JPL

Jet Propulsion Laboratory

Practical Planning & Scheduling

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JPL Clearance Numbers CL#01-0574 CL#09-2306, CL#09-3134

Outline

- Overview – Automated planning applications for space mission operations
- Earth Observing One Ground Scheduling
- Underwater Glider Mission Planning

Automated Mission Planning

- From mission goals
  - E.g. – image Kilauea (Lat/Lon)
- To command sequences
  - E.g.

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);
…

Why should you be interested in automated planning?

It can offer onboard autonomy to missions

- Enabling response when not in ground contact (earth orbit) or faster response (round trip light for deep space, or rapid automated response)
- It can reduce mission operations costs
- Automation can increase mission reliability in some cases
- Can enable improved mission analysis (more what if cases?)
- …

Examples

- Sensorweb
- Autonomous Sciencecraft Experiment on EO-1

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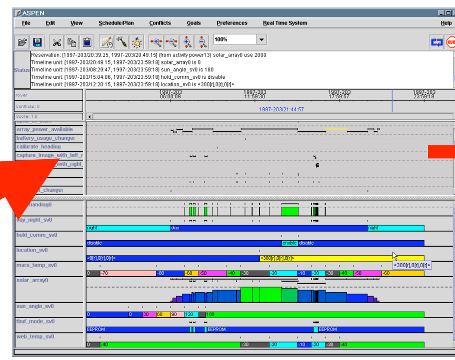
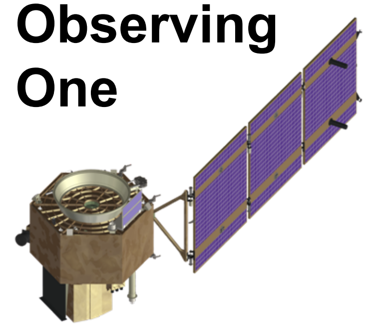
Sensorweb

Re-tasking



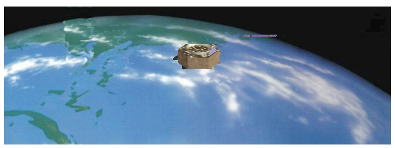
Earth Observing One



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

Science Response

Image taken by Spacecraft



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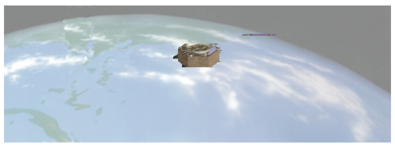
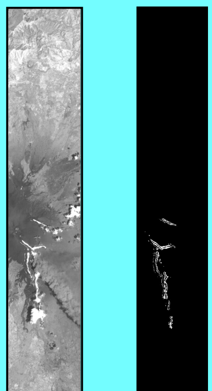
Science Response

Image taken by Spacecraft



Onboard Science Analysis

Event Detection



No event Detected: Delete Image

Event Detected

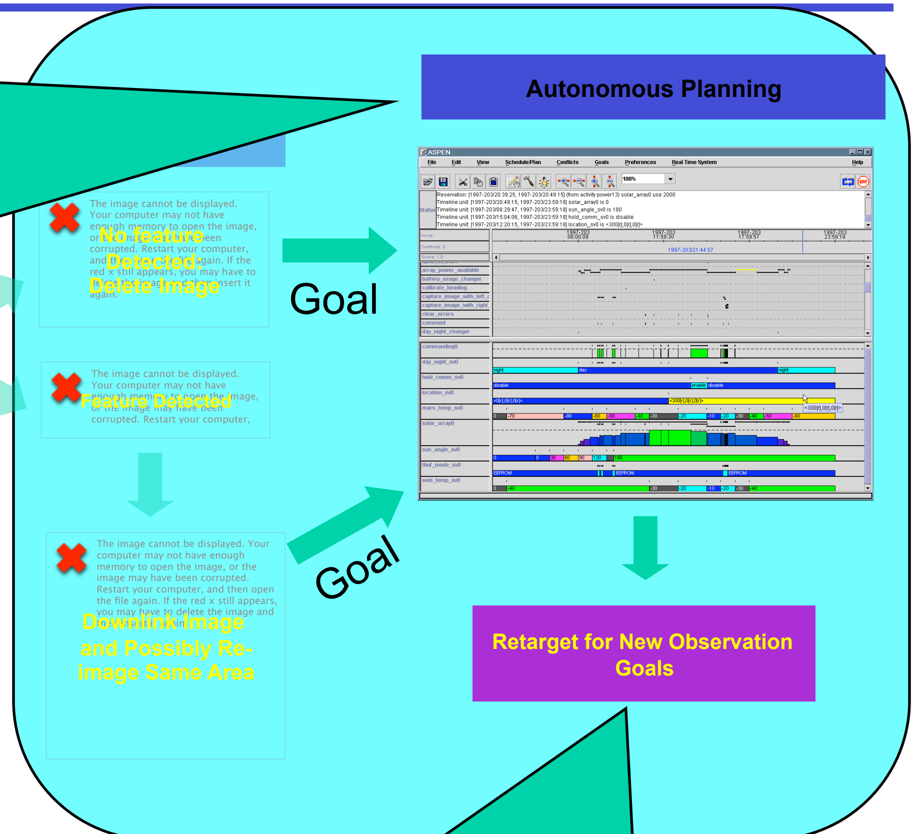
ASE uses state of the art Machine Learning to detect events in the presence of noise

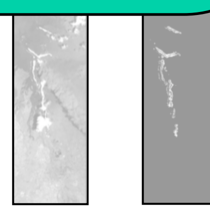
Track a wide range of science events – floods, volcanoes, cryosphere, clouds,…

