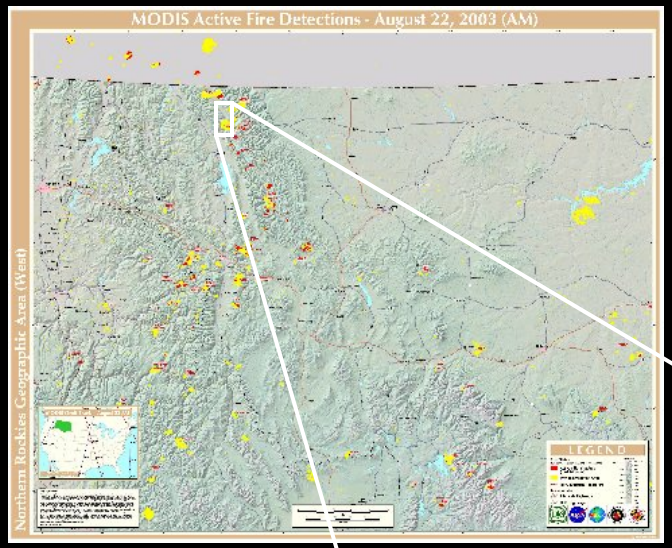
MODIS Active Fire Detection Map

Wildfire Science Event Trigger

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

Wildfire SensorWeb



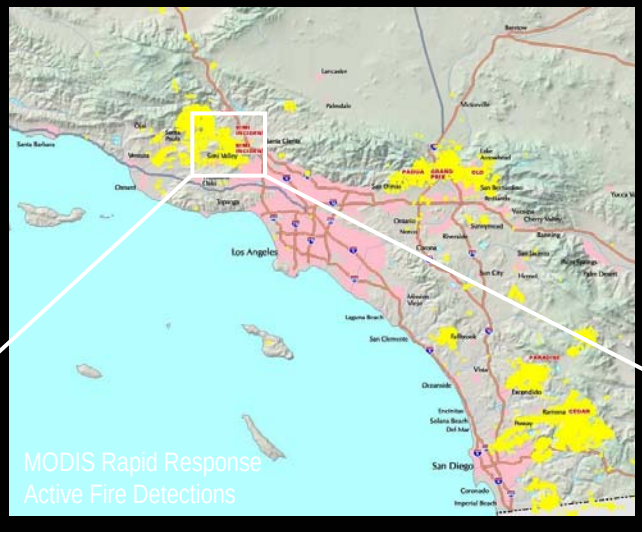
MODIS Rapid Response
Active Fire Detections

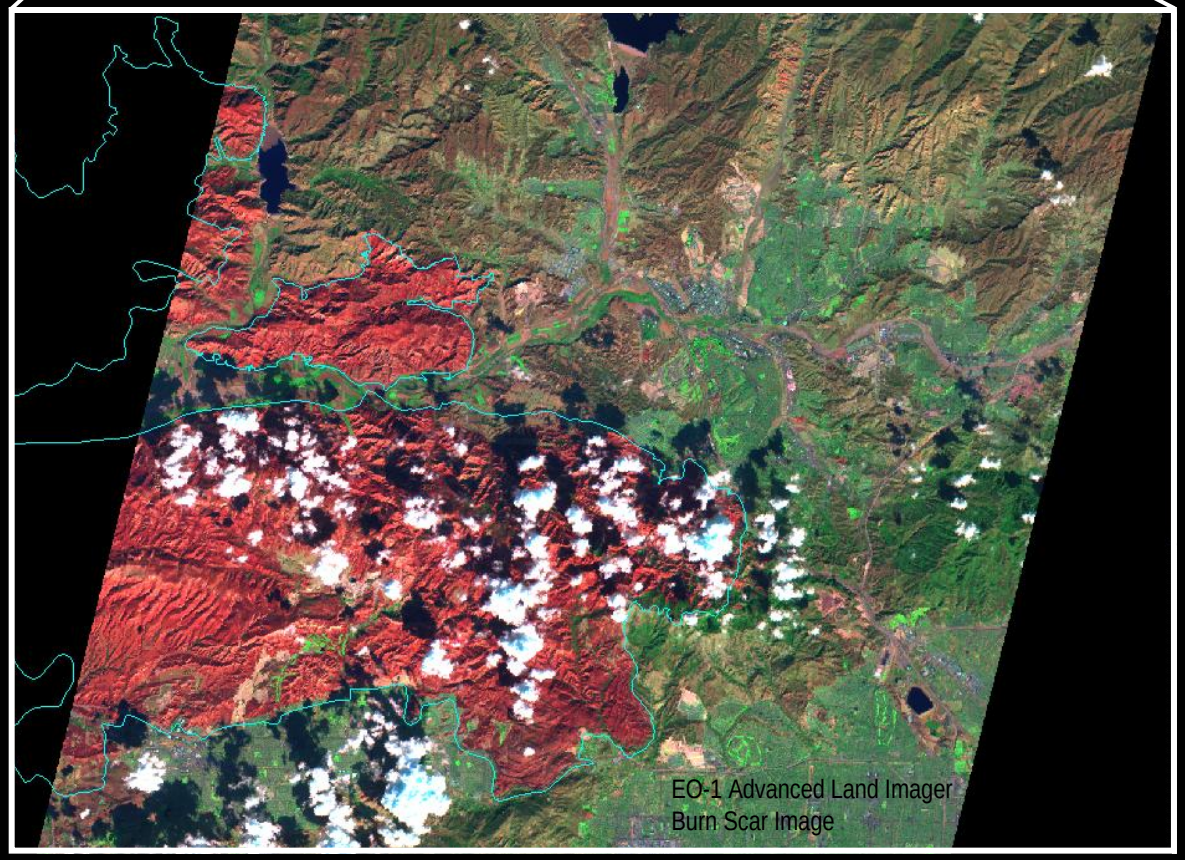
Robert Fire Demonstration
August 2003

EO-1 Advanced Land Imager
Burn Scar Image

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

Wildfire SensorWeb





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

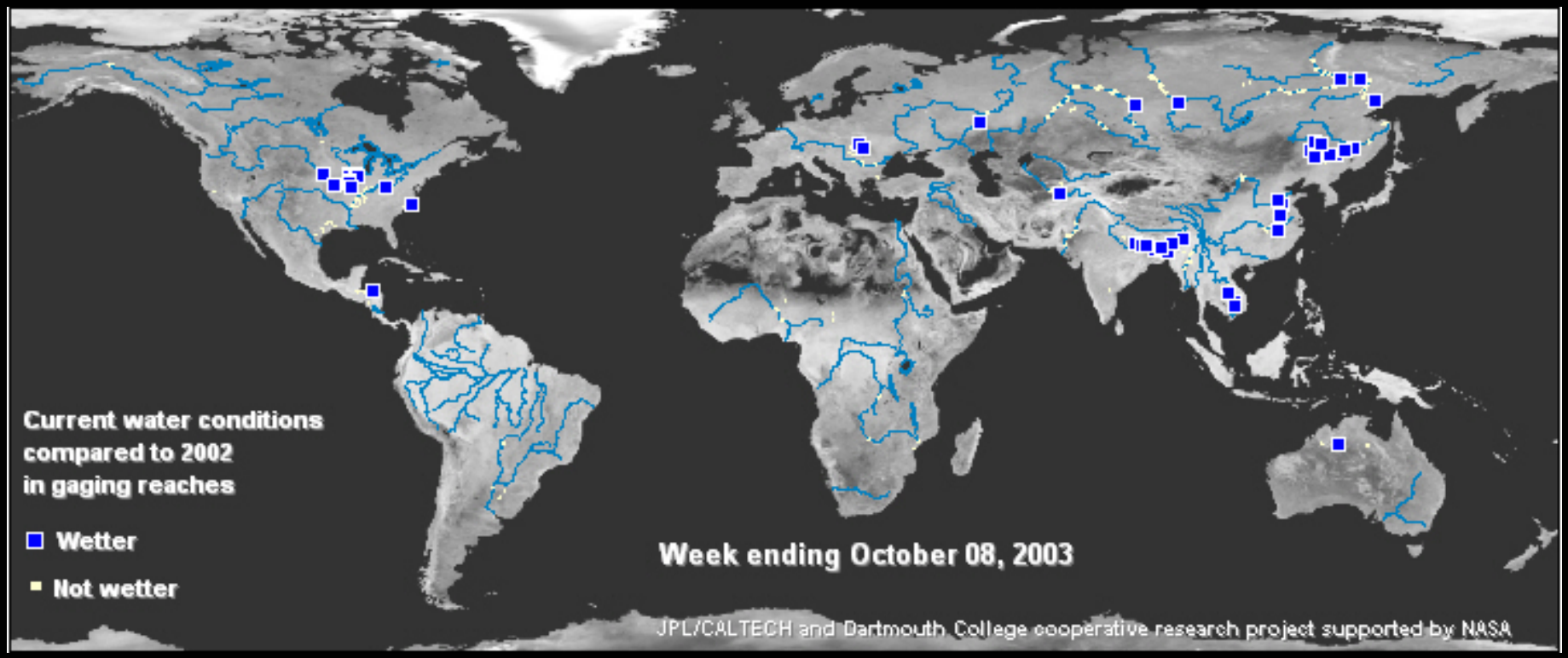
Uses Dartmouth Flood Observatory QUIKScat Global Flood Atlas:

B. Brakenridge, Anderson, Ngiem, Caquard, et al., "Flood Warnings, Flood Disaster Assessments, and Flood Hazard Reduction: The Roles of Orbital Remote Sensing," Proc 30th Intl Symp on Remote Sensing of the Environment, Honolulu, HI, Nov 10-14, 2003

