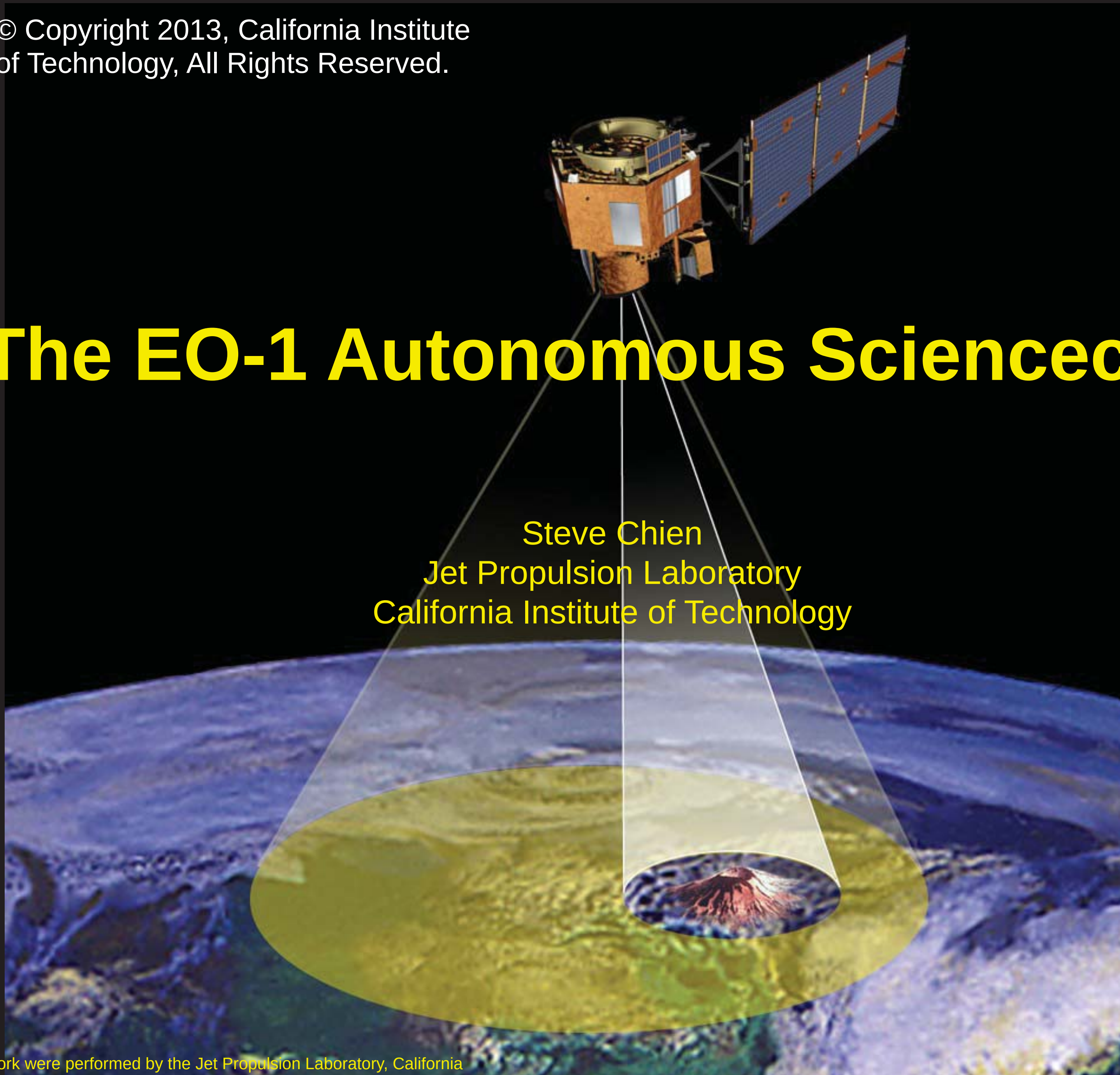


The EO-1 Autonomous Sciencecraft

Steve Chien
Jet Propulsion Laboratory
California Institute of Technology

JPL Clearances
CL#12-2856
CL#12-2847
CL#05-0079
CL#10-0794

Portions of this work were performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

ASE on EO-1 Example Mission Scenario

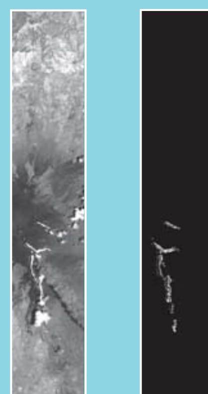
Image taken by Spacecraft

ASE on EO-1 Example Mission Scenario

Image taken by Spacecraft

Onboard Science Analysis

Event Detection



No Event Detection Delete Image

Event Detected

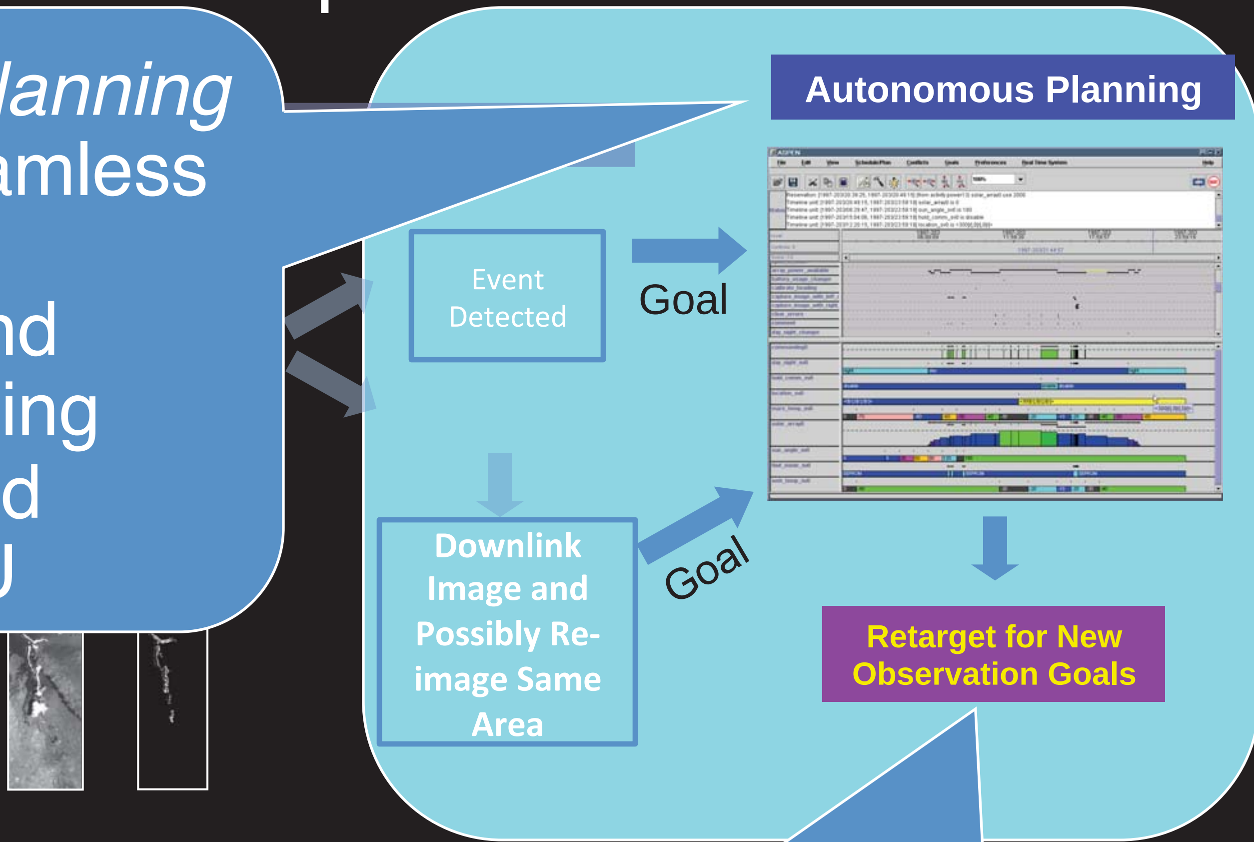
ASE uses state of the art Machine Learning to detect events in the presence of noise