Key Insight: No need to replicate ground science analysis – just detect activity

Science Response

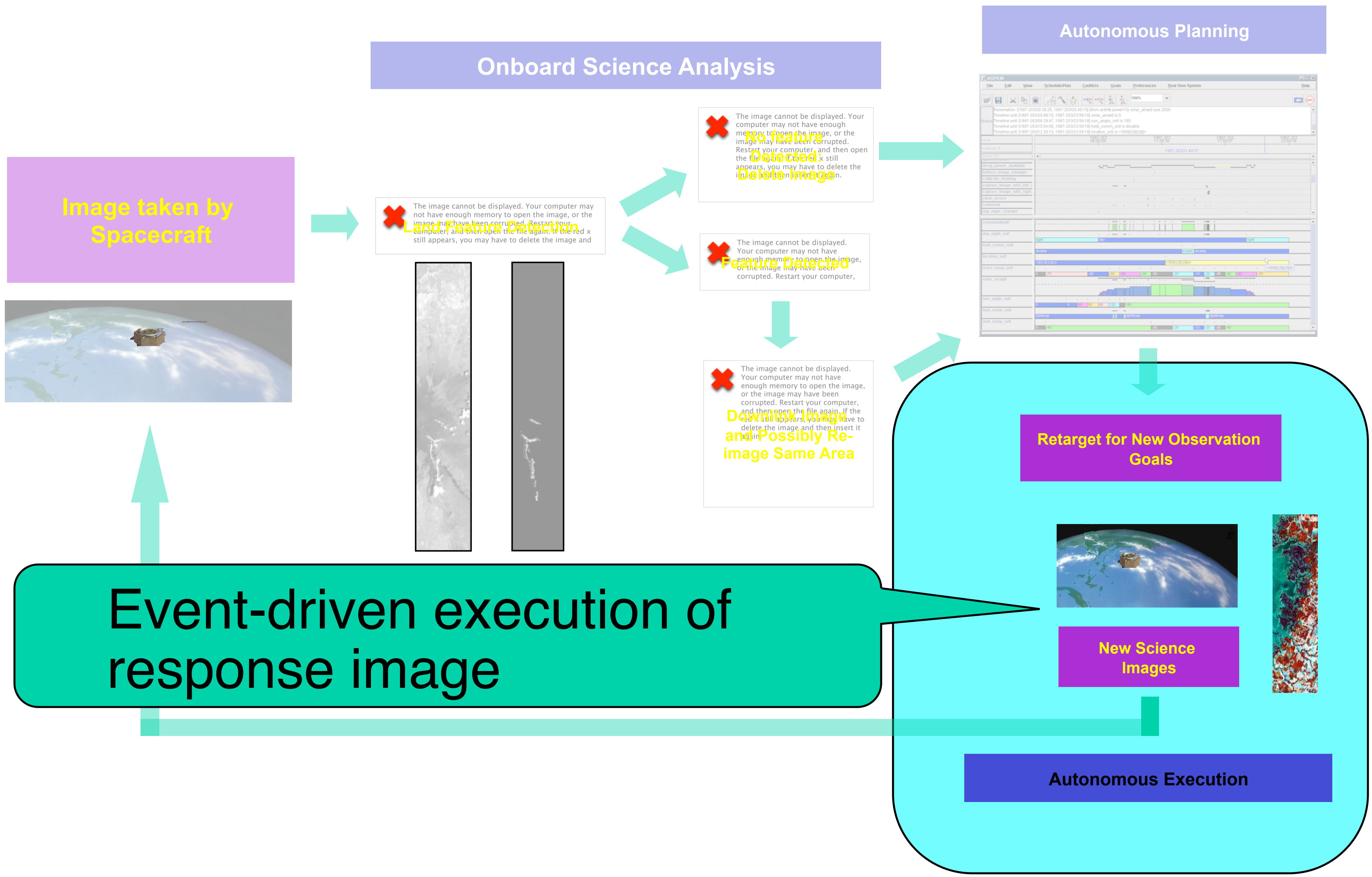
continuous planning - enables seamless long-duration operations and rapid replanning despite limited onboard CPU





Onboard planning enables rapid response to detected event

Science Response



7 May 2004 ASE monitors Mt. Erebus

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ASE images Erebus (Night) — 13:40 GMT

} +10 min

ASE initiates band extraction

} +28 min

ASE runs thermal classifier

} +29 min

THERMAL TRIGGERED

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THERMAL TRIGGERED

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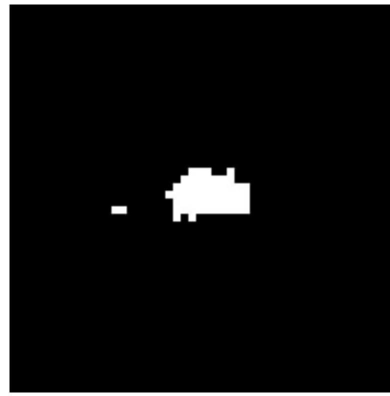
Planner selects reaction observation (Stromboli observation replaced)

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

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



+ 2 hours 18 minutes

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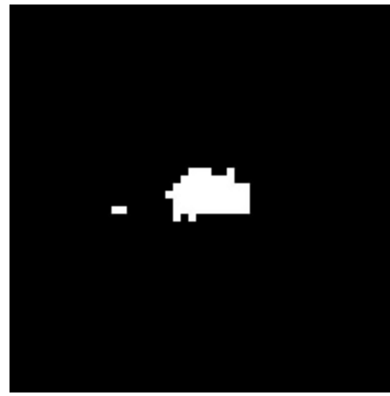
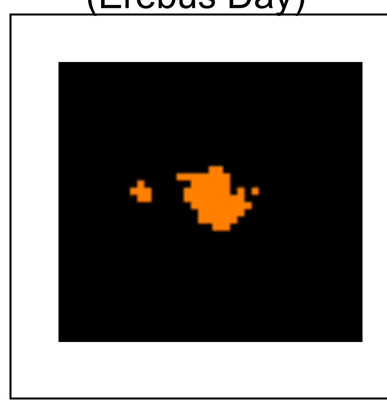
ASE images Erebus again — 20:10 GMT

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

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ASE images Erebus Night — 13:40 GMT

} +10 min

ASE initiates band extraction

} +28 min

ASE runs thermal classifier

} +29 min

THERMAL TRIGGERED

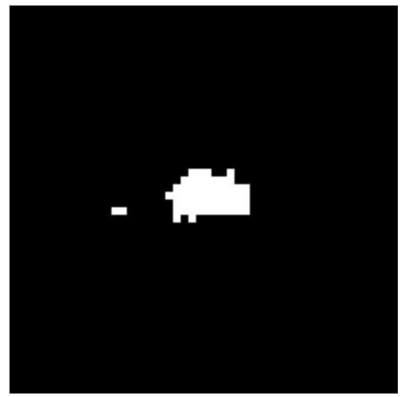
Planner selects reaction observation (Stromboli observation replaced)