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

Floods - Detection



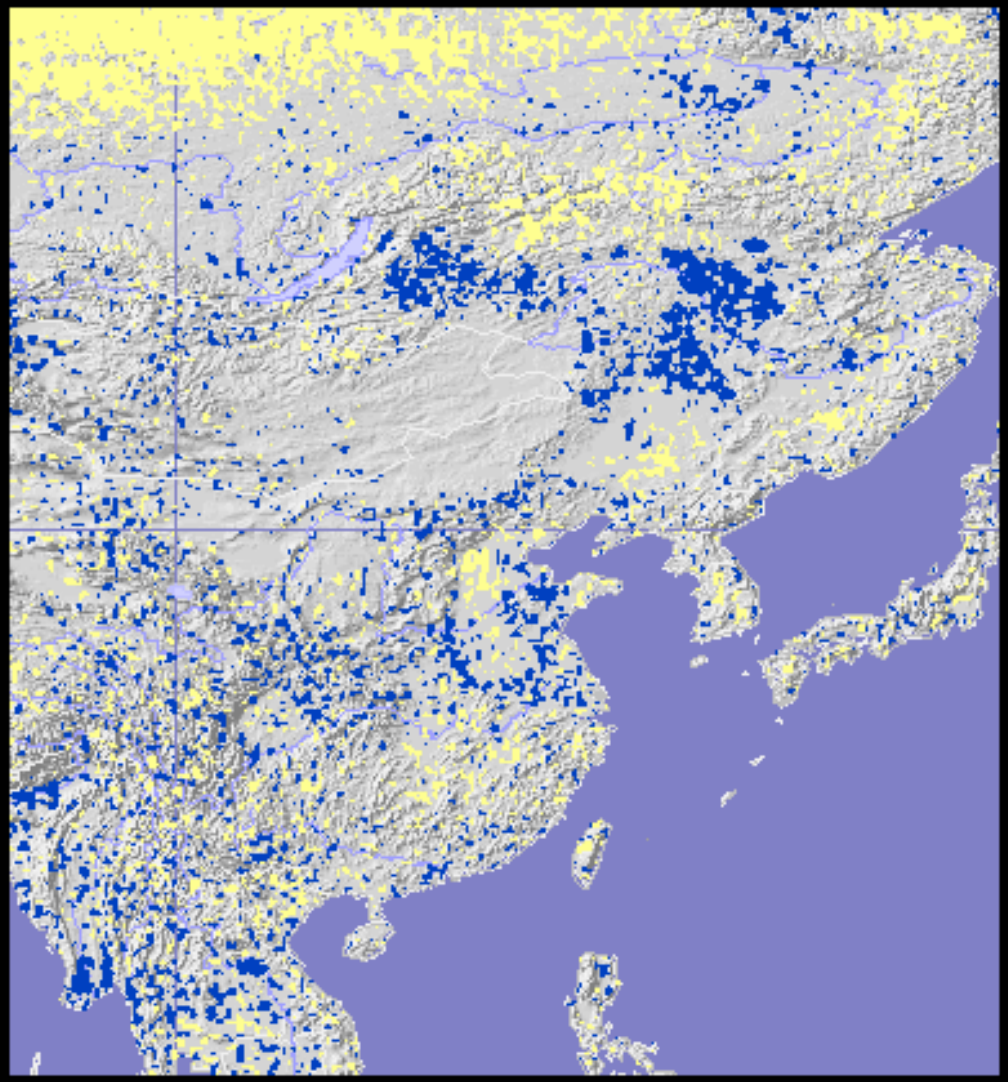
Dartmouth-Flood Observatory QuikSCAT

- 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

- QuikSCAT polarity ratio (“flood alert”) display for September 28, 2003.
- Blue and Yellow indicate increased and decreased surface water extent compared to September-October, 2002.

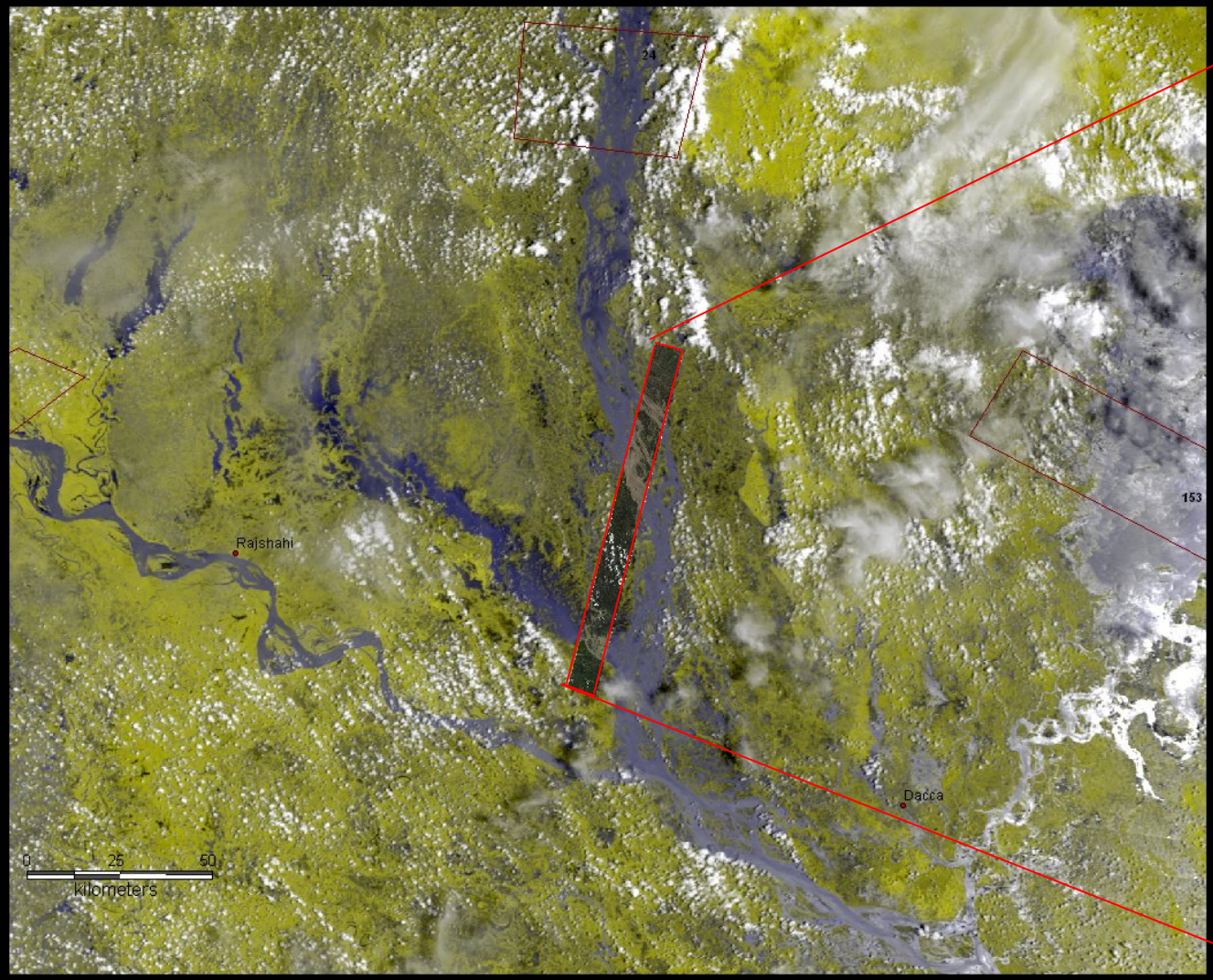


POC:
Brakenridge/DFO
Ngiem/JPL

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:

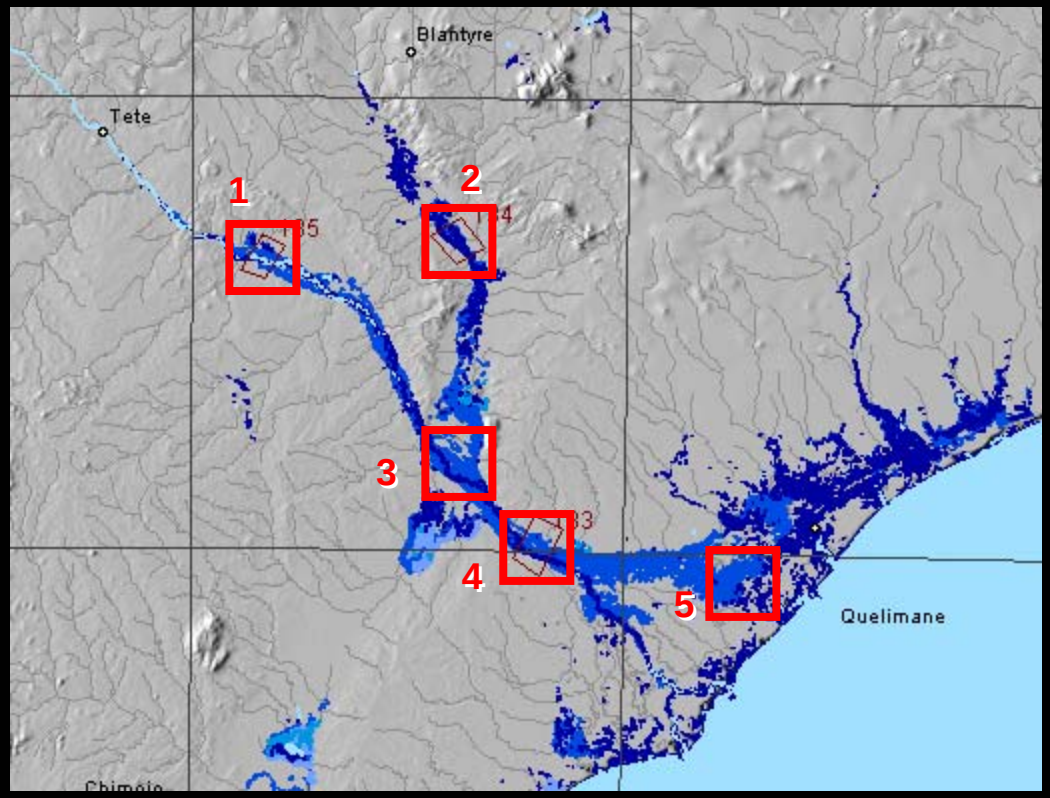
- ***key locations*** (pre-determined satellite gauging reaches) and
- ***times*** (active flooding regions)