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

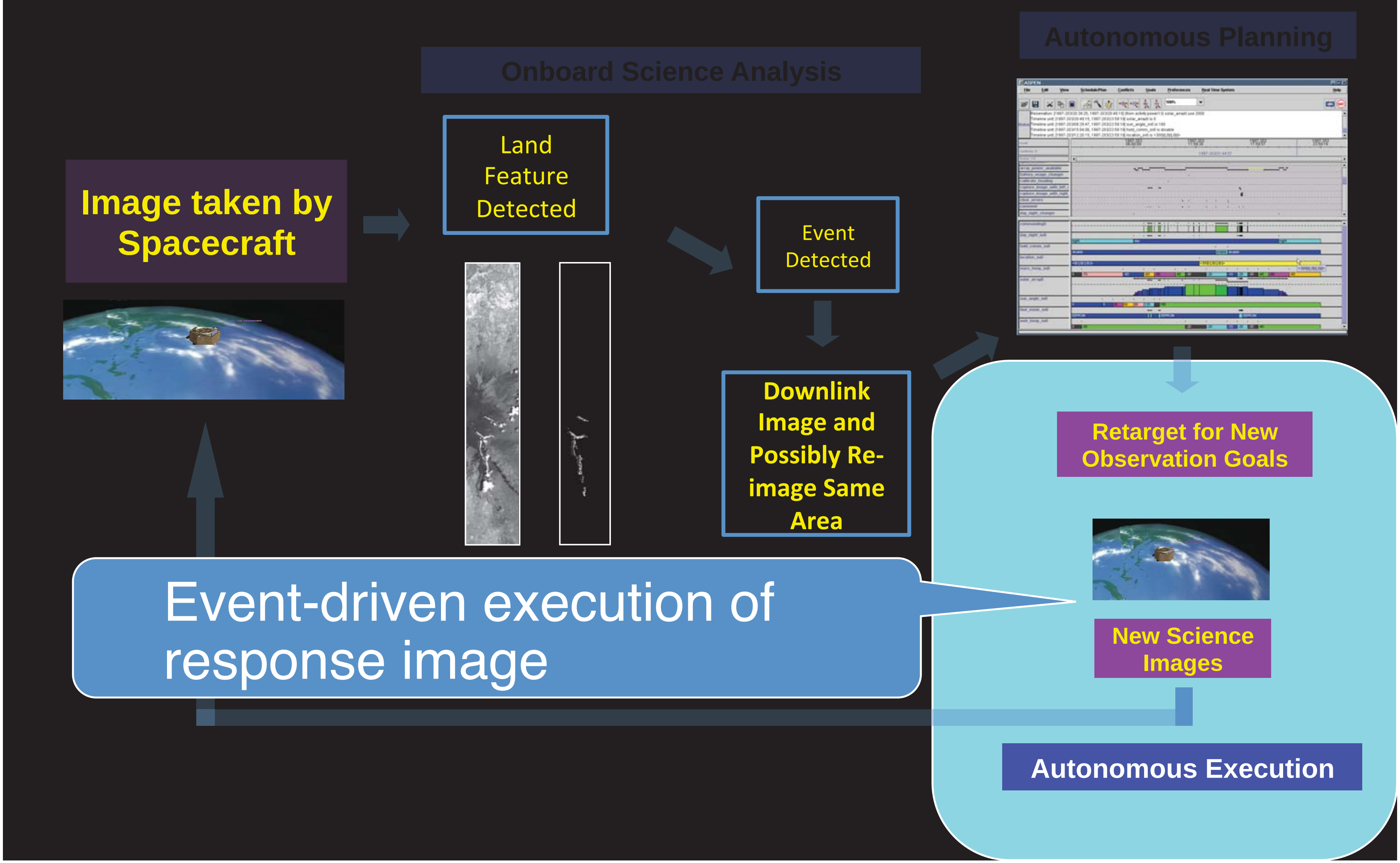
ASE on EO-1 Example Mission Scenario

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



Challenges for AI in Space

- 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 = ~ $200M (source wikipedia)
  - many years to replace; launch opportunity cost

7 May 2004 ASE monitors Mount 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 Mount Erebus

ASE images Erebus (Night) — 13:40 GMT

} +10 min

ASE initiates band extraction

} +28 min

ASE runs thermal classifier

} +29 min

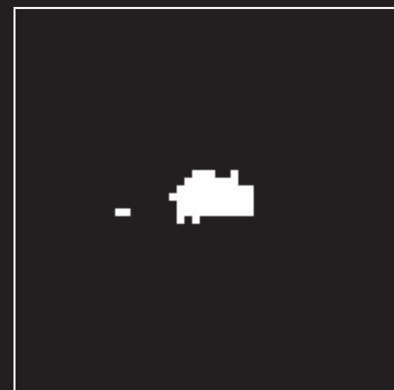
THERMAL TRIGGERED

Planner selects reaction observation (Stromboli observation replaced)

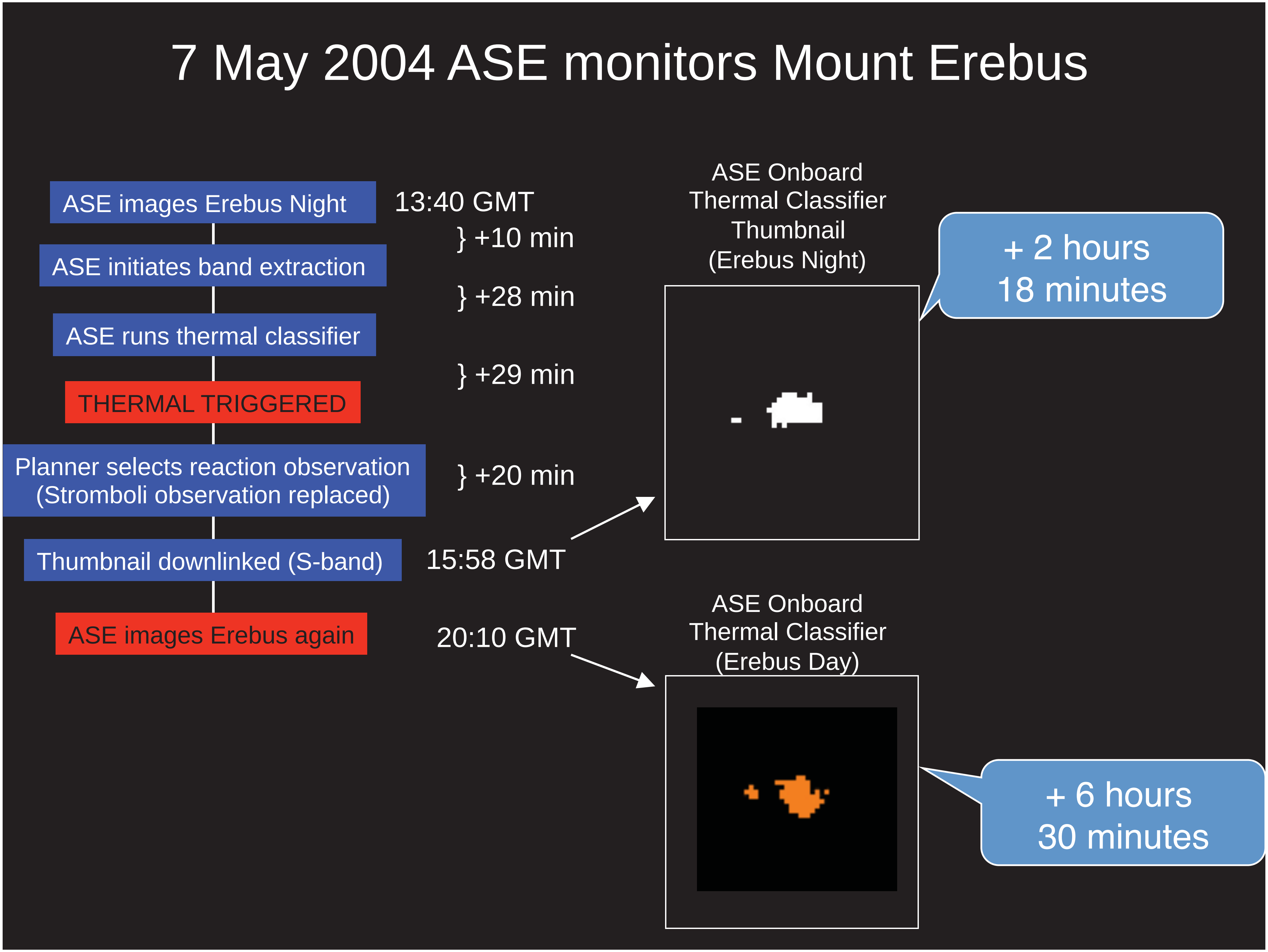
} +20 min

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

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



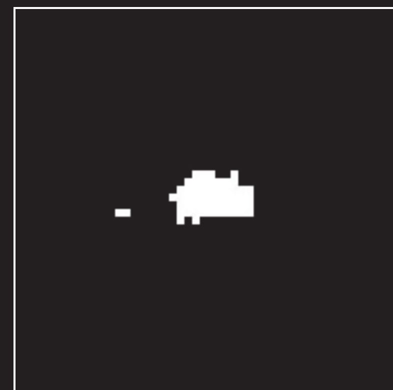
+ 2 hours 18 minutes


7 May 2004 ASE monitors Mount 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
ASE Onboard Thermal Classifier Thumbnail (Erebus Night)
+ 2 hours 18 minutes
ASE Onboard Thermal Classifier (Erebus Day)
+ 6 hours 30 minutes

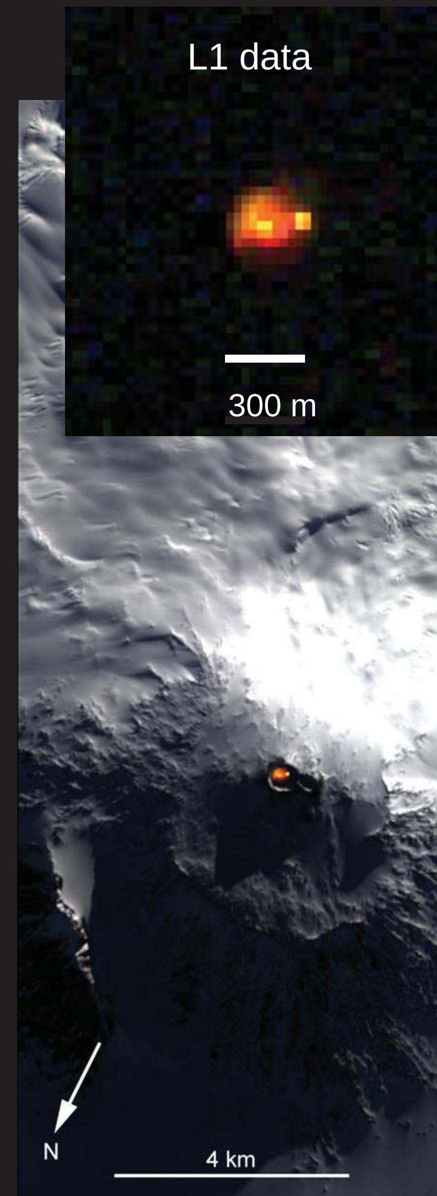
7 May 2004 ASE monitors Mount Erebus

- ASE images Erebus Night — 13:40 GMT
  - } +10 min
- ASE initiates band extraction
  - } +28 min
- ASE runs thermal classifier
  - } +29 min
- THERMAL TRIGGERED
  - } +20 min
- Planner selects reaction observation (Stromboli observation replaced)
- Thumbnail downlinked (S-band) — 15:58 GMT
- ASE images Erebus again — 20:10 GMT + 06:30