} +20 min

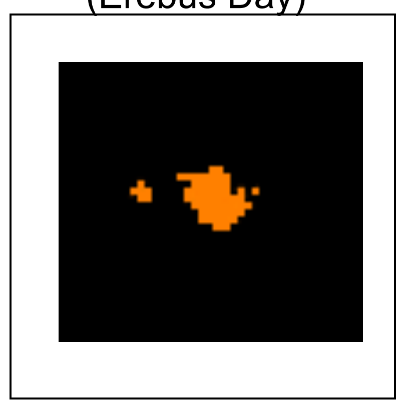
Thumbnail downlinked (S-band) — 15:58 GMT

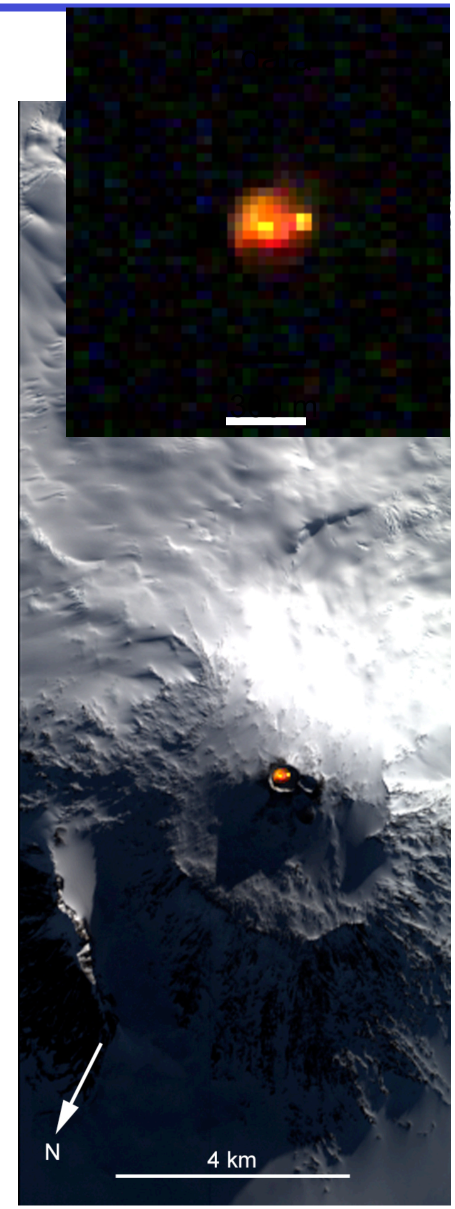
ASE images Erebus again — 20:10 GMT + 06:30

ASE Onboard Thermal Classifier Thumbnail (Erebus Night)



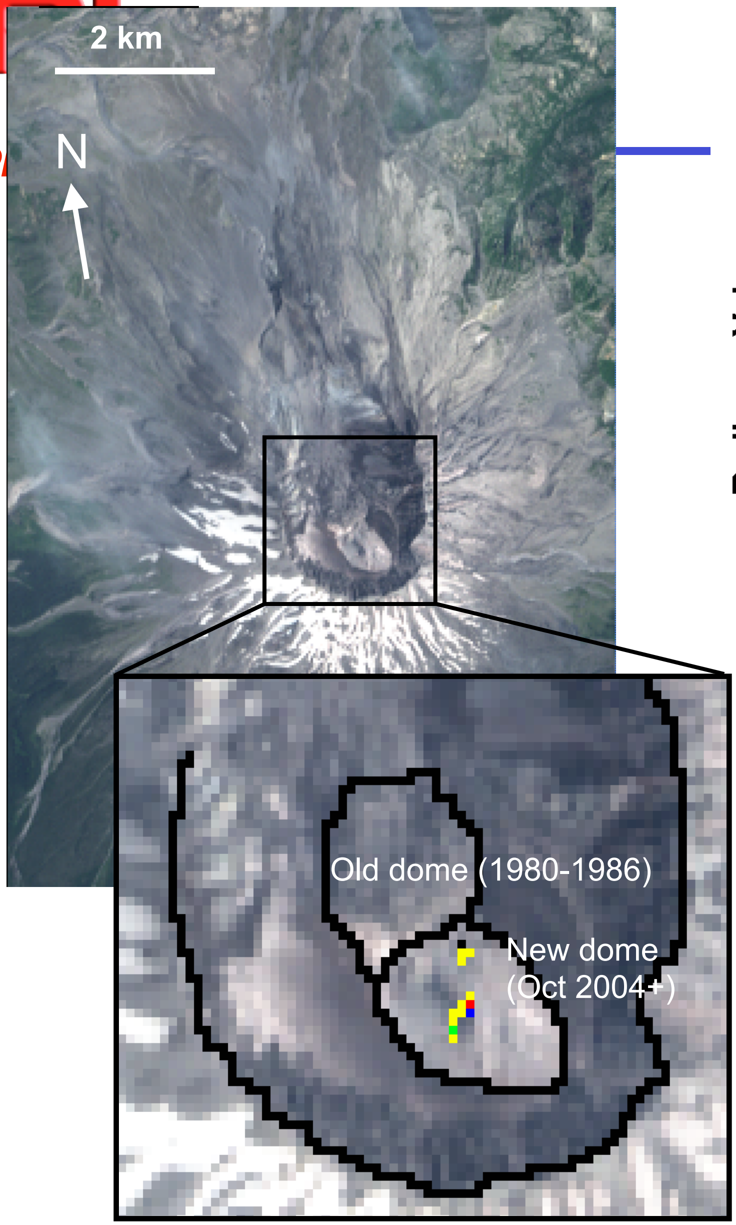
ASE Onboard Thermal Classifier (Erebus Day)