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:

Harris, A. et al., (2002) Web-Based Hot Spot Monitoring using GOES: What it is and How it Works, *Advances in Environmental Monitoring and Modelling* *http://www.kcl.ac.uk/advances* *Vol. 1 No. 3 (2002) pp.5-36*

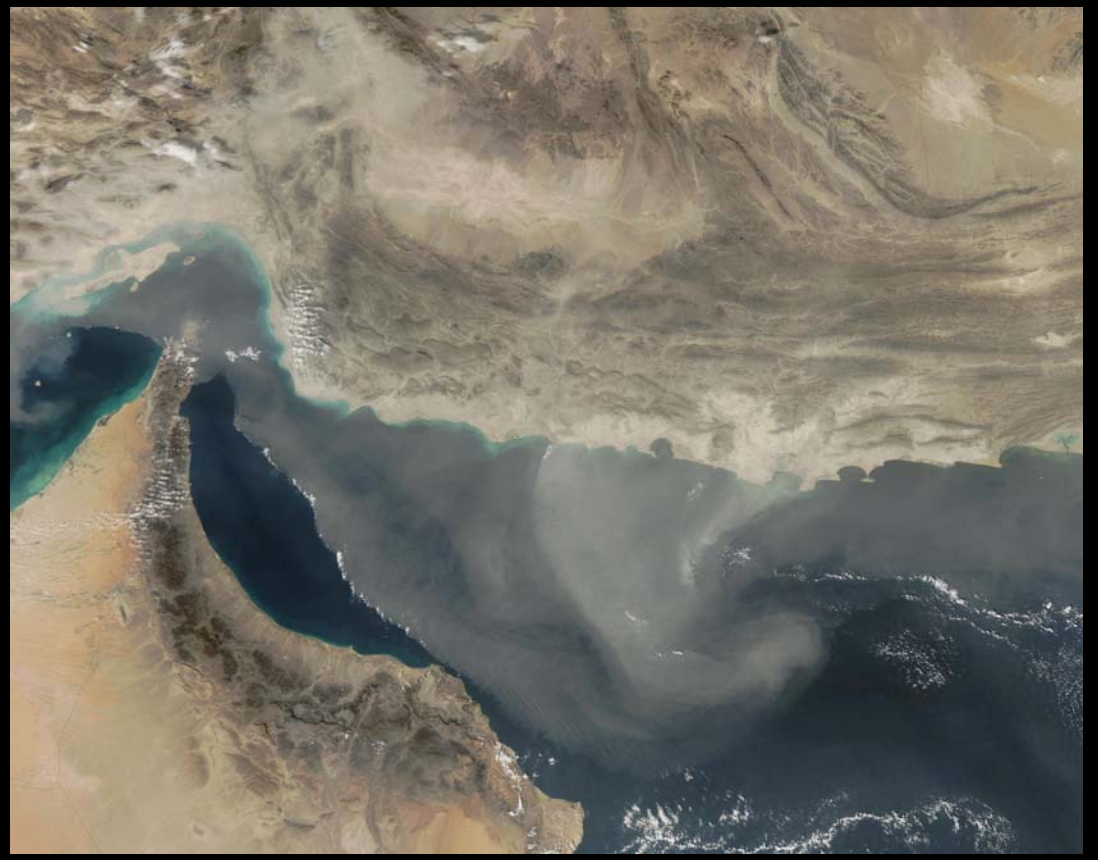
Wright, R., Flynn, LP, Garbeil, H, Harris, AJL, and Pilger, E. (2002). Automated volcanic eruption detection using MODIS. *Remote Sensing of Environment*, 82, 135-155.

Flynn, LP, Wright, R, Garbeil, H, Harris, AJL, and Pilger, E. (2002). A global thermal alert using MODIS: initial results from 2000-2001. *Advances in Environmental Monitoring and Modeling*, 1, 5-36.

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



Large scale dust storm in Persian Gulf.

POC: S. Miller, NRL Monterey.

MODIS Image of the day for 19th November 2003.
Courtesy MODIS Rapid Response Team.

Ice Breakup

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

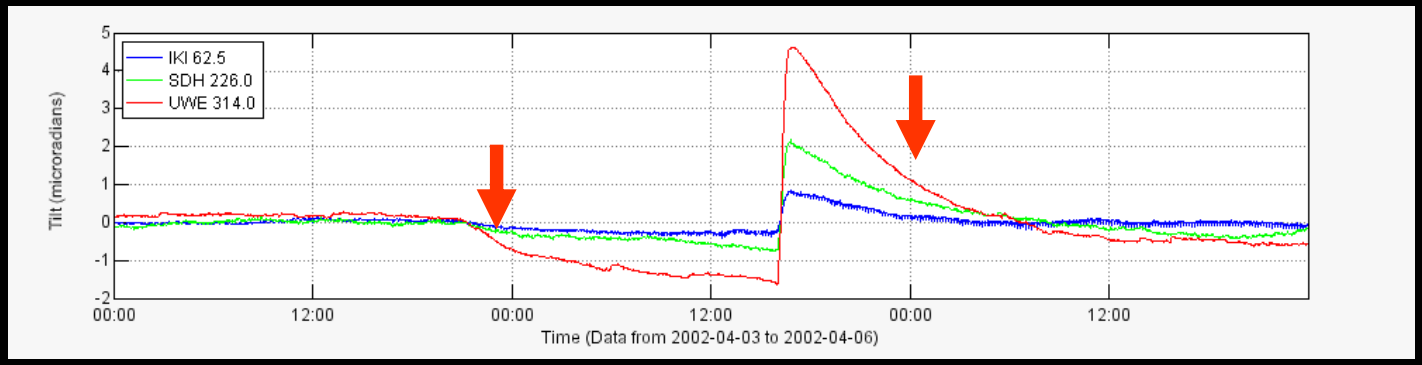
Eighteen (18) of MODIS imagery Dec 17, 2001- Jan 4, 2002

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

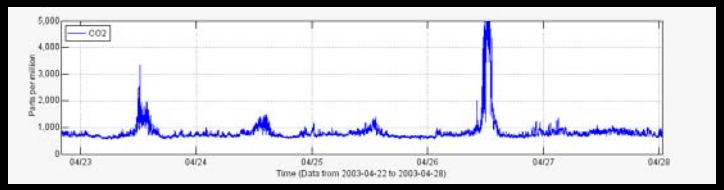
HVO instrumentation: tiltmeter net



Kilauea Caldera
April 5, 2002 event

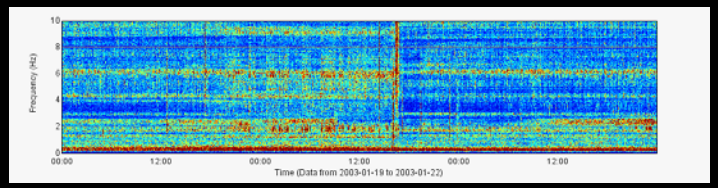
24 hrs from trigger to surface eruption: New flows detectable by EO-1 on order of days

Plus other sensors nets…

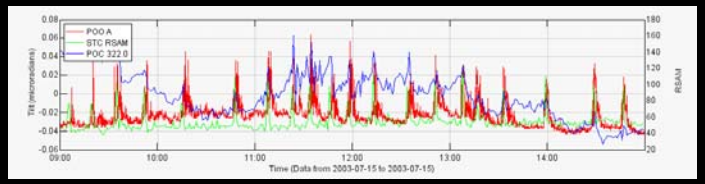


CO_2 Level in Kilauea Caldera, April 23-28, 2003

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



Seismic spectrogram



Tilt + Seismic + Radiometer (thermal)