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



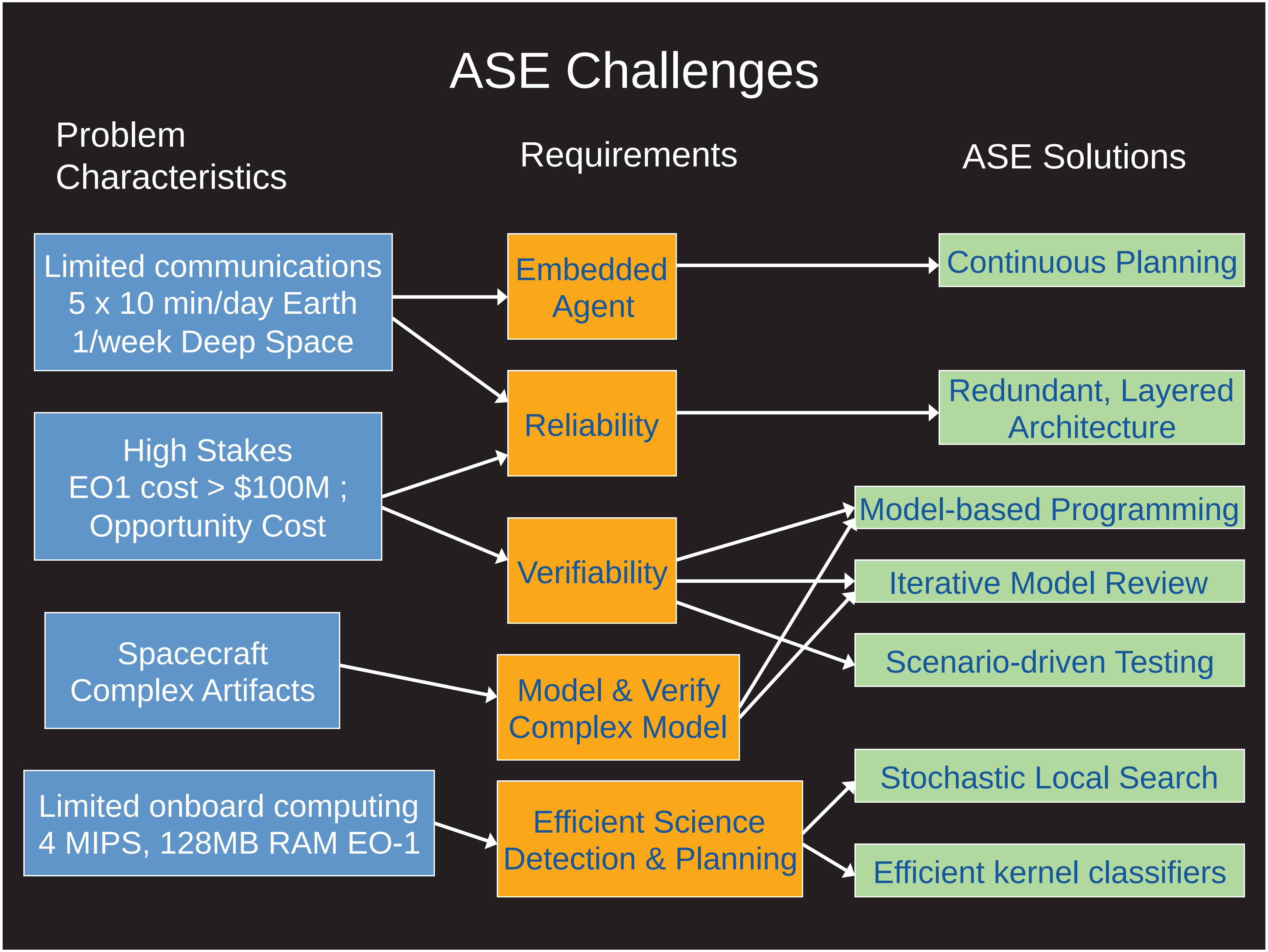
ASE Onboard Thermal Classifier (Erebus Day)



- **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**

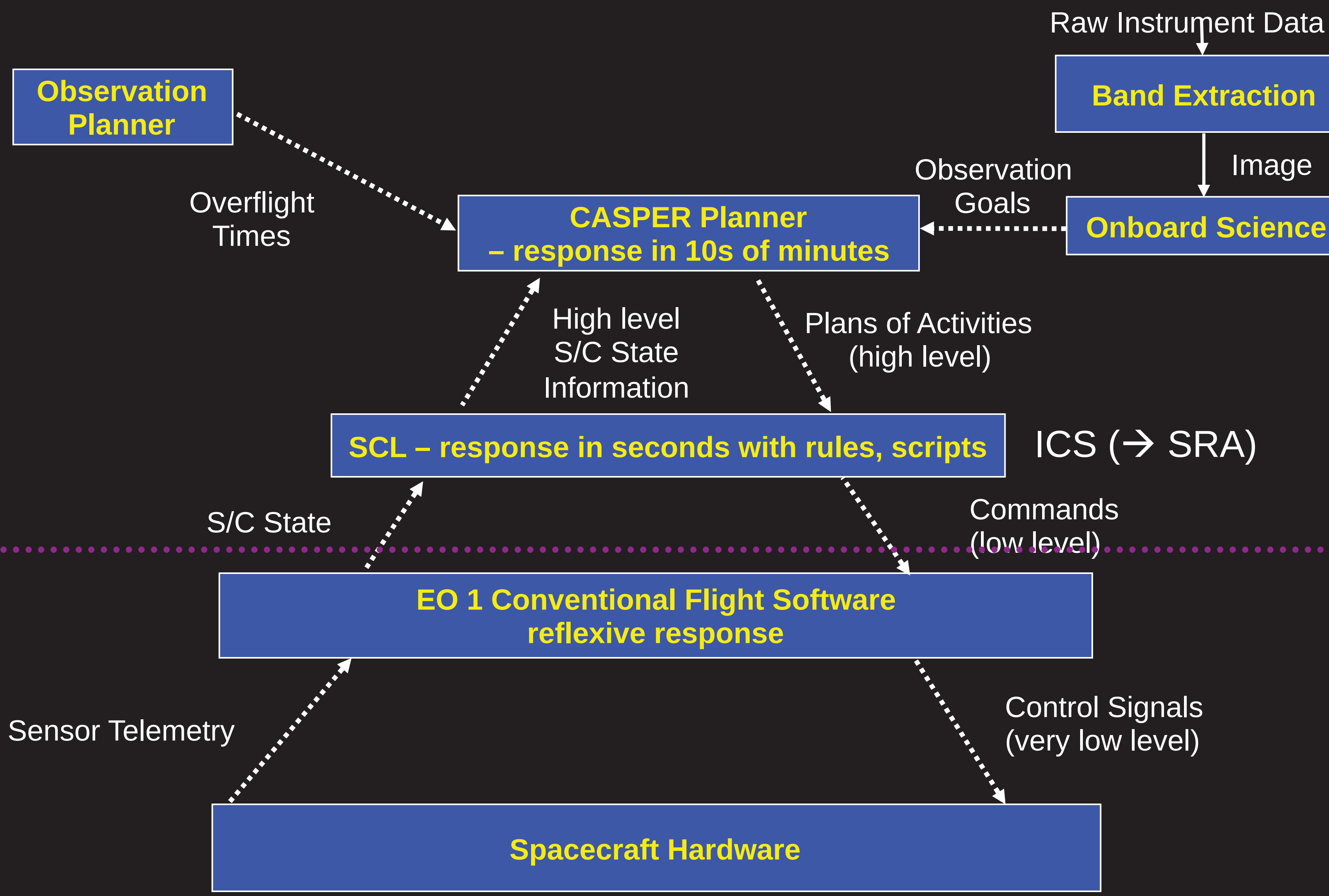
ASE Current Status

- Current count 47000+ 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 (Nov 2004-)**
  - **Enabled > 100x increase in science return**
    - **Measured as: # events captured / MB downlink**
  - **(2004) Enabled a reduction in net operations costs $3.6M/year → $1.6M/yr ; >$1M directly from ASE**
    - **Ops cost reduction enabled extended mission from 2005-2007, 2007-2009**
  - **Reduce re-planning time to respond to anomalies from: days → hours**
  - **(2009) R5 upgrade enabled increase in scene acquisition rate of +33%**
    - **Estimated added value $800K+ / year**
  - **ASE co-winner NASA Software of the Year 2005**



ASE Challenges
Problem Characteristics
Requirements
ASE Solutions
Limited communications
5 x 10 min/day Earth
1/week Deep Space
High Stakes
EO1 cost > $100M ;
Opportunity Cost
Spacecraft
Complex Artifacts
Limited onboard computing
4 MIPS, 128MB RAM EO-1
Embedded Agent
Reliability
Verifiability
Model & Verify Complex Model
Efficient Science Detection & Planning
Continuous Planning
Redundant, Layered Architecture
Model-based Programming
Iterative Model Review
Scenario-driven Testing
Stochastic Local Search
Efficient kernel classifiers