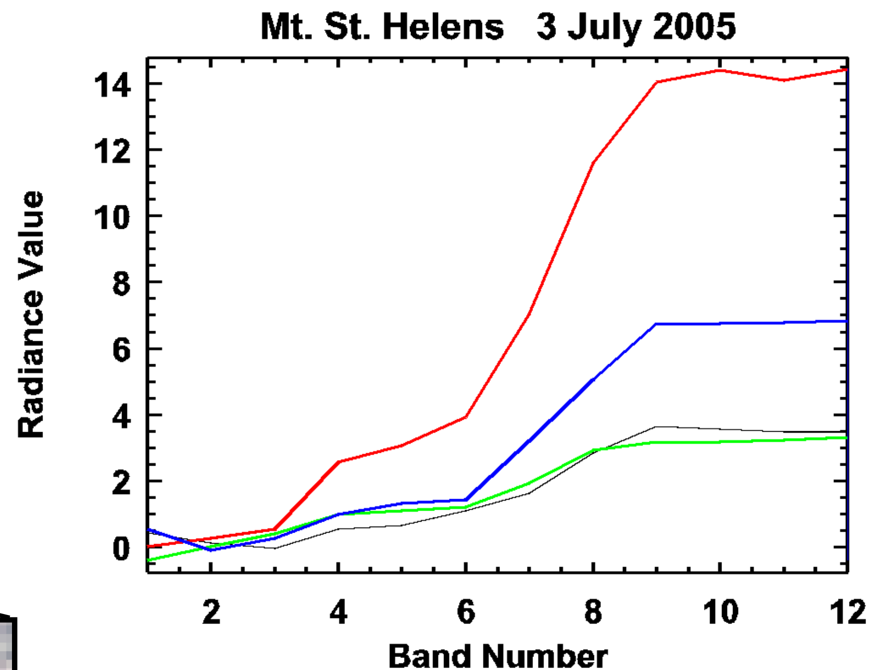




ASE enabled rapid notification of volcanic event
ASE enabled rapid re-imaging of this event
Autonomous response as normal operations!

- **Highest leverage for deep space missions**





Band	Wavelength, µm	Band	Wavelength, µm
1	0.630	7	2.022
2	1.245	8	2.103
3	1.266	9	2.254
4	1.599	10	2.264
5	1.659	11	2.274
6	1.780	12	2.285

Davies, Chien et al. Remote Sensing of the Environment, in press.

ASE Current Status

Current count > 23000+ 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**
- **Enabled a reduction in net operations costs $3.6M/year → $1.6M/yr; $1M/yr directly attributed to EO-1**
  - **Operations cost reduction critical in enabling extended mission**

ASE/EO-1 Operations expected to continue through 2011+

Flight Software Architecture

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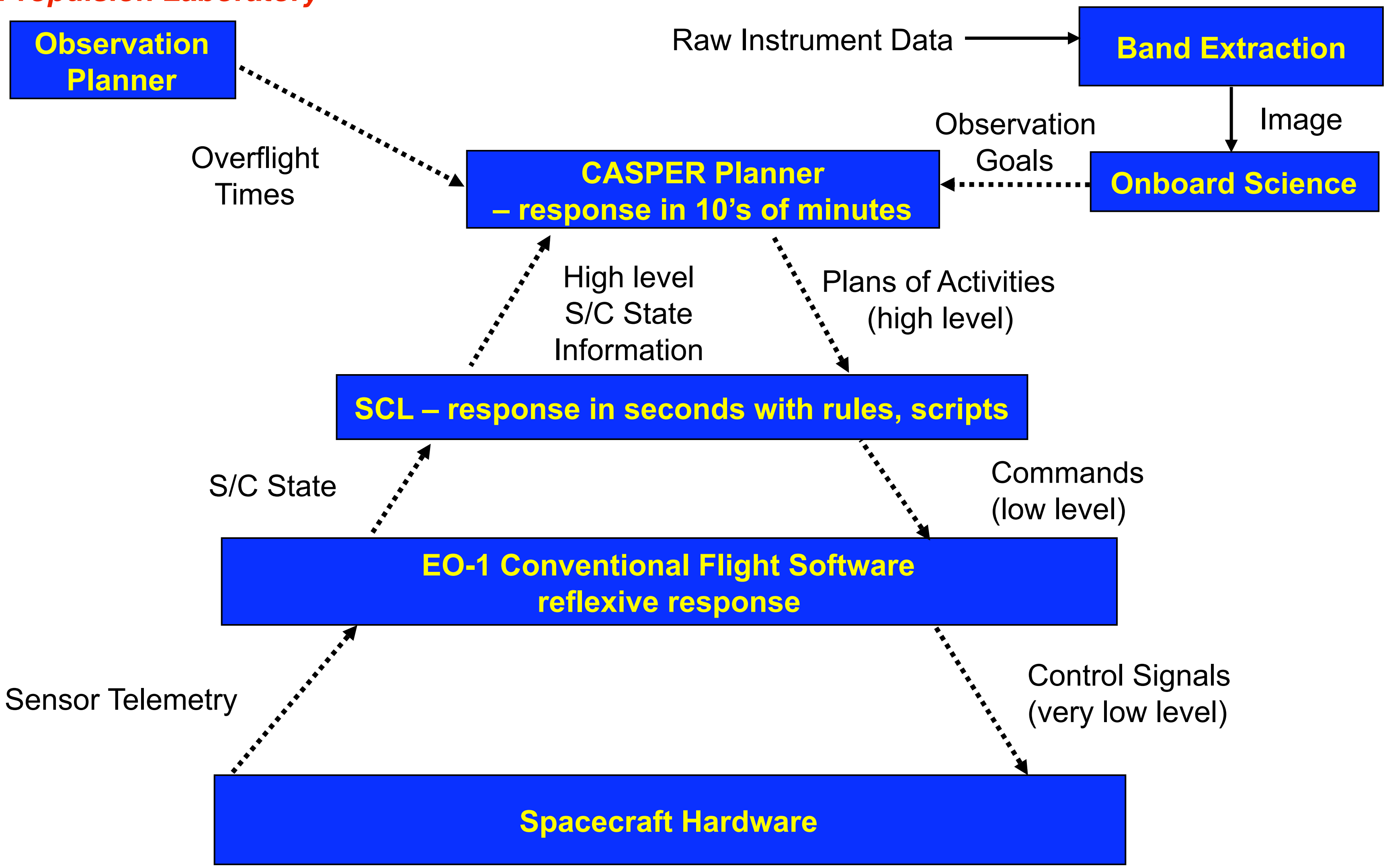