The Cookie Monster
May 2002 – January 21, 2003
Photograph by J. Kauahikaua

POC:
P. Cervelli/HVO

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

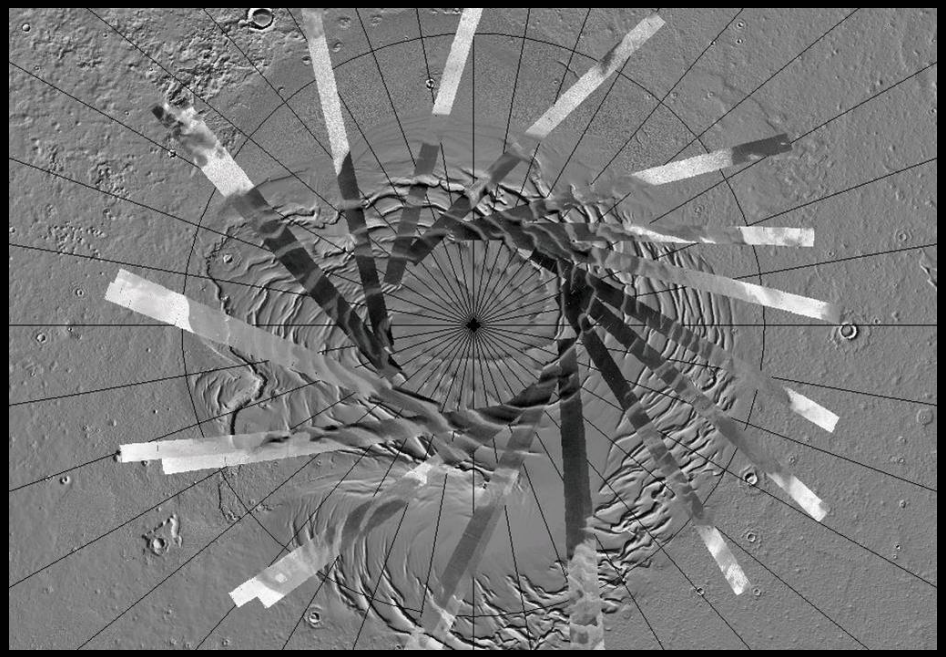
Sensorwebs: The Future

- 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

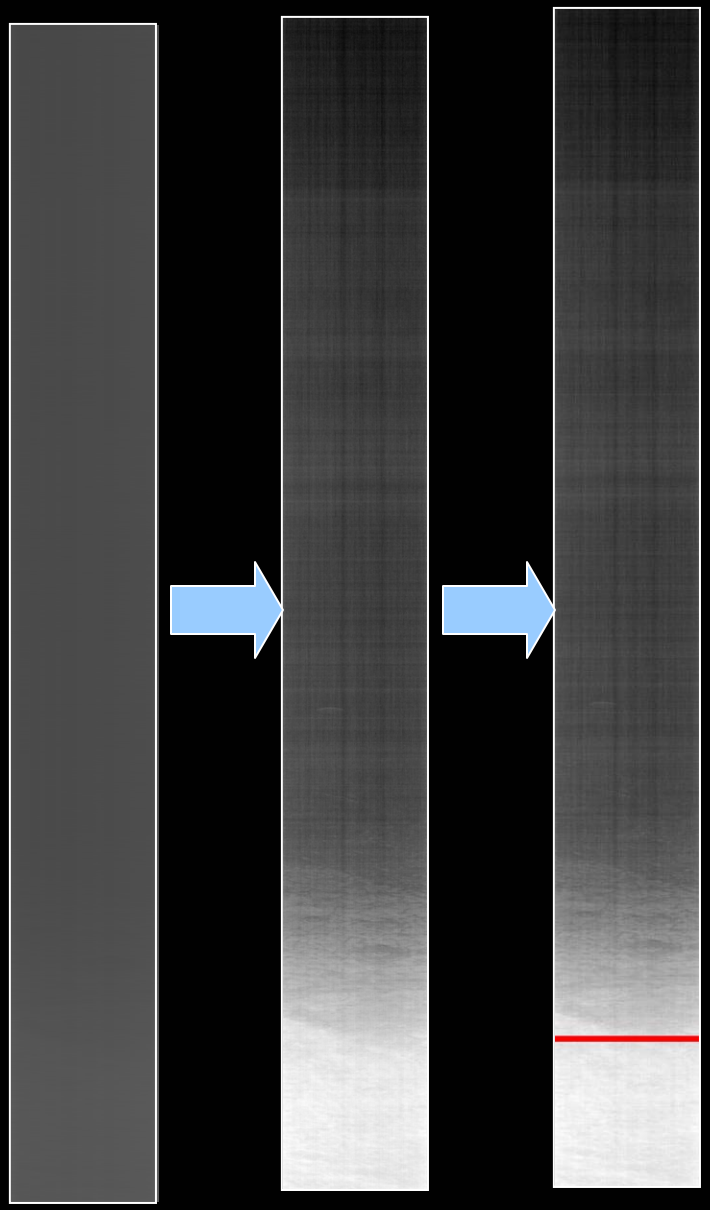


Mars, North Pole, THEMIS orbits 4319-4399 (northern summer)

JMARS - Noel Gorelick/ASU

- Develop means for automatically tracking CO_2 ice cap formation and retreat onboard Odyssey using THEMIS;

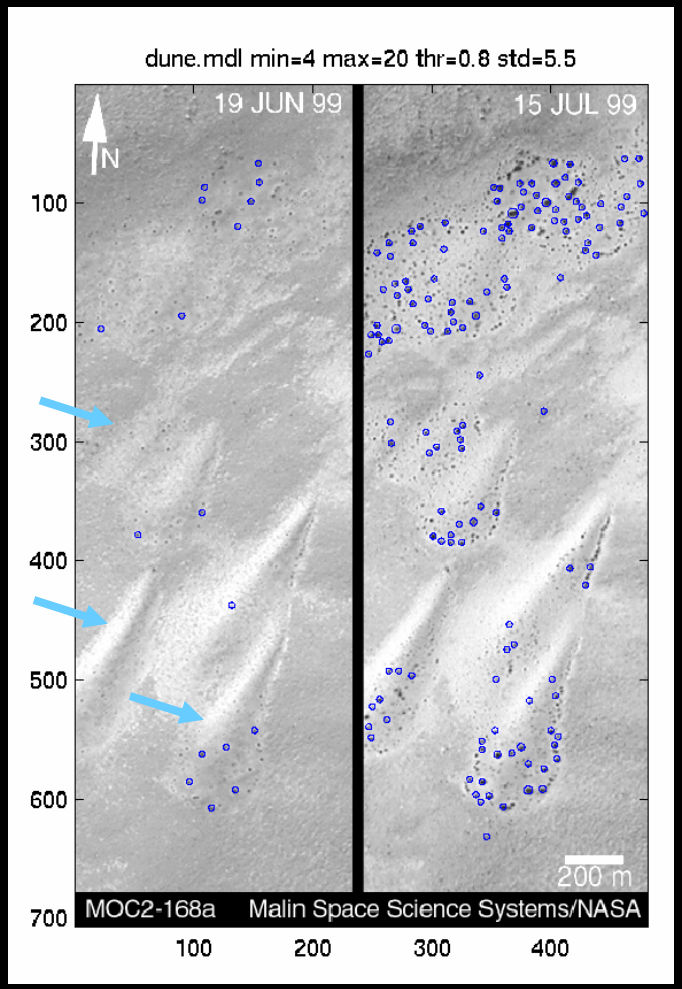
- THEMIS PI (Christensen) requested onboard science capabilities for ODY 2nd extended mission: dust storms, clouds, thermal anomalies, polar volatiles