ASE Flight Software Architecture

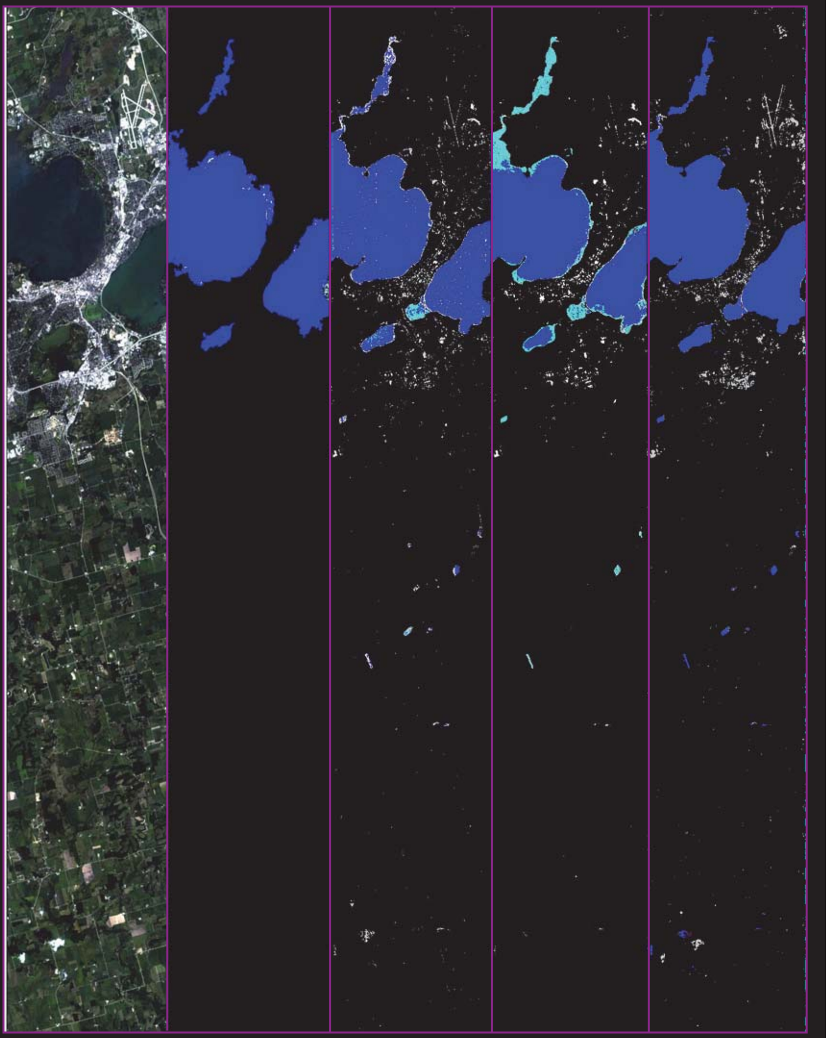


Land, Ice, Water, Snow Detection

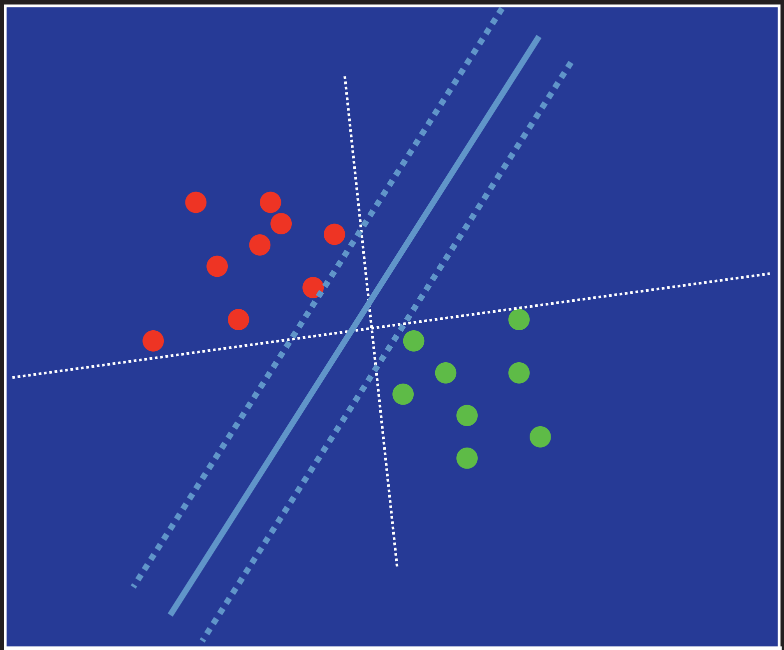
- Primary Purpose
  - Identify areas of land cover (land, ice, water, snow) in a scene
- Three algorithms:
  - Scientist manually derived
  - Automatic best ratio
  - Support Vector Machine (SVM)

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



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)

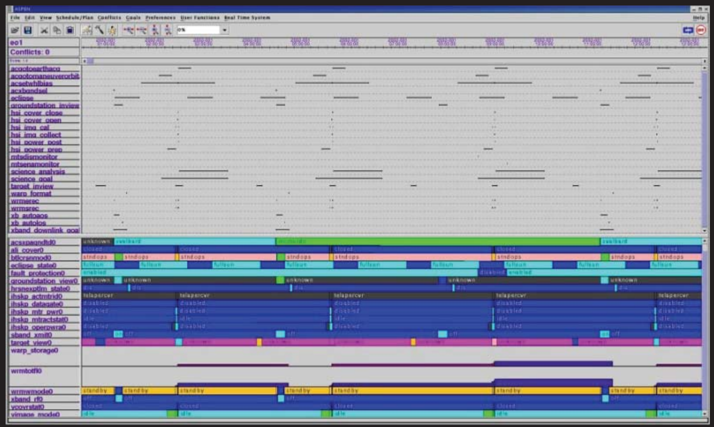
Onboard Replanning

Goals:

science requests,
downlink requests,
maneuver requests

Constraints:

memory,
power



Activity Plan:

2003:233:16:49:57 CMD AC SET WHEEL BIAS(PARAMETERS);
2003:233:17:56:57 CMD ACGOTOMANEUVER(PARAMETERS);
2003:233:18:07:06 CMD ALI SETFPEPOWER(POWER PARAMETERS);
2003:233:18:07:06 CMD HYP HEATER STANDBY;
2003:233:18:07:16 CMD HYP SET SWIR (PARAMETERS);
2003:233:18:07:26 CMD HYP SET VNIR(PARAMETERS);
2003:233:18:11:06 CMD ALI CONFIG FPE(PARAMETERS); …
2003:233:18:17:06 CMD BCM MODES PARAMETERS;
2003:233:18:17:16 CMD WRMSREC(PARAMETERS);
2003:233:18:17:54 CMD ALI SET FPE (PARAMETERS);

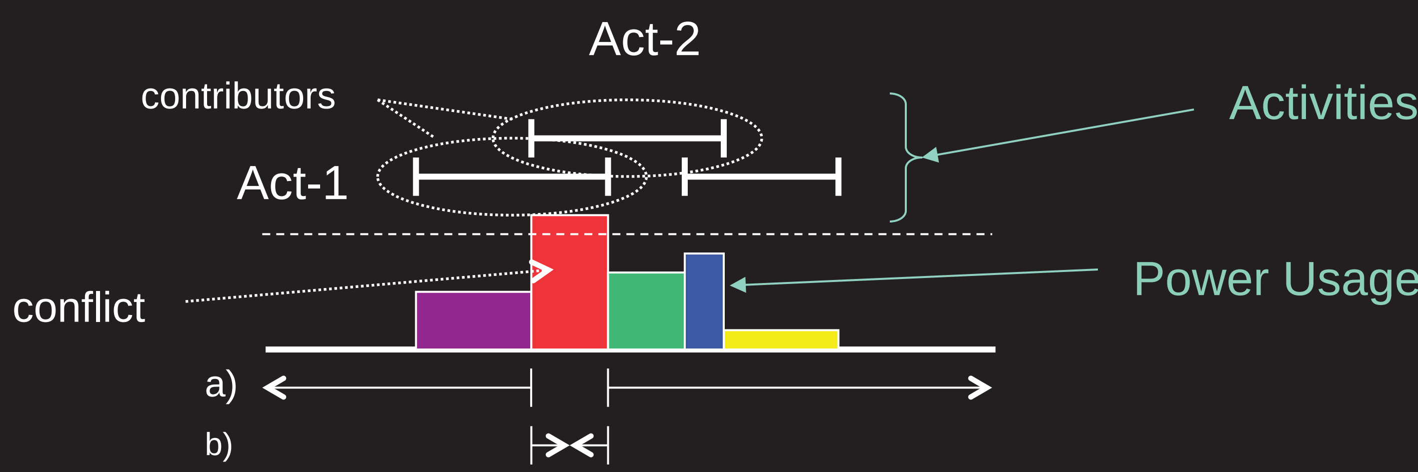
… NOTE: Commands modified for ITAR.

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?

Model-based Programming
Autonomy = Model + Engine

- Autonomy Software consists of two parts
- Engine
  - Supports general constructs which recur in multiple applications
    - Activities, States, Resources in CASPER planner
    - Forward-chaining rules, scripts, monitors, in SCL
- Model
  - Written in engine-specific language
    - Model of EO-1 activities in ASPEN Modeling Language*
    - Model of additional EO-1 constraints in SCL rules and scripts

- Conventional Wisdom
  - Model-based Software increase software reuse

* ASPEN licensed to scores of institutions, used in a wide range of deployments including spacecraft, aerial vehicles, surface and underwater vehicles, etc.

CASPER - SCL Comparison

CASPER Activity

```
// Start the WARP recording
activity WARP record
{
 ...
 reservations =
   // reserve the required number of
   // files on the WARP
   warp_total_file_count use
                activity_warp_file_count,
   // change the warp to record mode
   // when complete
   warp mode change_to "record" at_end,
 ...
}
```

SCL Script

```
-- Start the WARP recording
script WARP record
  ...
        verify
        WARP_current_file_count
              + activity_warp_file_count  <= 63
        and WARP_current_file_count
              + activity_warp_file_count >= 1
and
  ...
end WARP record
```

* model elements modified for ITAR compliance.