Continuous Planning on ASE

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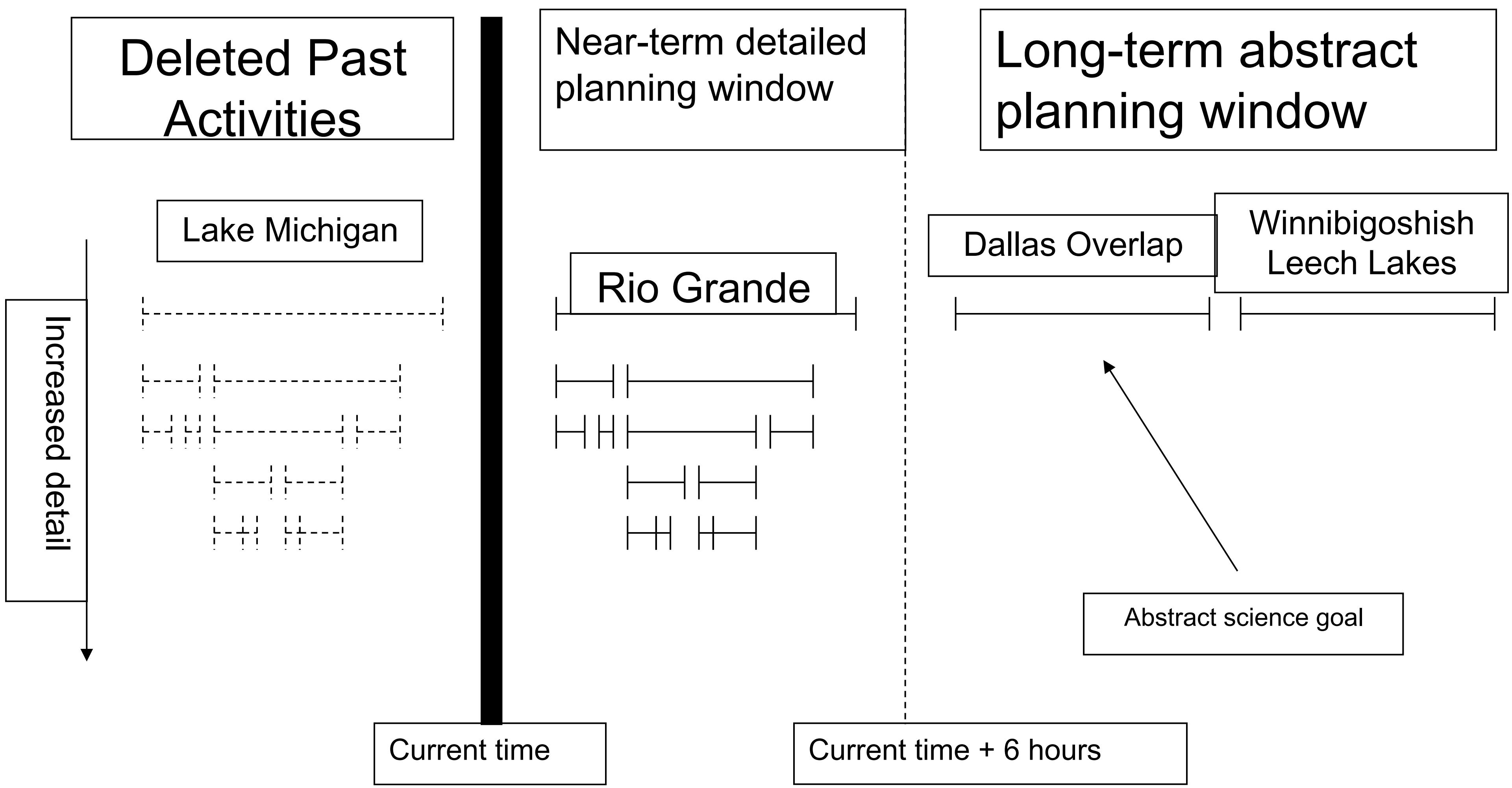


Impact of Continuous Planning on EO-1

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

Constructive versus Iterative Scheduling Approaches

Constructive approaches

- As decisions are taken, the set of possible schedules is reduced
- Once all decision variables have been assigned, or once a certain condition has been achieved wrt remaining possible schedules (no possibility of resource conflicts)
- Examples: most of the constraint-based techniques we have considered thus far

Iterative approaches

- Search proceeds alternatively by transforming one schedule (or set of schedules) into another
- Schedules are iteratively improved until some termination criteria is met
- Examples: the techniques we are about to consider

Committed Planning

Models

- Describe the environment and all agents in the environment.
- More principled and inspectable than rules

Algorithms

- Solution constructors
- Repair
- Packing

Models

Constraint based modeling system

Activities

- Start time and end time
- Other activities
- Effects on states
- Parameters

Timelines

- Represent the state of the world
- States and resources
- Black-box timelines (Generalized Timelines)

Activity Example

Warmup Activity

- Can be assigned a warmup rate and a destination temperature.
- Consists of a heaterOn activity and a heaterOff activity.
- Its duration is a function of the starting temperature and the destination temperature.
- Its power use is a function of the warmup rate.
- Its energy use is a function of the warmup rate and the duration.

State Example

Filter wheel

- States are red, green, blue, closed
- Wheel turns only clockwise, so allowed transitions are from red to green, green to blue, blue to closed, and closed to red.