EDR Processed Labeled

K. Wagstaff, R. Castano

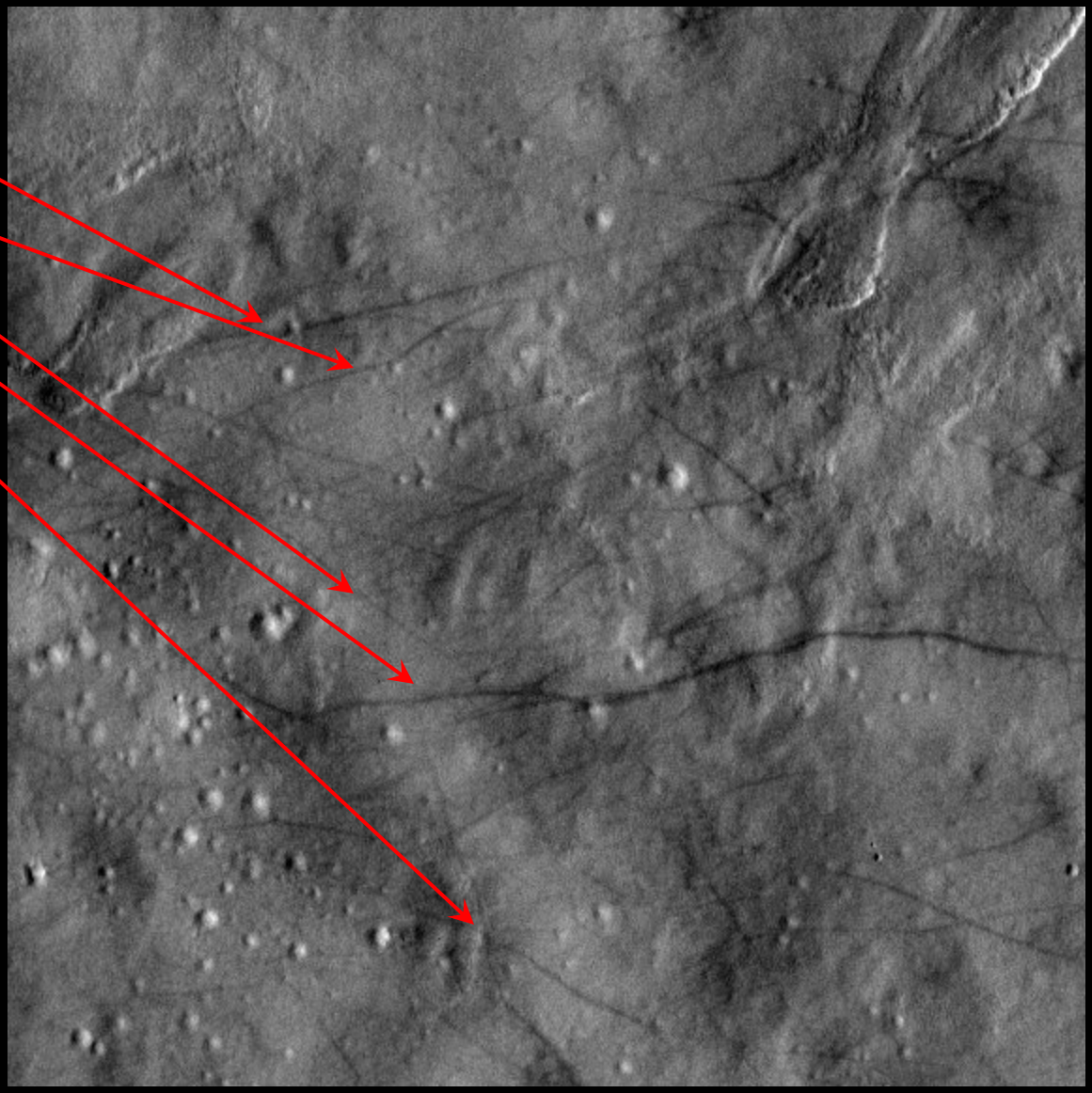
Martian Aeolian Features



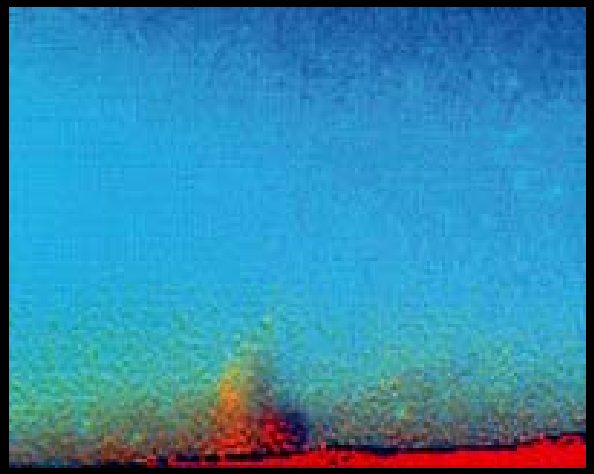
Wind Streaks and Dune Caps

Dark Slope Streaks

Dust Devil tracks in THEMIS/Odyssey Imagery



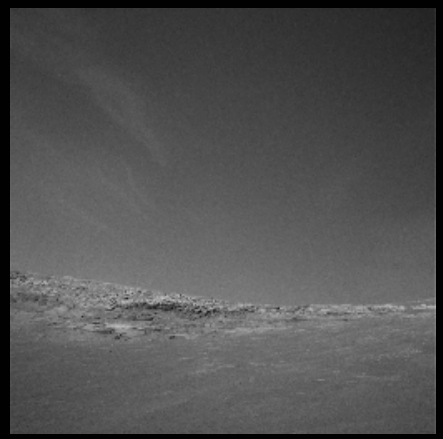
Dust Devil as captured by Pathfinder

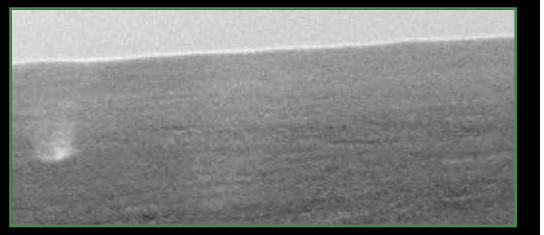


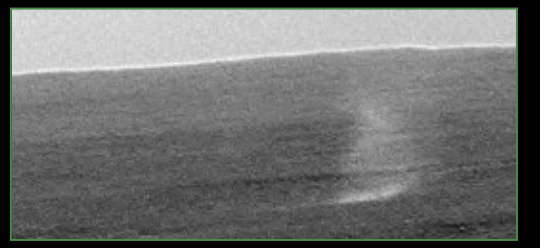
Mars Exploration Rovers

- 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)

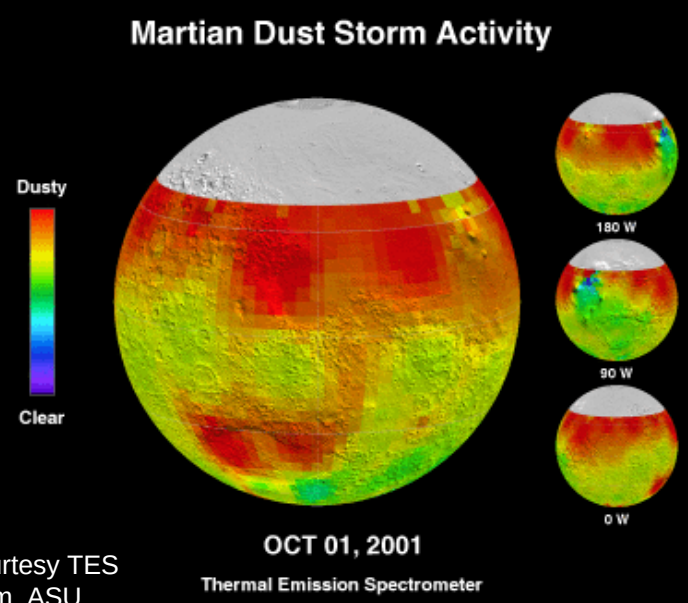
S. Chien, R. Castano

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

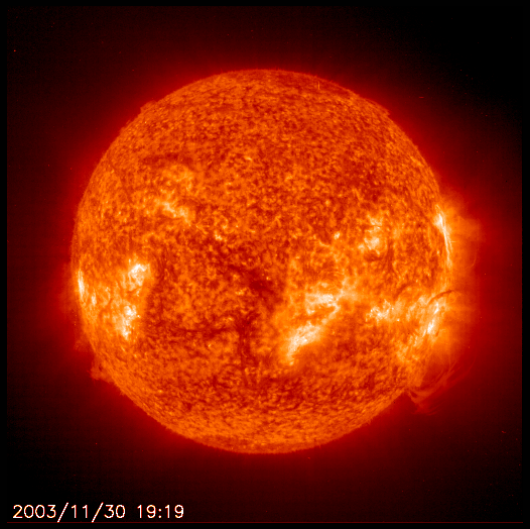


Courtesy TES team, ASU

Tracking Magnetospheric Events

Aurora as seen by
IMAGE FUV instrument

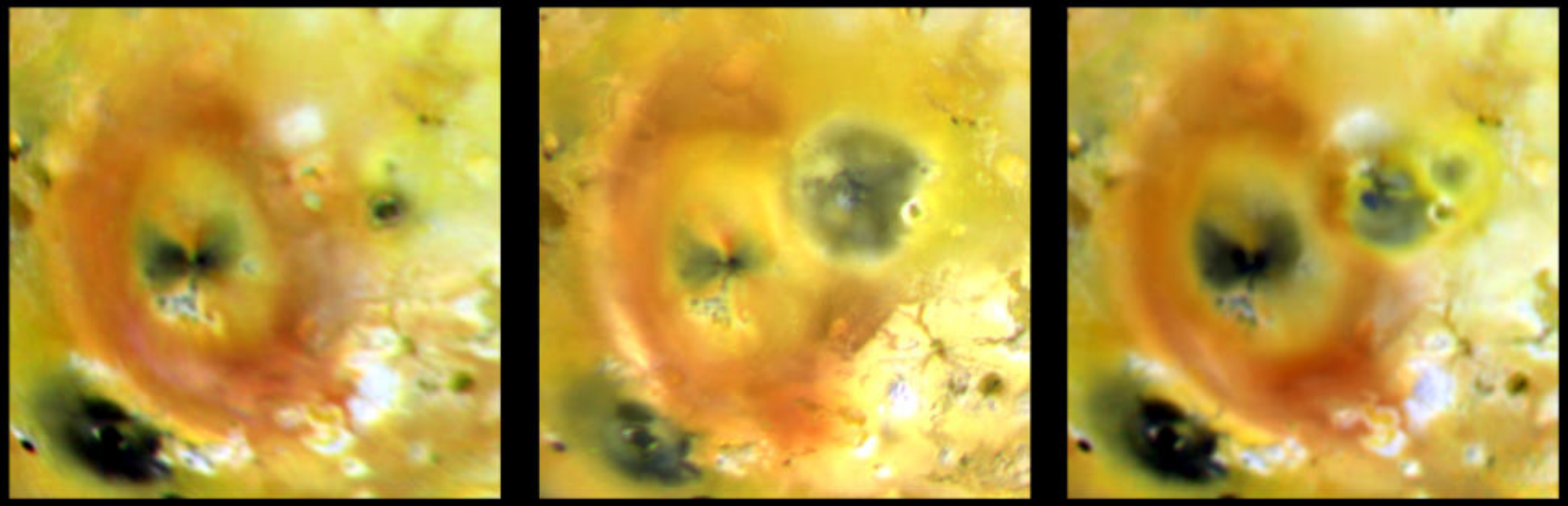
Space Weather



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

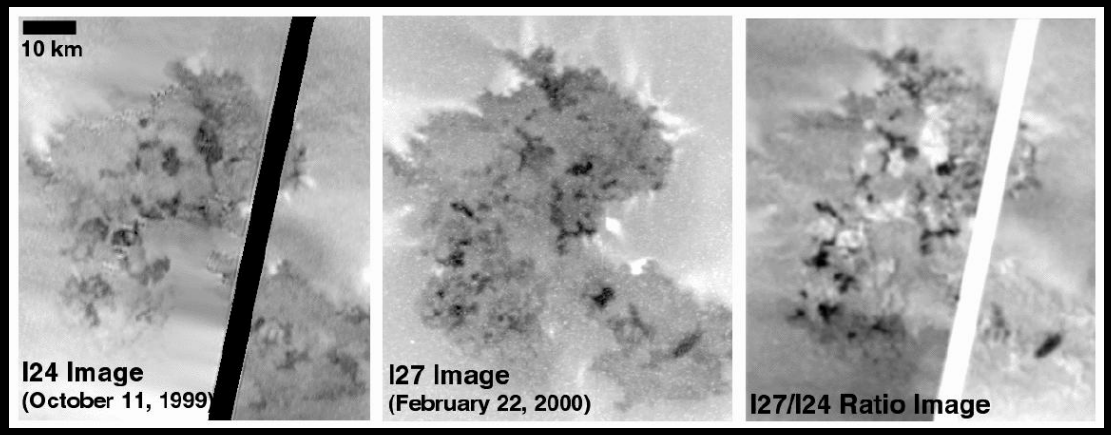
Earth orbiting Magnetospheric Observers automatically respond by reconfiguring to acquire best data