Software Reuse

- ASE provides excellent baseline to measure model-based software reuse
  - Techsat-21 operations software adapted to EO-1 operations
  - Same components flown on Three Corner Sat (3CS)

Module	EO-1 code	Reused from TS-21	Reuse
CASPER Flight	223	200	
SCL Flight	214	200	
Science Flight	50	0	
Ground Automation	25	0	
Testing	40	20	
Total	593	420	70%

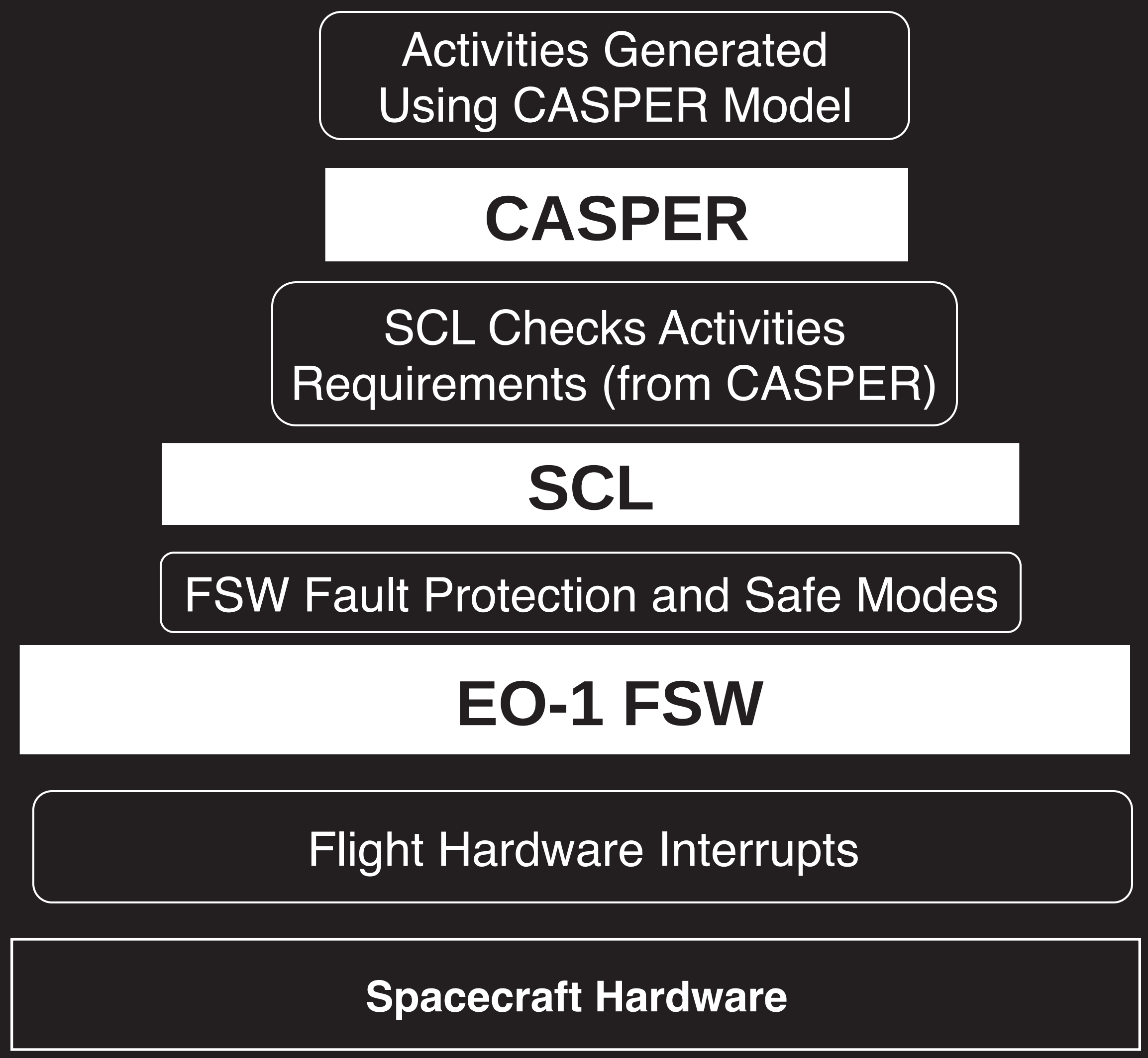
In Kloc

ASE Validation

- Primarily concerned with spacecraft safety.
- Validation combination of
  - architecture, development, formal and informal methods, and testing.
- ASE addresses these through:

1. Layered architecture
2. Informal methods (Iterative model-review)
3. Formal methods
4. Scenario-based ground testing
5. Incremental deployment

Layered Architecture



Informal Methods: Iterative Model Review & Systems Engineering

	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.

Formal Methods

- ASE software checked using static analyzers (memory, pointers, etc.)
  - Recurrent checks as part of regular build process
  - All flagged warnings required team review
- Key spacecraft safety checks produced automatically generated code to ensure model consistency
  - ASPEN model constraints used to automatically generate SCL run-time checks

Test Case Design

- Nominal Cases
- Off-Nominal Cases
  - Outside normal operations, but valid.

Initial State
eclipsed: full sun
ACS mode: nadir
warp allocated: 10 Gb (out of 45)
hyperion cover: closed

Observation Goal
target start: 600s
target end: 900s
image start: 630s
image duration: 12s
science: cloud cover

- Extrema Cases
  - Usually invalid, exercises error handling

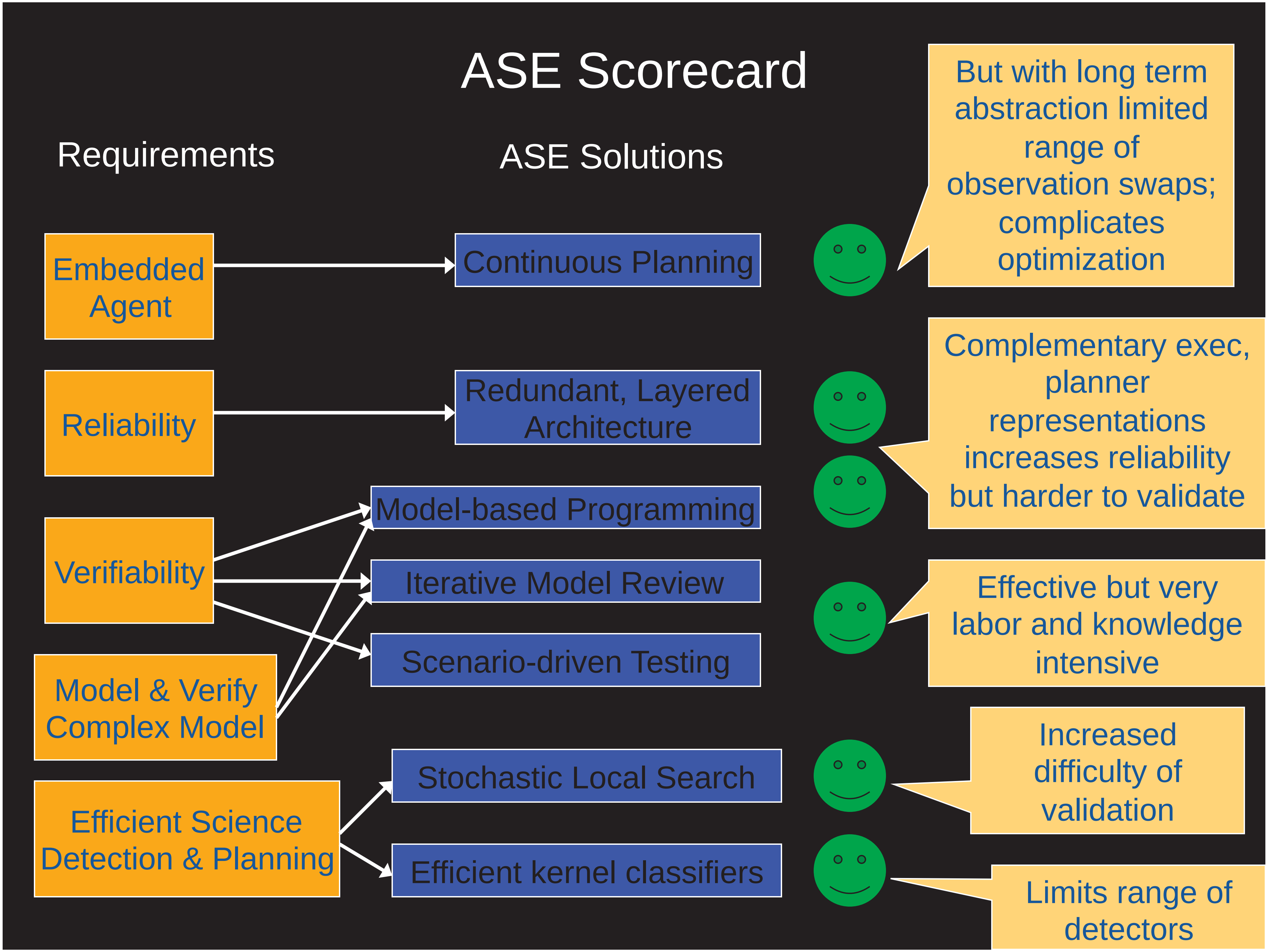
Initial State
eclipsed: full sun
ACS mode: nadir
warp allocated: 45 Gb (full)
hyperion cover: open
…

Observation Goal
target start: 600s
target end: 1200s
image start: 630s
image duration: 60s
science: cloud cover

- Each test case covers up to 7 days of operations

Incremental Development & Flight

- ASE software was developed (and flown) using a spiral methodology
  - Seven (7) spirals of increasing capability: A, B, R(-1), R0, R1, R2, R3
  - R(-1), R1, R2, R3 spirals flown on EO-1; R3 mainstream operational, R4 & R5 later added.
- Key software development practices to ensure quality software
  - All formal code submissions were reviewed by a second core developer
    - Dual signoff required prior to check-in
  - Online discrepancy/issue tracking system with retained history
  - Nightly builds and regression test runs to ensure rapid correction
- Integrated incremental testing plan
  - Unit testing, subsystem testing, and system testing
- Incremental flights of increasing capability
  - R(-1), R1, R2, R3


ASE Scorecard
Requirements
ASE Solutions
Embedded Agent
Continuous Planning
But with long term abstraction limited range of observation swaps; complicates optimization
Reliability
Redundant, Layered Architecture
Complementary exec, planner representations increases reliability but harder to validate
Verifiability
Model-based Programming
Iterative Model Review
Scenario-driven Testing
Model & Verify Complex Model
Effective but very labor and knowledge intensive
Efficient Science Detection & Planning
Stochastic Local Search
Increased difficulty of validation
Efficient kernel classifiers
Limits range of detectors