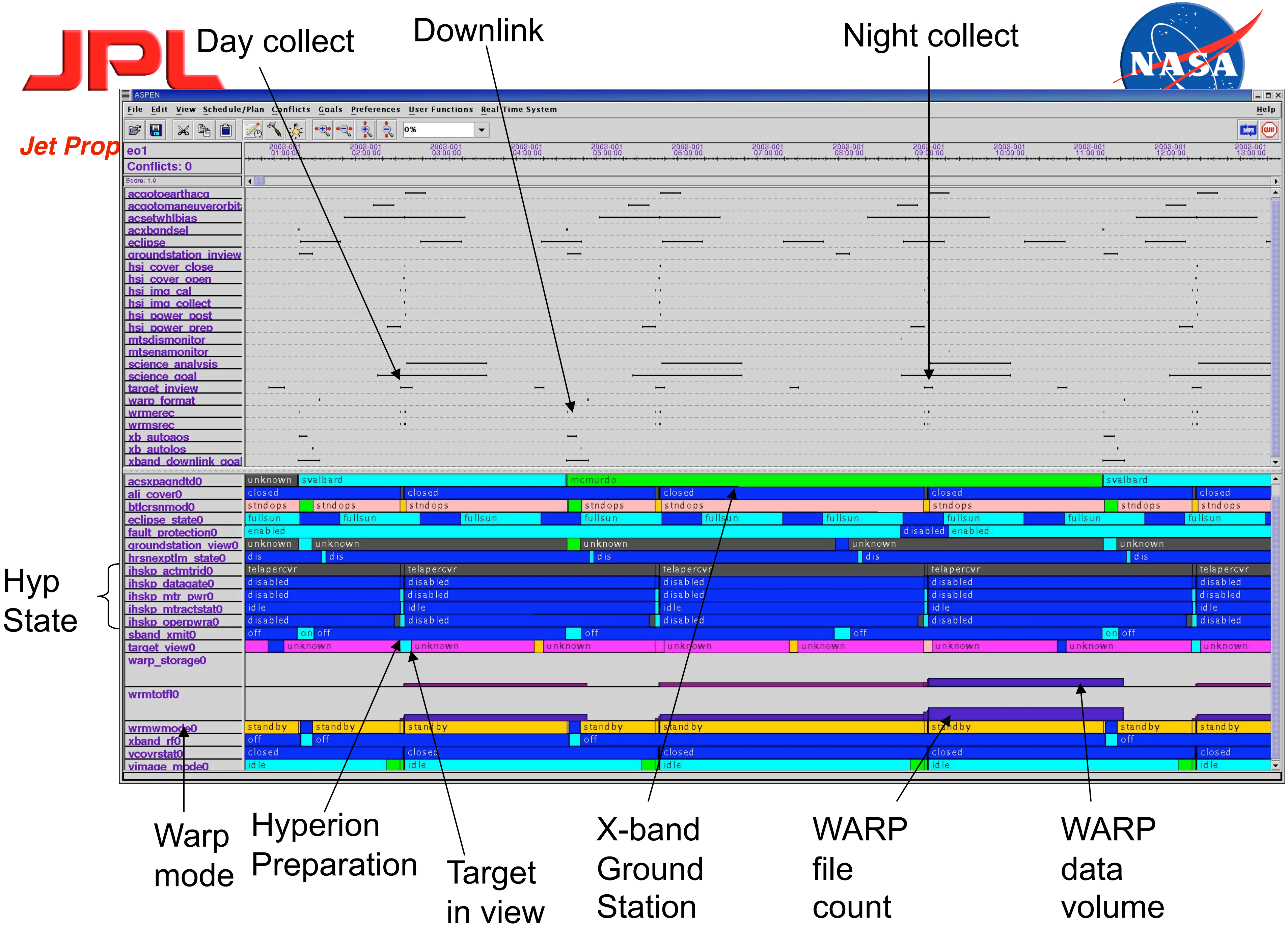
Resource Example

Power

- Non-persistent (non-depletable)
- Minimum power level must be 10
- Maximum power level is 100

Energy

- Persistent (depletable)
- Minimum energy level is 0
- Maximum energy level is 100


Day collect
Downlink
Night collect
Hyp
State
Warp
mode
Hyperion
Preparation
Target
in view
X-band
Ground
Station
WARP
file
count
WARP
data
volume

Algorithms

Solution constructors

- Forward Dispatch (Greedy – in order of time)

Repair

- Conflicts
- Repair Methods
- Choice Points
- Heuristics

Packing

- Earliest
- Latest
- Loosest

Forward Dispatch

Narrow the times for activities according to know temporal constraints and everything that has been scheduled so far.

Choose an activity to schedule based on “earliest deadline” heuristic.

Schedule the activity while trying to minimize constraint violations (may not be in order)

Repeat until all activities are scheduled.

Iterative Repair

- Identify the conflicts
- Choose a conflict to repair
- Choose a method to repair the conflict
- Based on the method and conflict, make any other associated choices
- Attempt the repair based on the choices
- Repeat until no more conflicts exist in the schedule

Conflicts

A conflict is a constraint violation

Temporal constraint violations

- *A* starts at end of *B* *A* starts at 100, but *B* ends at 50

Resource usage violations

- Power maximum is 50 but there are 2 activities that use 30 each at the same time

State usage violations

- *B* requires that the filter be blue but the filter is red during *B*

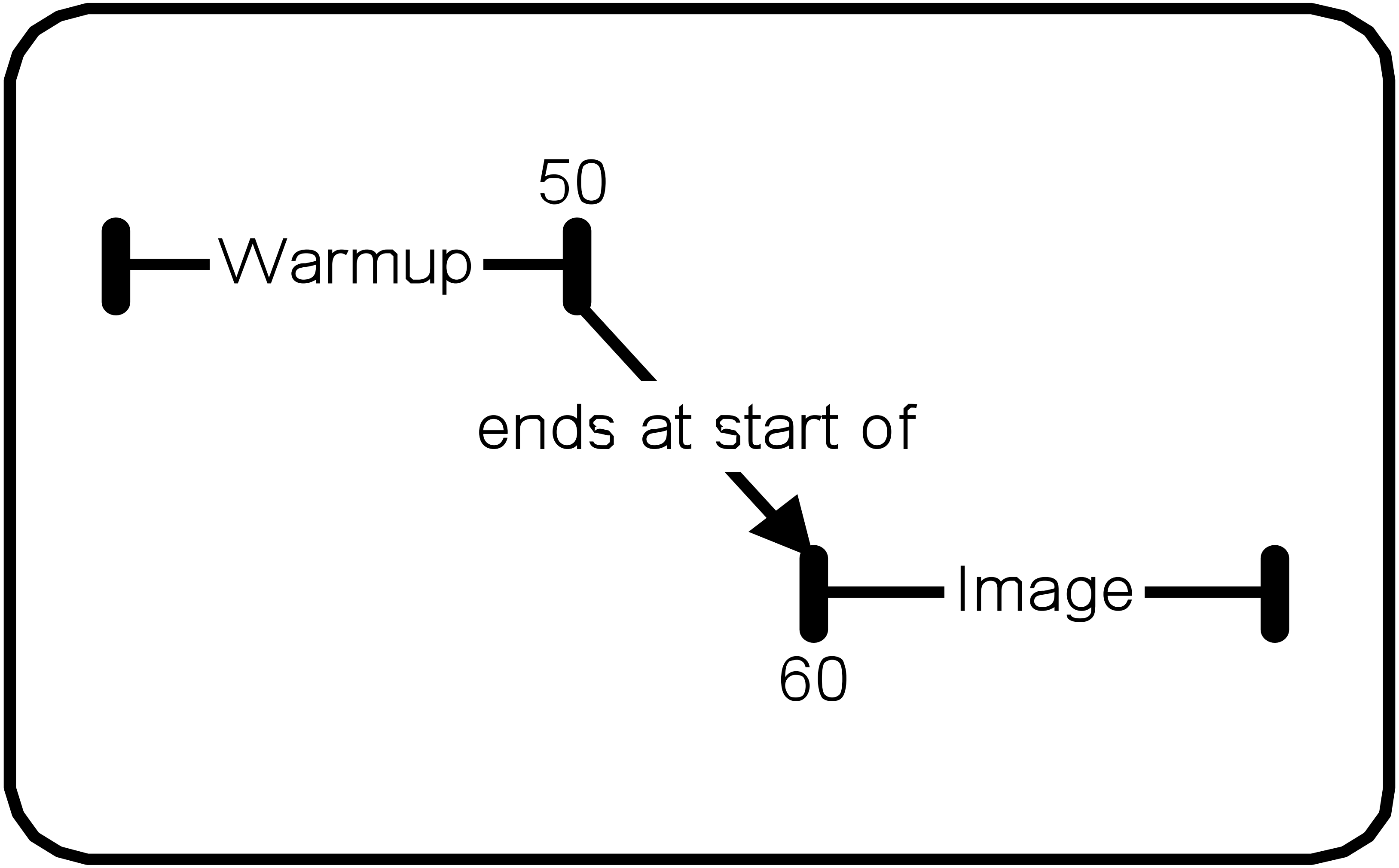
State transition violations

- The light can go from red to green, green to yellow, and yellow to red but *C* causes the light to go from green to red