Change Detection on Io



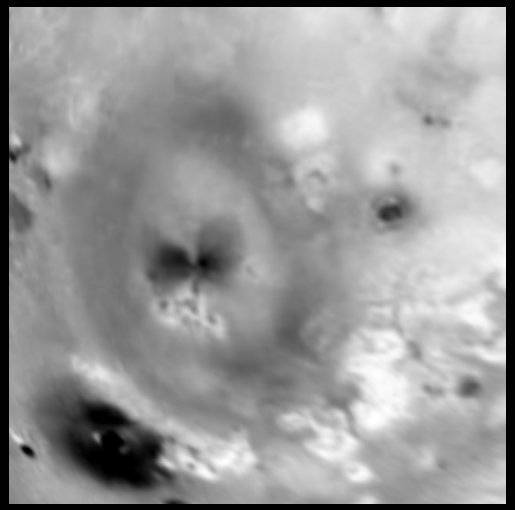
Changes at Pele and Pillan, 1997-1999 (visible)

- 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

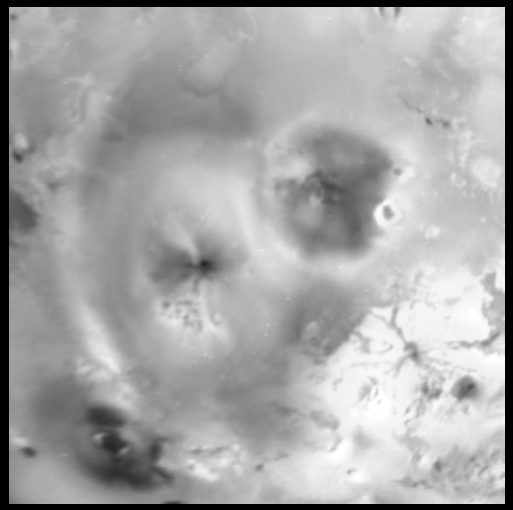


Emplacement of lava flows, Prometheus, 1999-2000

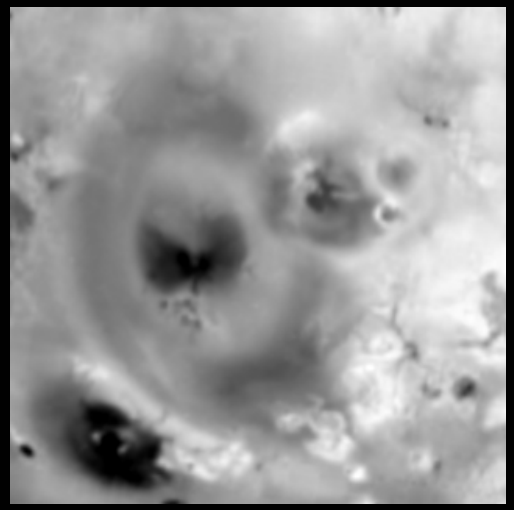
Change Detection on Io - 2



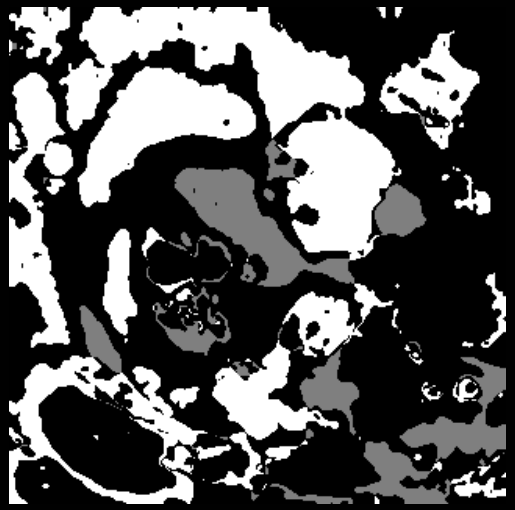
1. G7 April 1997 Galileo SSI



2. C10 September 1997

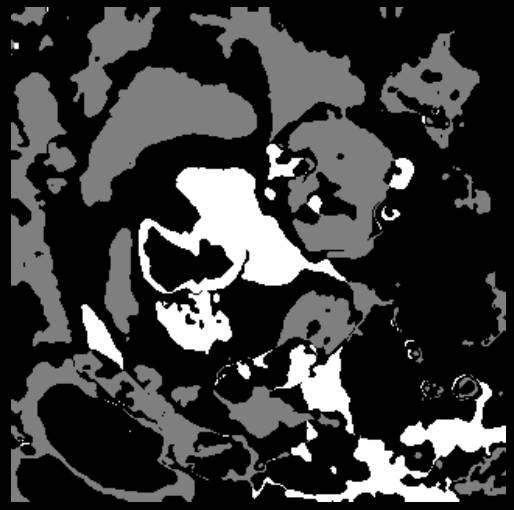


3. C21 July 1999



Changes 1-2

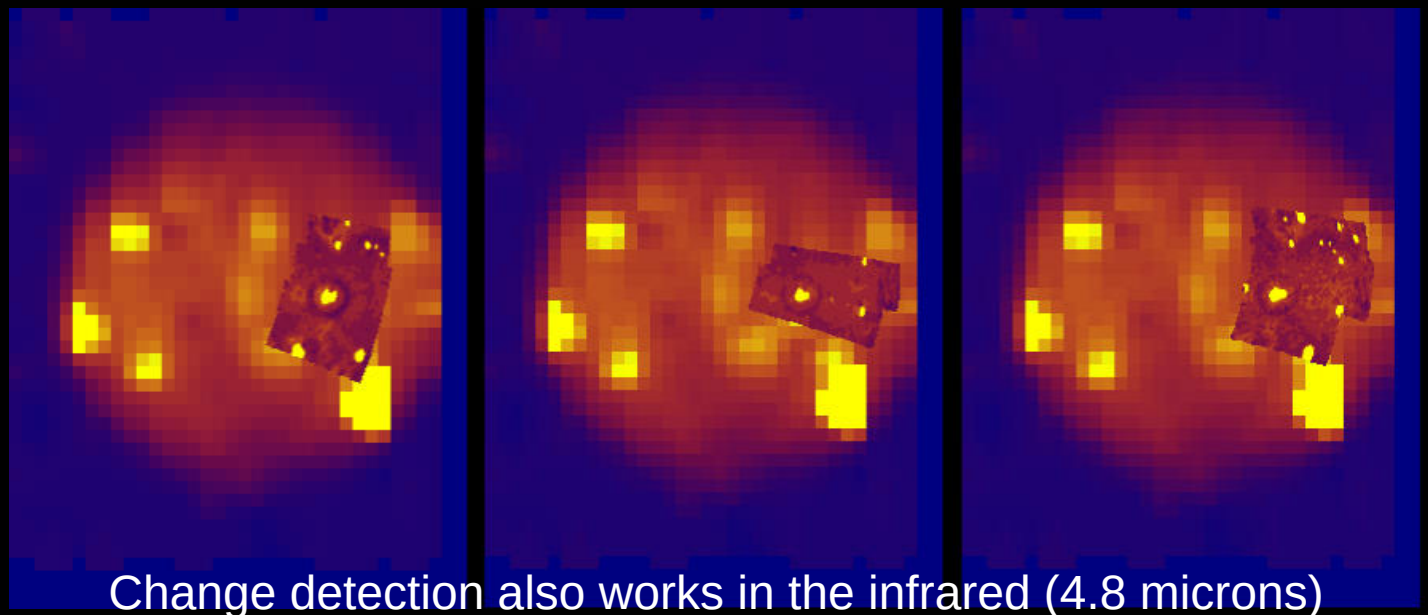
Changes 2-3



Changes 1-3

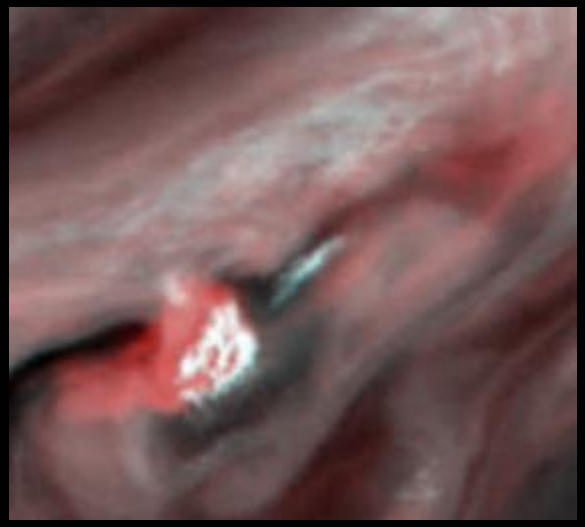
Galileo at Io

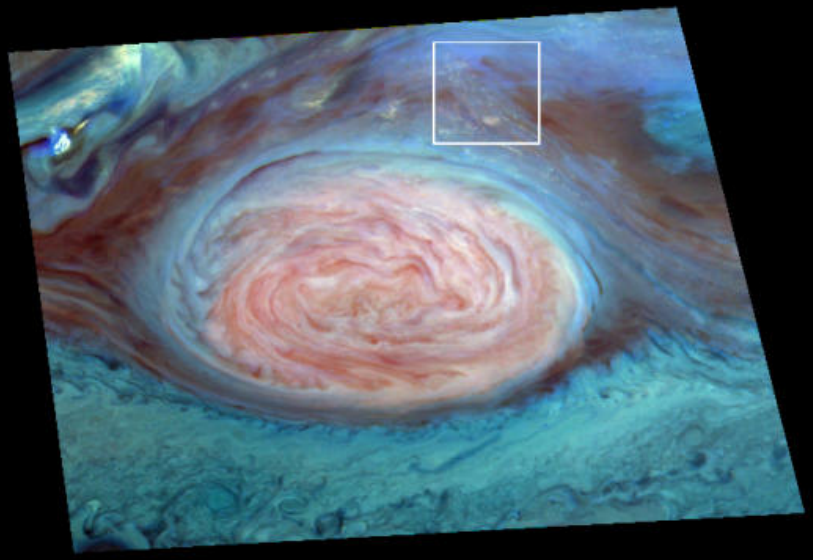
Feature Identification: Plume detection

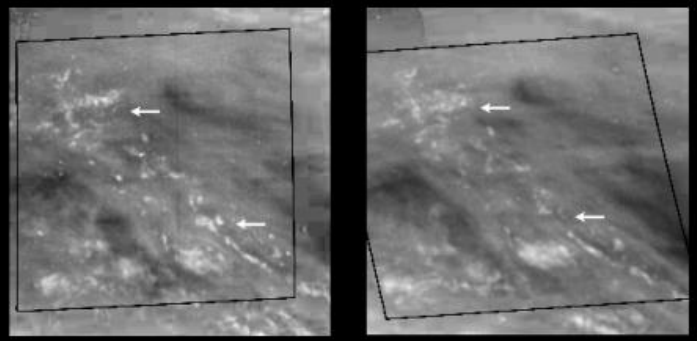


Change detection also works in the infrared (4.8 microns)