Observations

Software must be Operator-proof

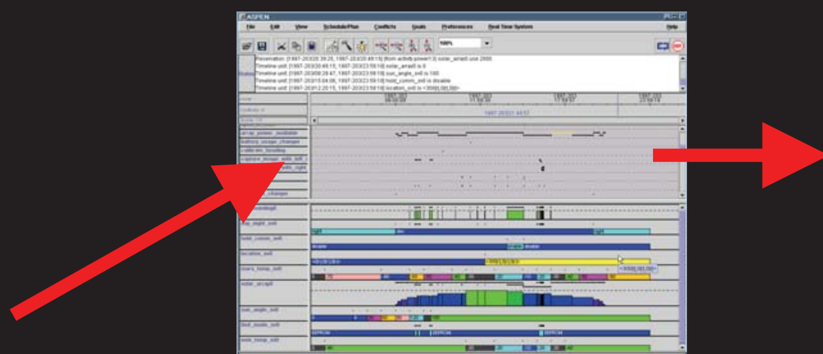
- Goal load anomaly
- Blind acquisition anomaly

- Supervisory systems could provide additional reliability
  - New work on software monitoring and diagnosis

- Most Issues are systems engineering…
  - But manifested in software because majority of systems complexity is in software

Sensorweb

Re-tasking

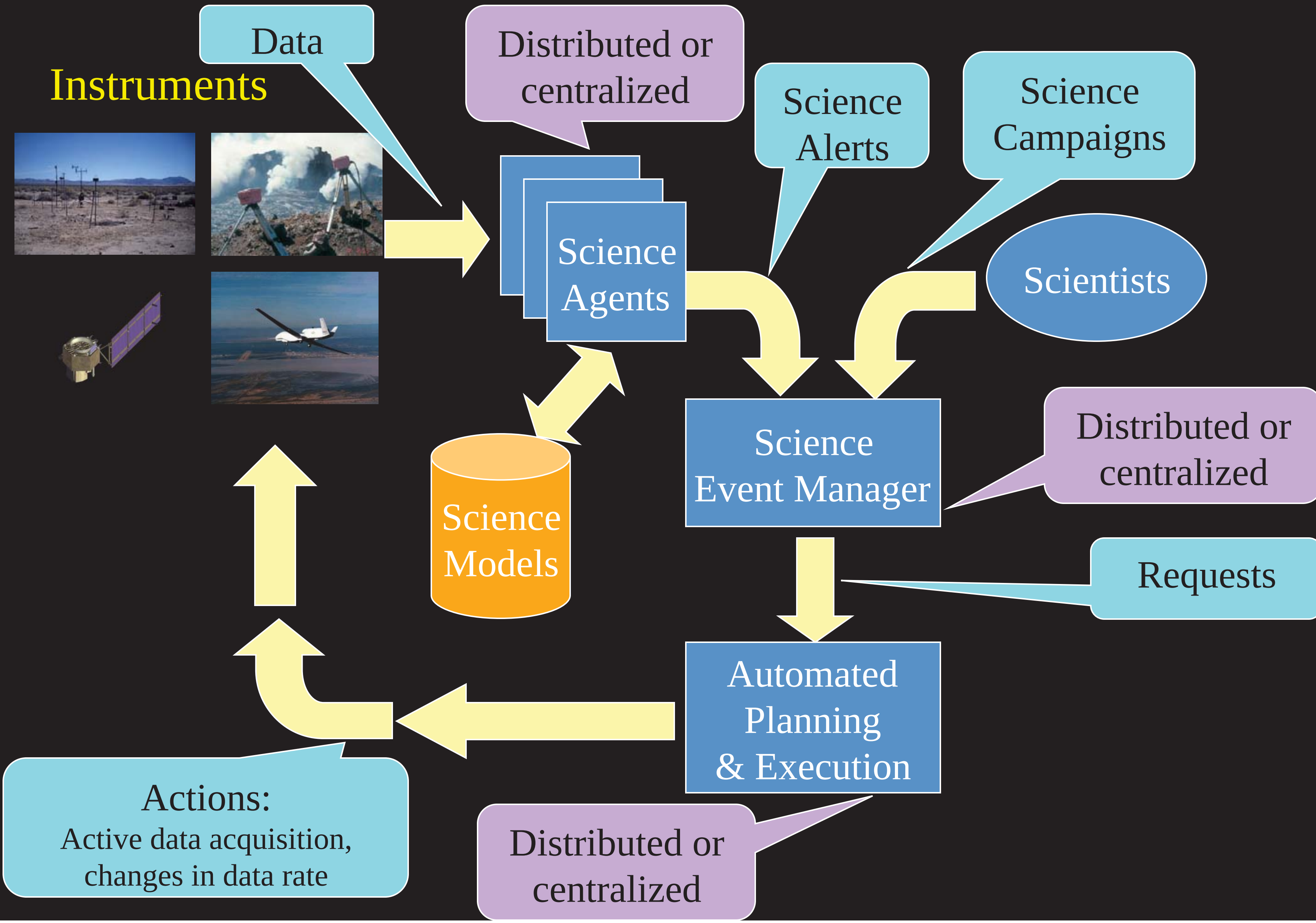


Earth Observer One

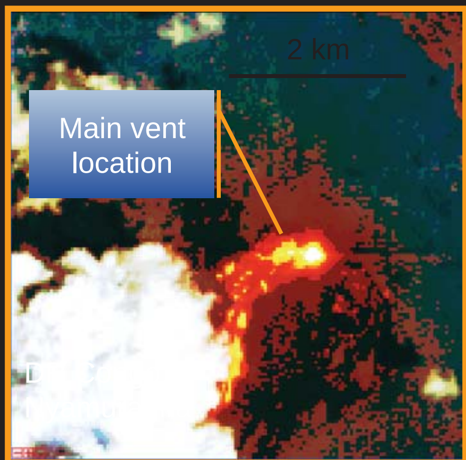
Worldview-2, Geo-Eye-1, Ikonos, Radarsat-2

In 24/7 operations from 2004 - present

Sensorweb Architecture

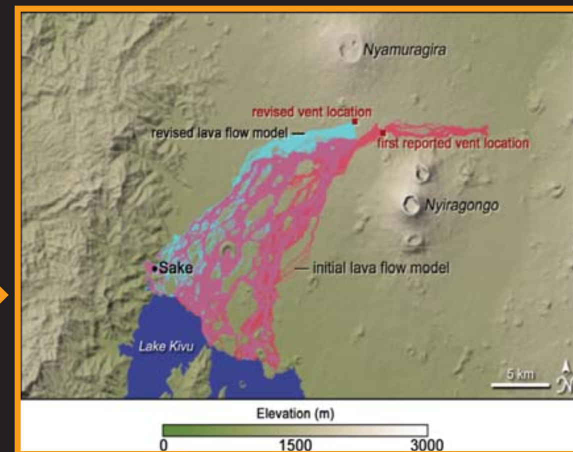


Volcano SensorWeb



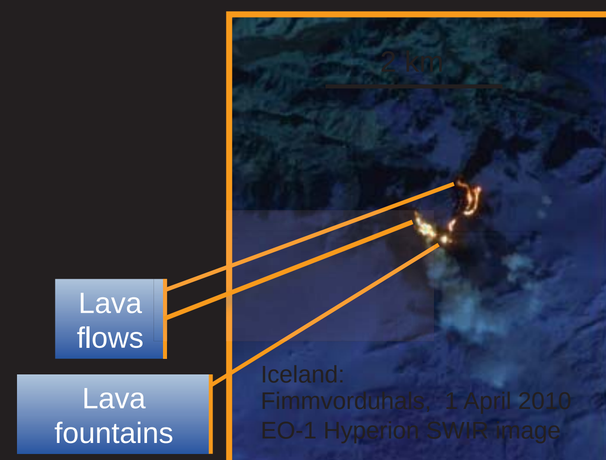
EO-1 Hyperion SWIR image of destructive lava flows at Nyamuragira, DR Congo, 4 Dec 2006.

This vital data acquisition allowed pinpointing of the vent and enabled accurate modeling of likely lava flow direction.



"This was a stunning demonstration of the capability of an autonomous system to obtain and provide vital information during a volcanic emergency."
- Gari Mayberry, Geoscience Advisor, USAid

Alert: Uses alerts from multiple sources (*in situ* sensors, MODIS, AFWA,VAAC, et al.)
Response: Alerts are used in a prioritized fashion to trigger follow up targeted satellite observations.
Product Generation & Delivery: Rapid data processing, thermal maps,modeling of eruption parameters, and posting to end users.SensorWeb now includes in-situ sensor monitoring of Icelandic volcanoes: http://en.vedur.is/earthquakes-and-volcanism



A. G. Davies, S. Chien / JPL

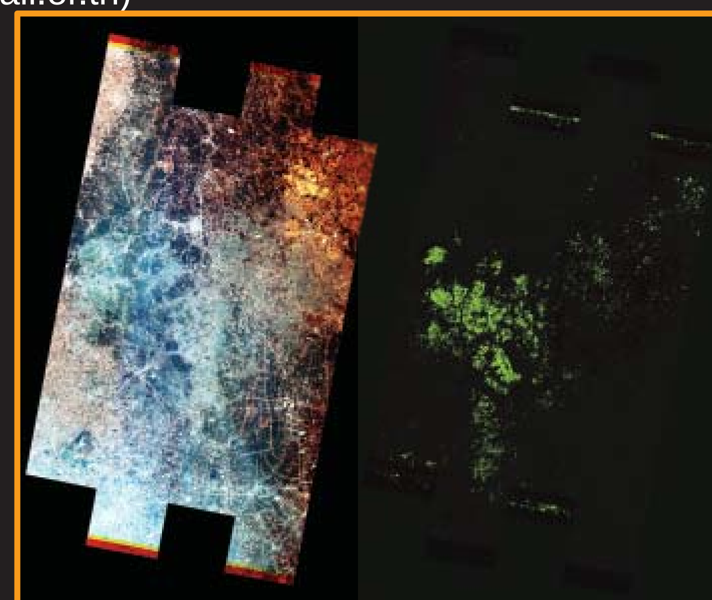
Thailand Flood SensorWeb

- **Detect:** Pull 2x daily LANCE-MODIS subsetted data, support Vector Machine Learning (SVM) & band ratio methods of classifying gauging reaches against baseline dry scores
- **Respond:** Earth Observing 1 autonomously responds to acquire more detailed imagery; Worldview-2, Geo-Eye-1, Landsat-7 ETM, Ikonos, Radarsat-2 data tasking semi-automated
- **Product Generation & Delivery:** Data and flood products electronically delivered to Thailand Hydro Agro Informatics Institute (http://www.haii.or.th)