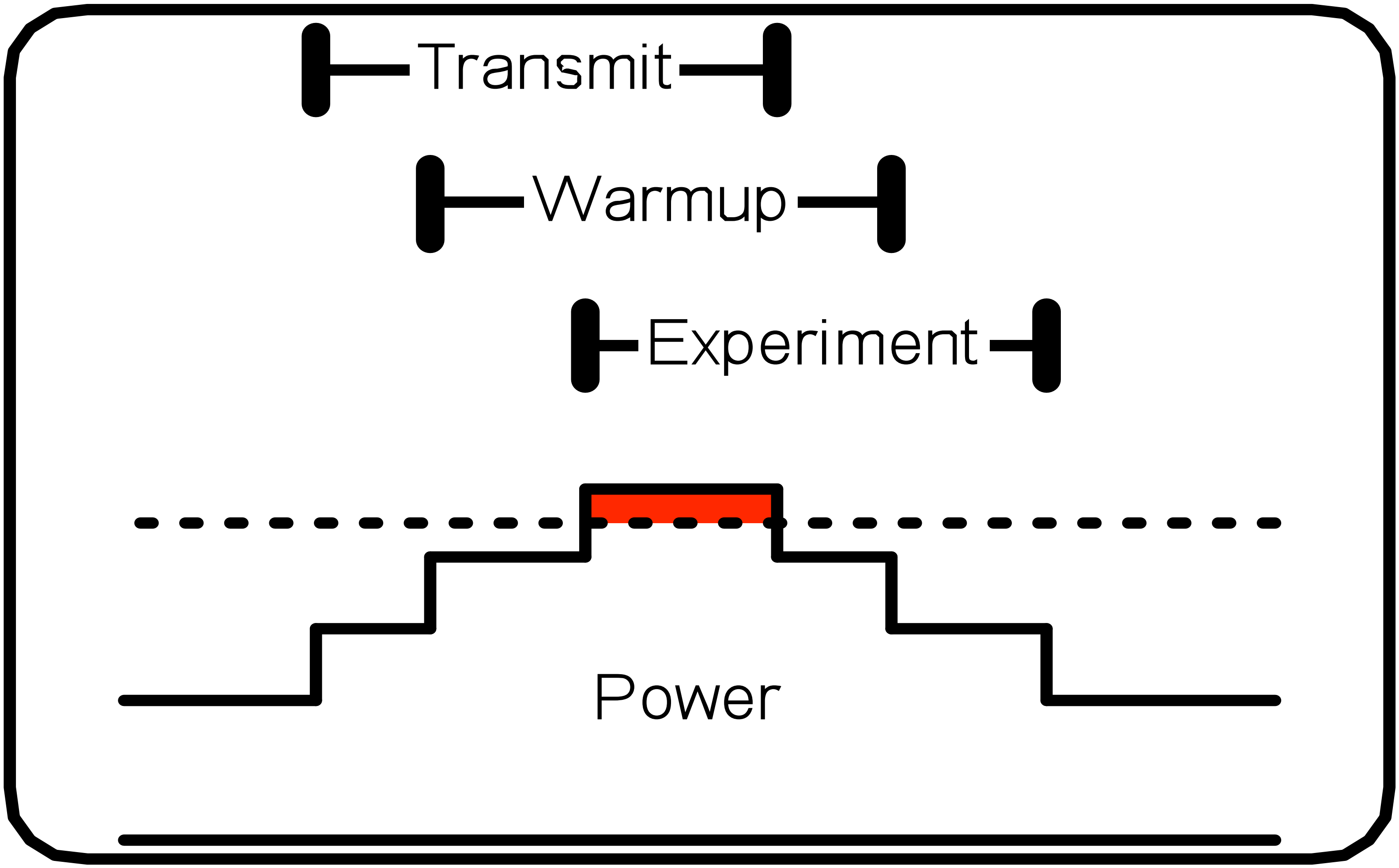
Dependency violations

- x = 1, y = 2 z = (x + y) but currently z = 0

Temporal Constraint Violation



Resource Violation Example



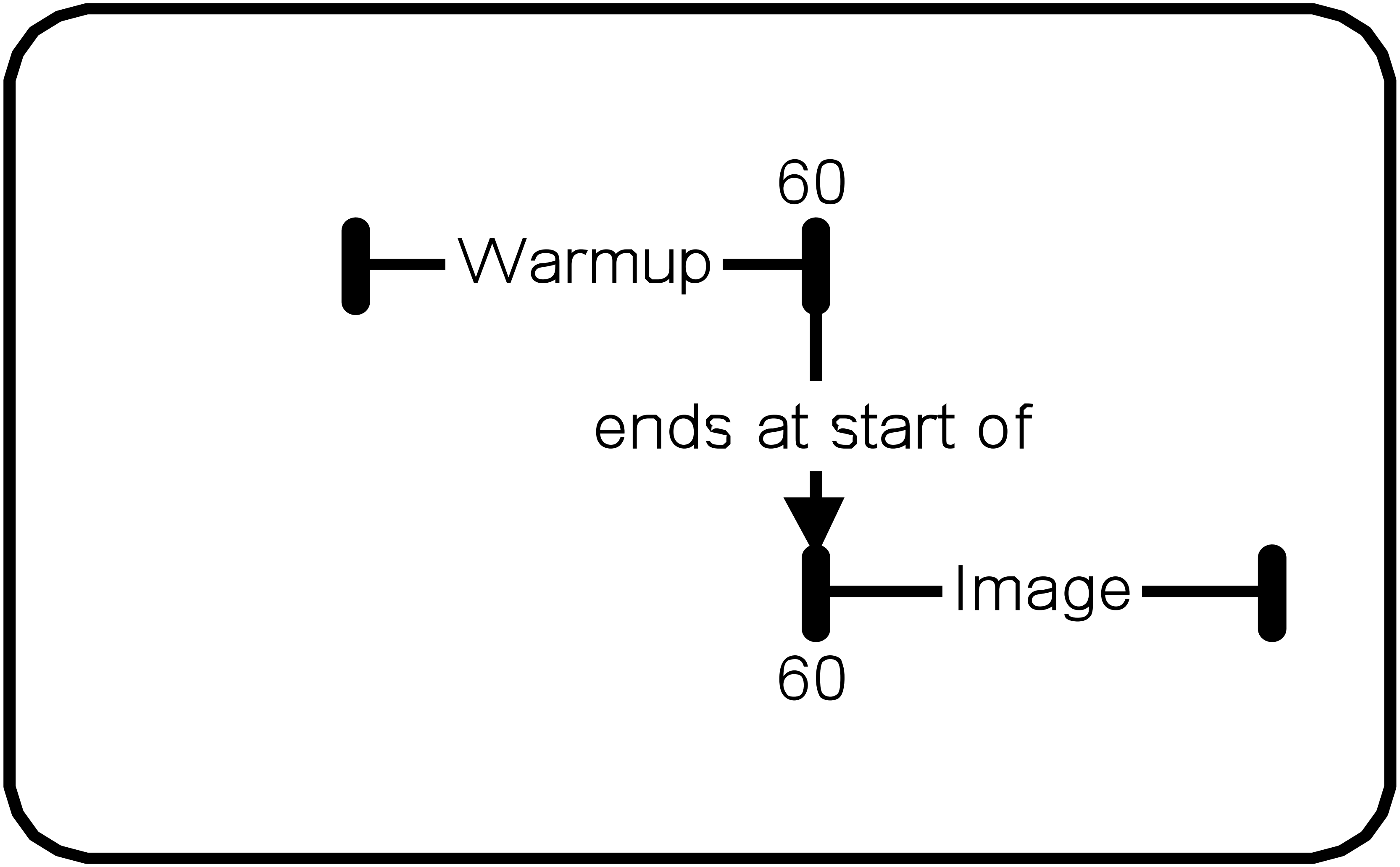
Repair Methods

Repair Method: an operation that leads to fixing the conflict