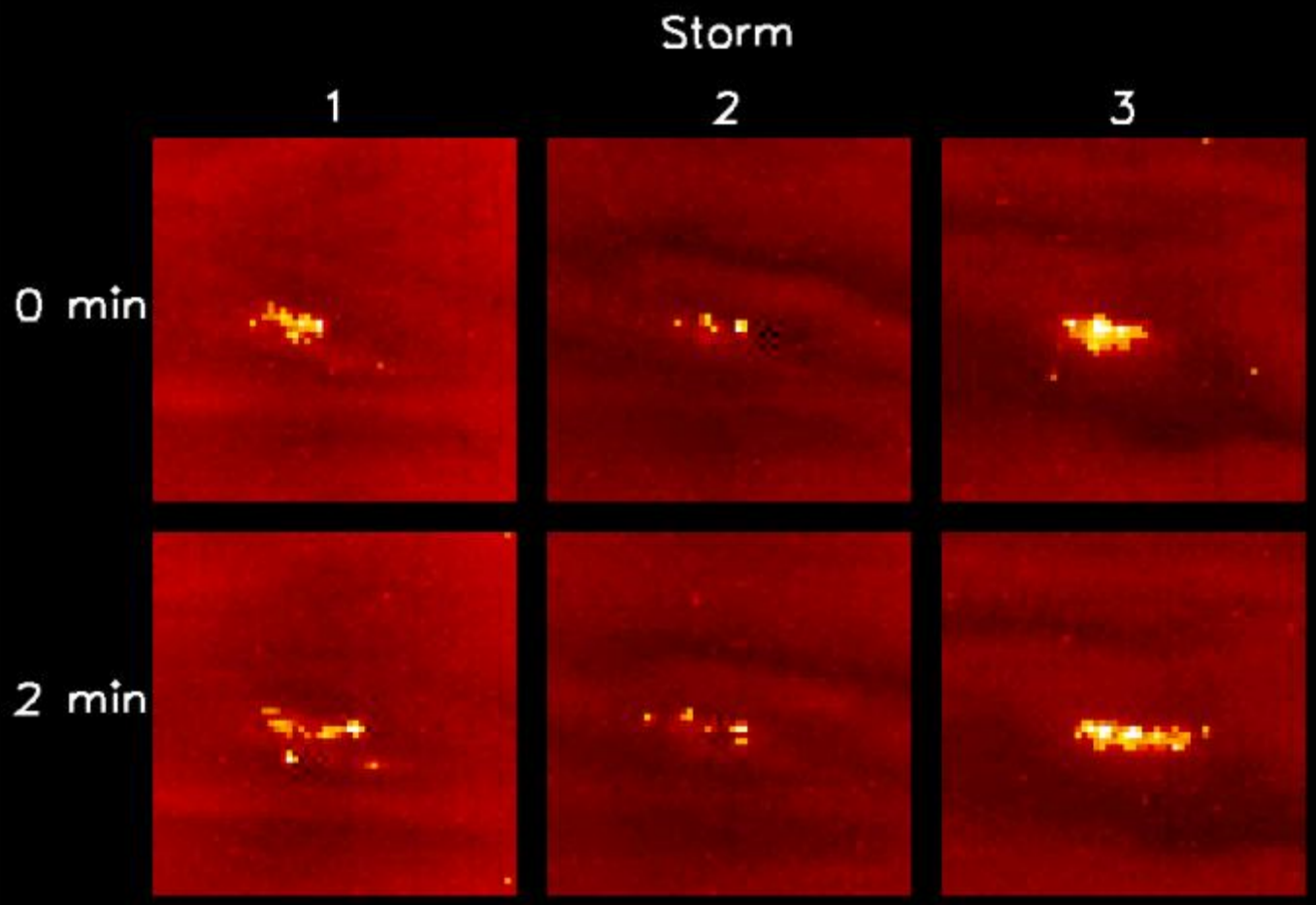
Tracking Jovian Atmospheric Features



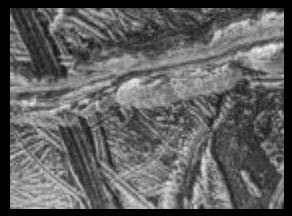




Tracking Jovian Lightning



Tracking Europan Surface Changes

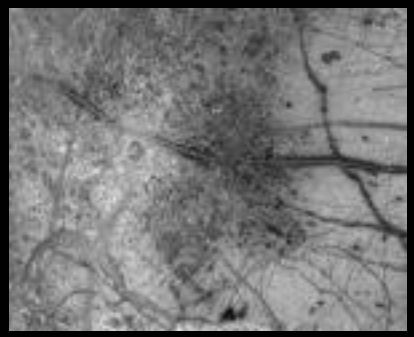


Extract and track segmentation of boundaries

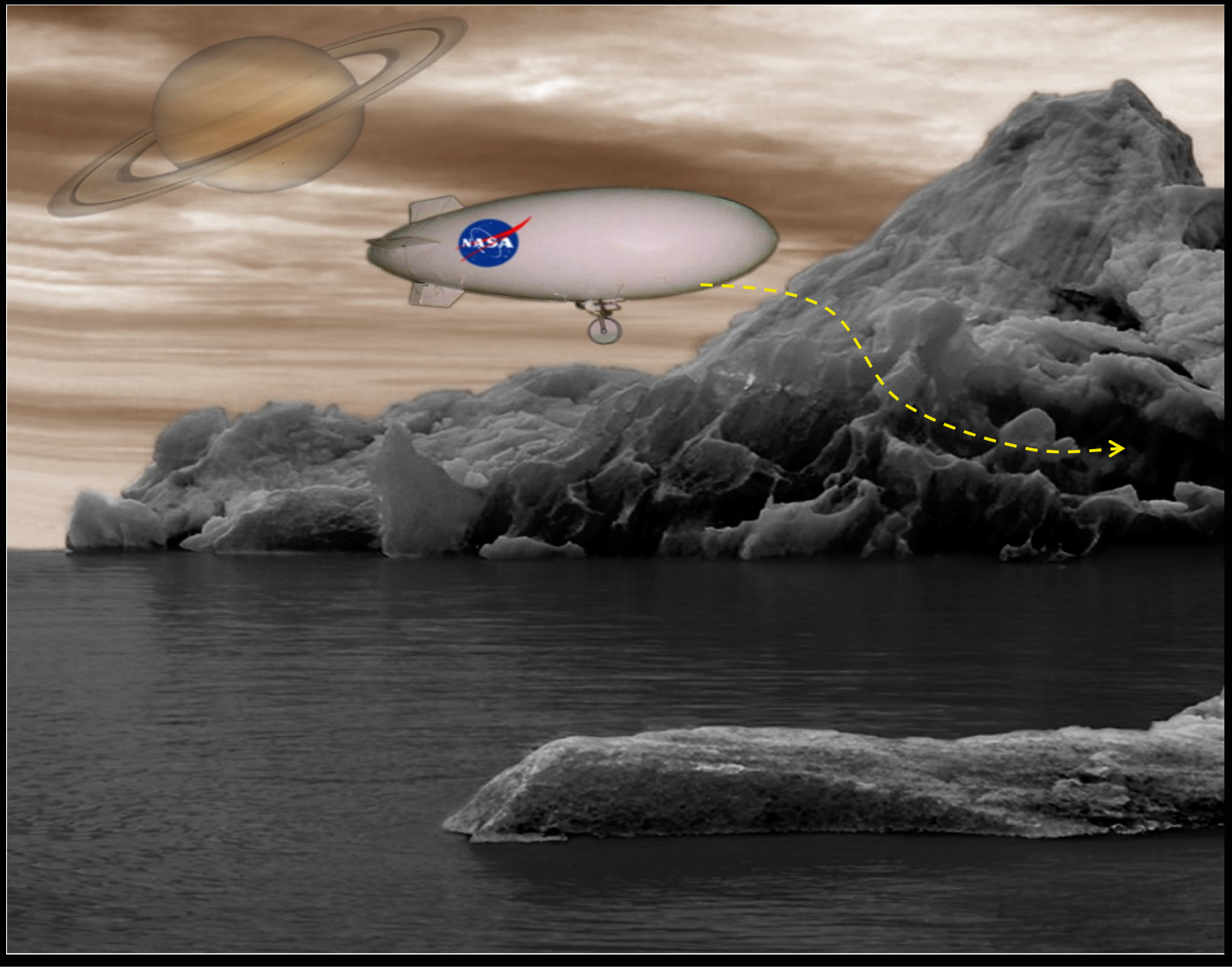
Extract and track region boundaries

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

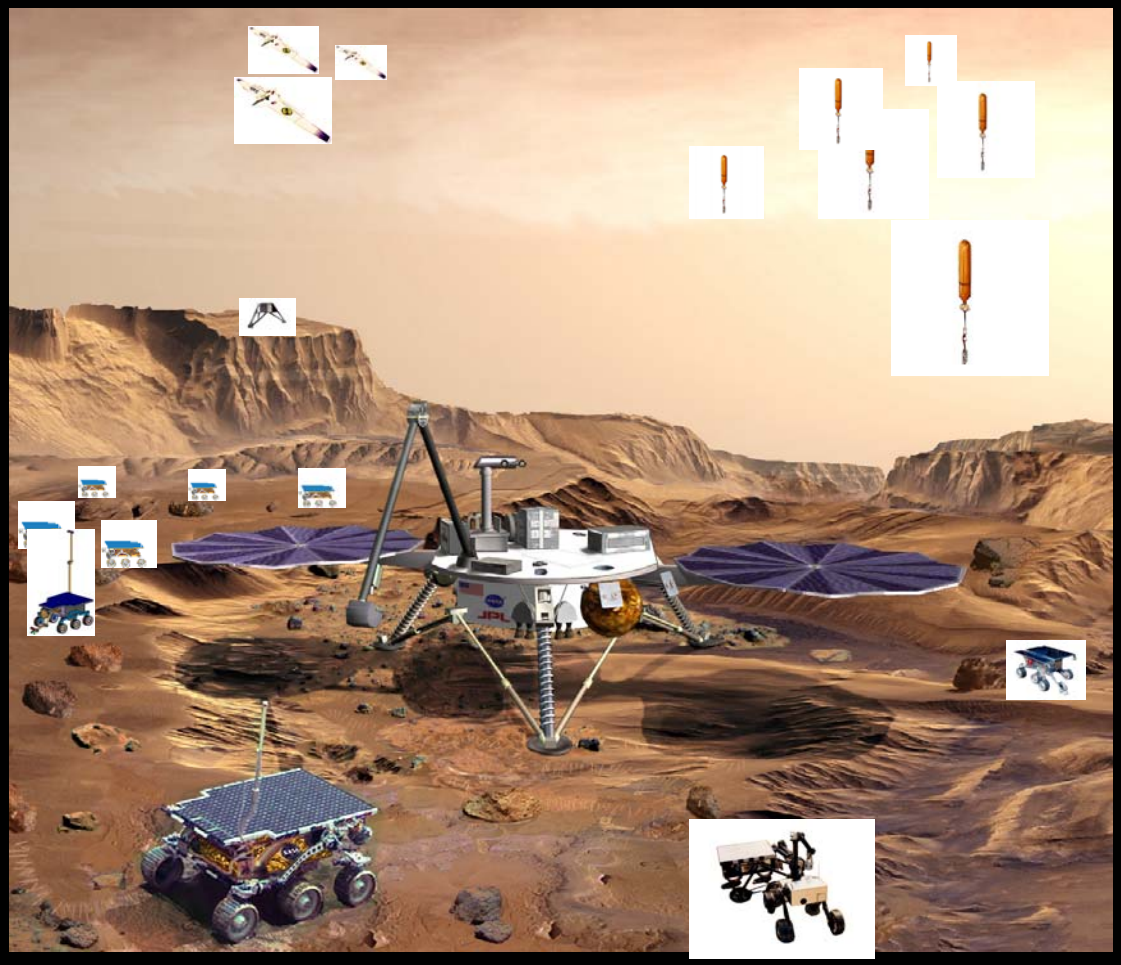
- Thickness and composition of ice-cap
  - energy expended to penetrate surface
  - data volume and type collected
  - ability to communicate while below cap (reliability, rate)
  - effectiveness of melting strategies (fast v. slow)
- Properties of underground ocean
  - energy and time cost to move/explore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



- Long-term environmental changes (general warming trend)
- Medium-term environmental changes (seasons)
- Shorter-term environmental changes (storms)
- Hardware degradation