MODIS 28 Nov 2010 Imagery of Thailand Flooding (band 7-2-1)
Est. damage over $1.67B USD [Thailand MCOT, CNN], Oct–Nov 2010

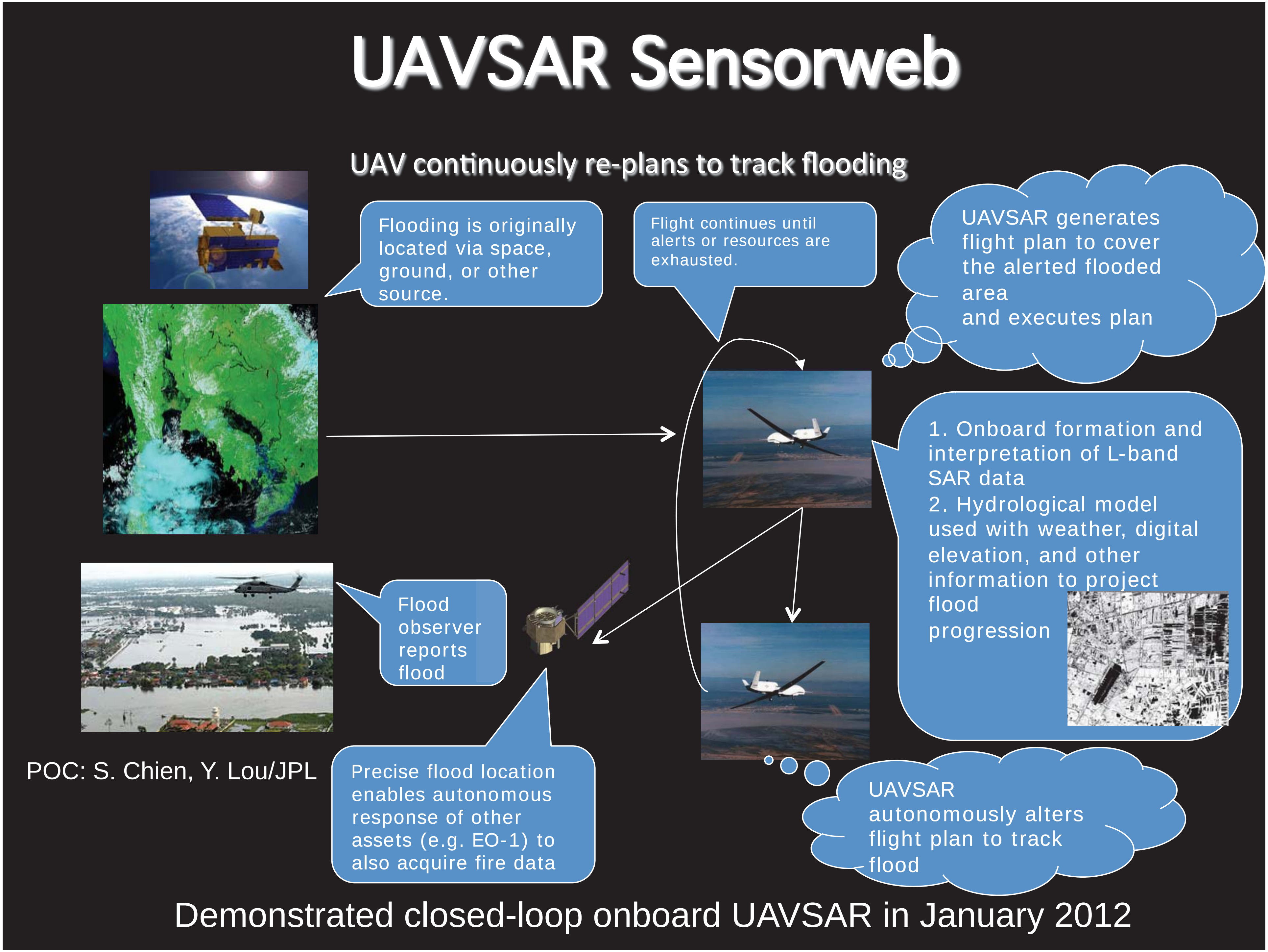
"The Thailand Flood SensorWeb provides a unique capability to detection, monitoring, response, and mitigation of flooding in Thailand"
Dr. Royol Chitadron, Director, HAII Thailand

Detect:
(L) MODIS imagery of Bang Pla Ma from 20 Jan 2011
(R) Classified surface water extent from MODIS image

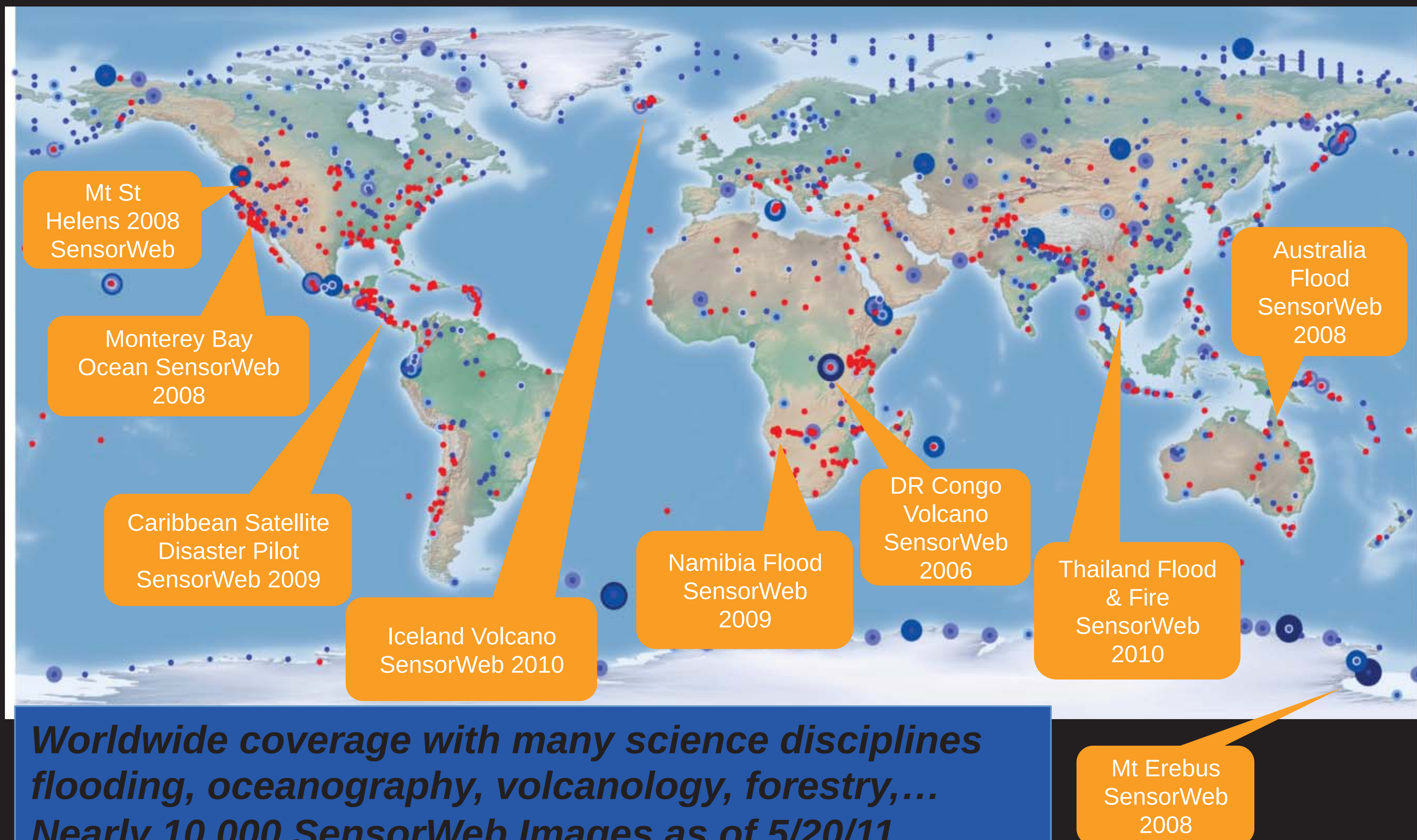


Respond → Generate → Deliver
(L) ALI imagery of Bang Pla Ma from 21 Jan 2011
(R) Classified surface water extent from ALI image

S. Chien / JPL


UAVSAR Sensorweb
UAV continuously re-plans to track flooding
Flooding is originally located via space, ground, or other source.
Flight continues until alerts or resources are exhausted.
UAVSAR generates flight plan to cover the alerted flooded area and executes plan
1. Onboard formation and interpretation of L-band SAR data
2. Hydrological model used with weather, digital elevation, and other information to project flood progression
Flood observer reports flood
Precise flood location enables autonomous response of other assets (e.g. EO-1) to also acquire fire data
UAVSAR autonomously alters flight plan to track flood
POC: S. Chien, Y. Lou/JPL
Demonstrated closed-loop onboard UAVSAR in January 2012

SensorWeb Images



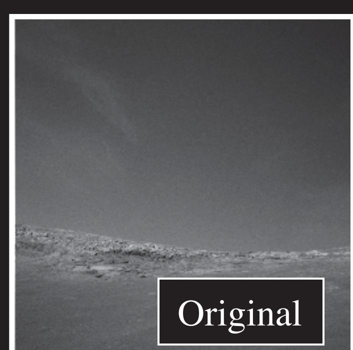
Worldwide coverage with many science disciplines flooding, oceanography, volcanology, forestry,…
Nearly 10,000 SensorWeb Images as of 5/20/11

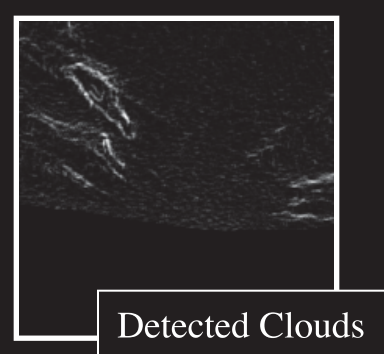
Awarded Honorable Mention, NASA Software of the Year, 2011.

MER-WATCH

- Autonomy software deployed to MER and in operational use (2007-)

Dust Devils
8 Aug 2005

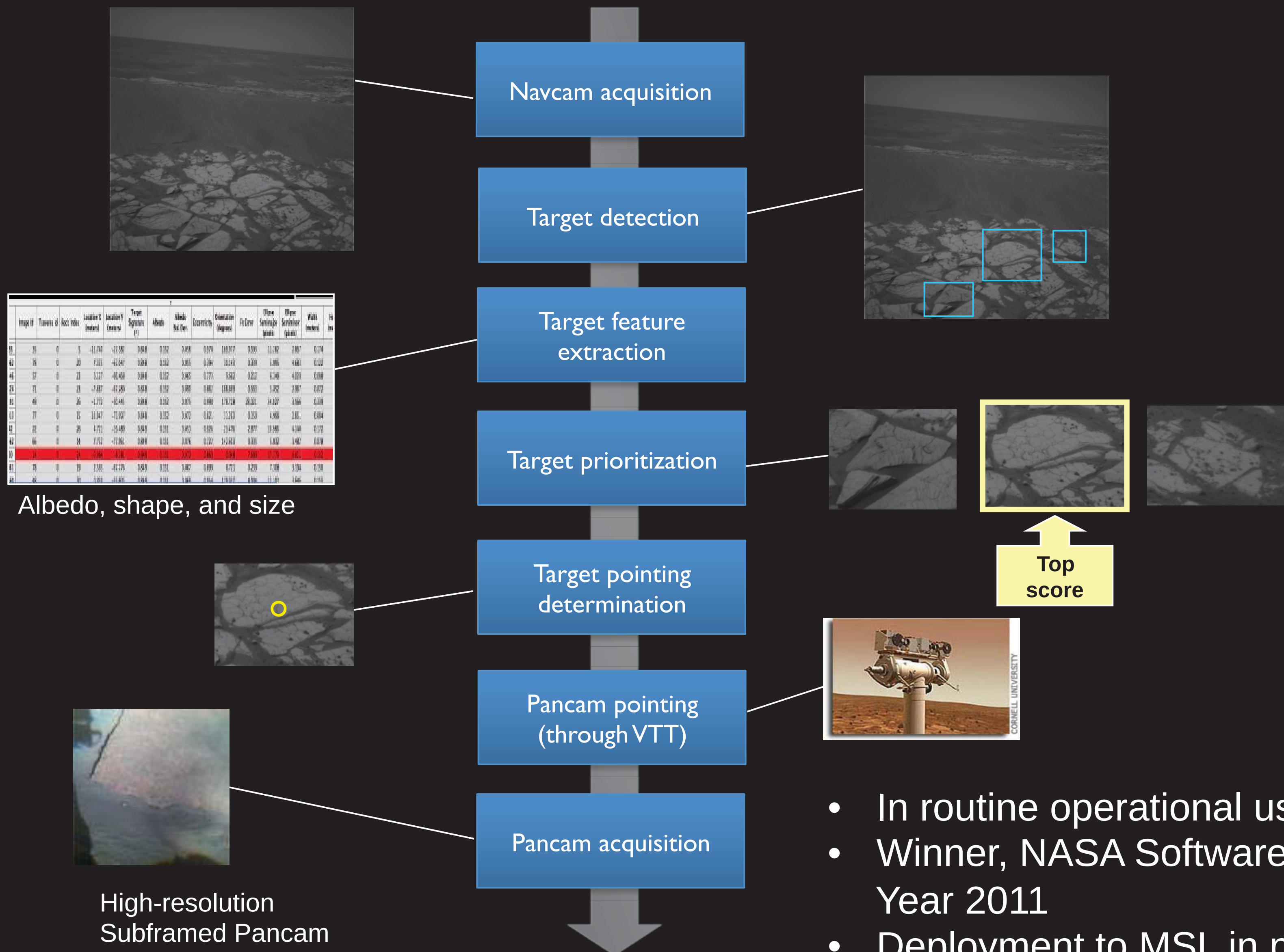




Clouds

POC: S. Chien/JPL

AEGIS for MER



- In routine operational use 2010 –
- Winner, NASA Software of the Year 2011
- Deployment to MSL in progress.

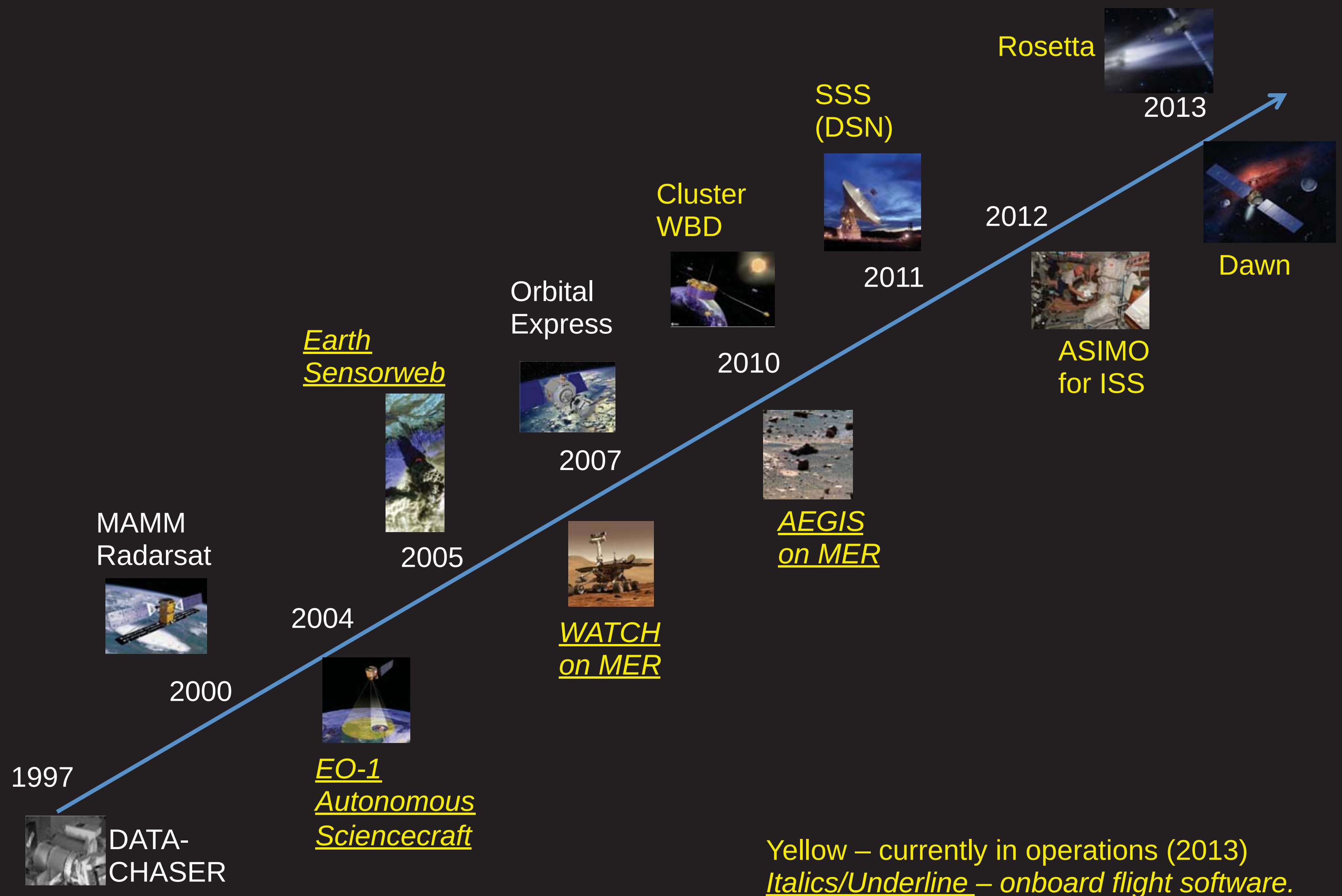
POC: T. Estlin/JPL

Conclusions

- AI for Spacecraft Autonomy is here and now at NASA!
- Onboard autonomy can
  - Enable returning the most important data - return data products, not raw data
  - Enable rapid response to short-lived 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
- Risks from autonomous systems can be managed, with planning and effort

AI is revolutionizing space exploration!

JPL Autonomy in Operations



Space Autonomy Topics Relevant to Airspace Autonomy

- Automated planning, scheduling, resource management
- Onboard vision based control
- Disruption tolerant networking
- ISHM/Fault Management
- Validation of Autonomous Systems

For Further details see:

- DATA-CHASER
  - S. Chien, G. Rabideau, J. Willis, T. Mann, Automating planning and scheduling of shuttle payload operations, Artificial Intelligence, Volume 114, Issues 1–2, October 1999, Pages 239-255.
- MAMM-Radarsat
  - B. Smith, B. Engelhardt, D. Mutz, "The RADARSAT-MAMM Automated Mission Planner," AI Magazine, V. 23, No. 2, 2002.
- ASE (ase.jpl.nasa.gov)
  - S. Chien, R. Sherwood, D. Tran, B. Cichy, G. Rabideau, R. Castano, A. Davies, D. Mandl, S. Frye, B. Trout, S. Shulman, D. Boyer, "Using Autonomy Flight Software to Improve Science Return on Earth Observing One, *Journal of Aerospace Computing, Information, & Communication*, April 2005, AIAA.
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