- Communications performance
- Mobility
- Sensor effectiveness

  …

Adaptive, self-organizing Exploration Agents

- conduct extended (decades long) environmental and geological Martian survey

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:
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- 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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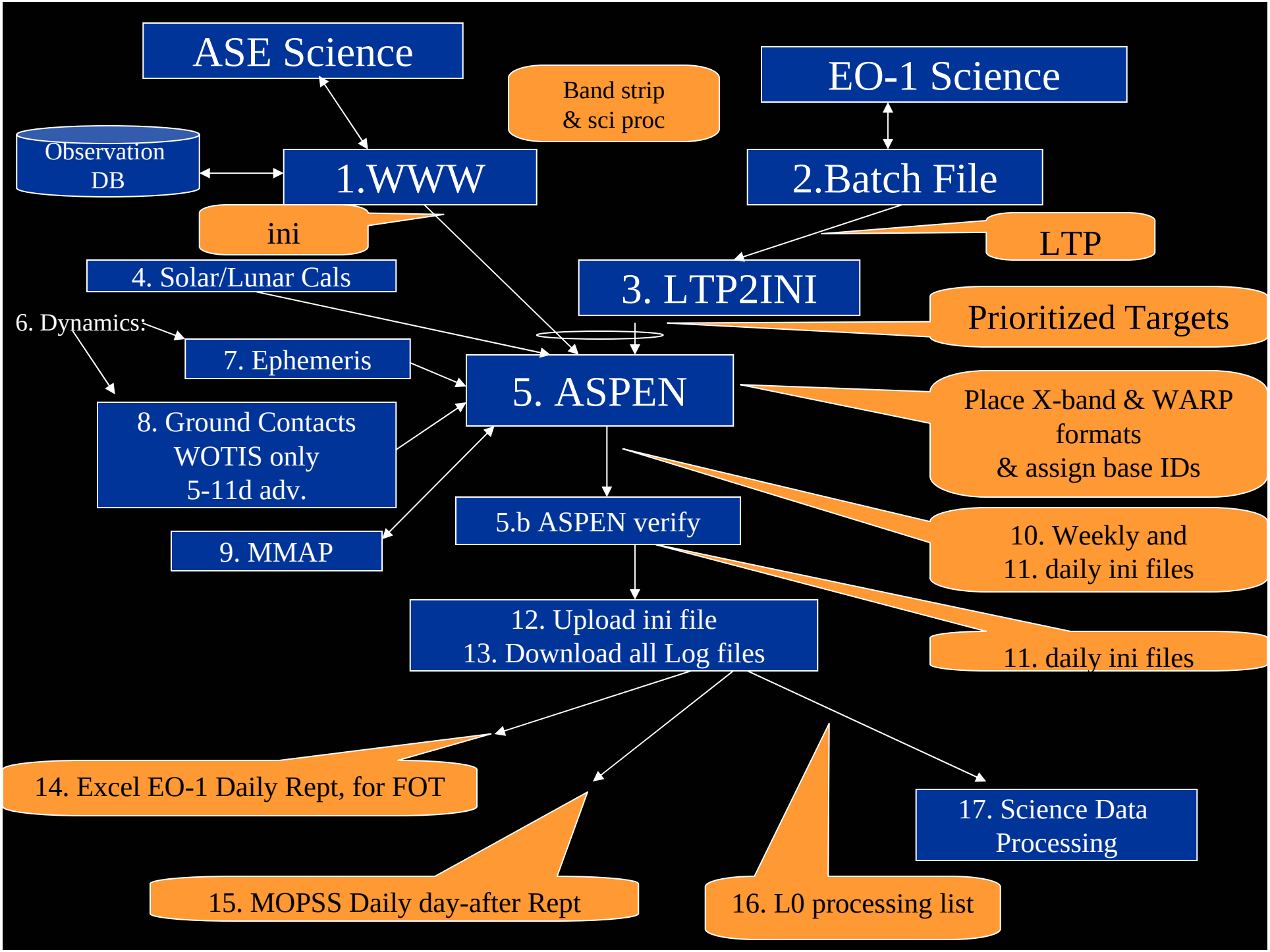
ASE Science
Band strip
& sci proc
EO-1 Science
Observation
DB
1.WWW
2.Batch File
ini
LTP
4. Solar/Lunar Cals
3. LTP2INI
Prioritized Targets
6. Dynamics:
7. Ephemeris
5. ASPEN
Place X-band & WARP
formats
& assign base IDs
8. Ground Contacts
WOTIS only
5-11d adv.
5.b ASPEN verify
10. Weekly and
11. daily ini files
9. MMAP
12. Upload ini file
13. Download all Log files
11. daily ini files
14. Excel EO-1 Daily Rept, for FOT
17. Science Data
Processing
15. MOPSS Daily day-after Rept
16. L0 processing list

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”