Depends on the conflict and the model

- Some repair methods are useless for some conflicts
- Some repair methods are not possible with some models

Move Repair Method Example



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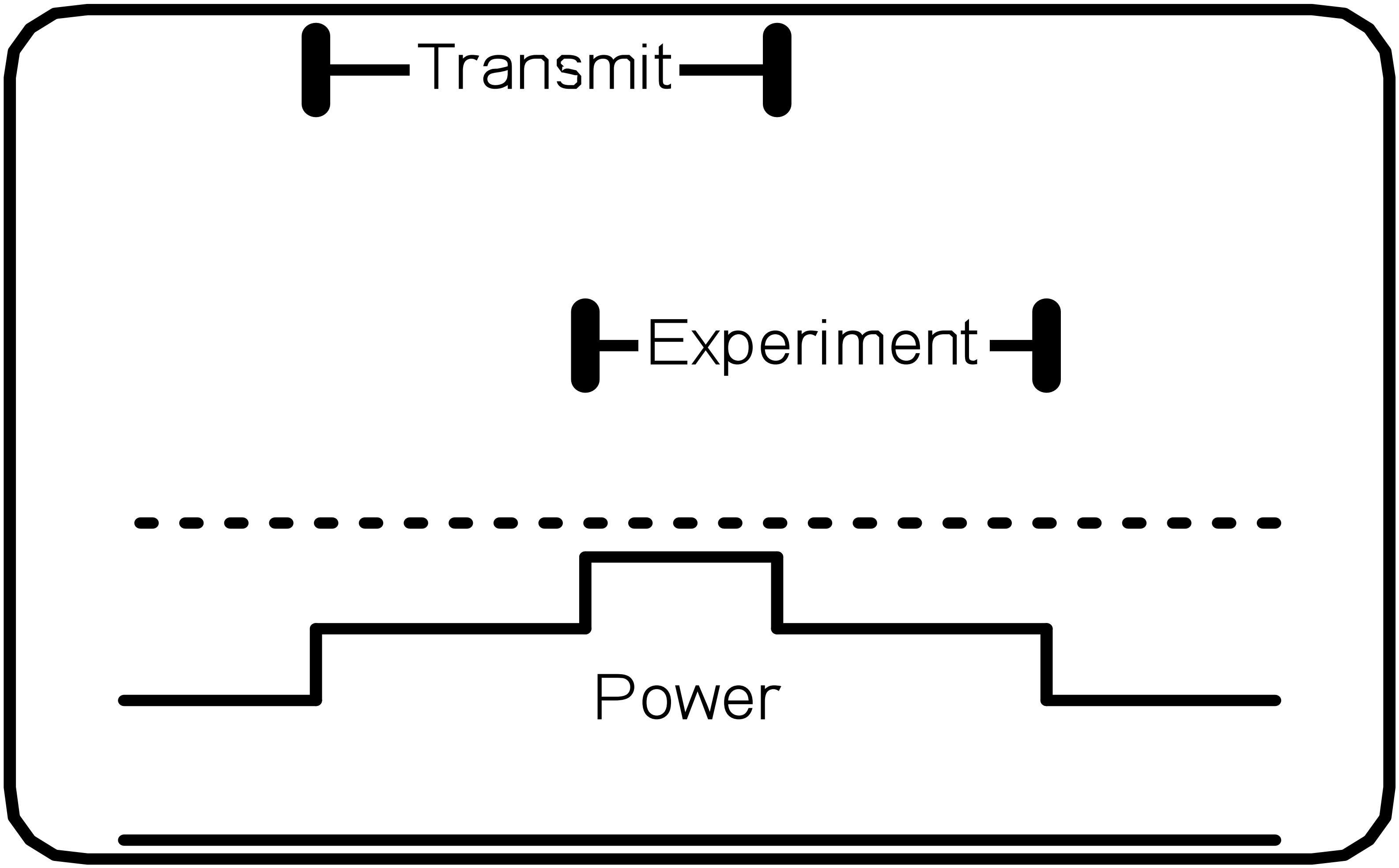
Delete Repair Method Example



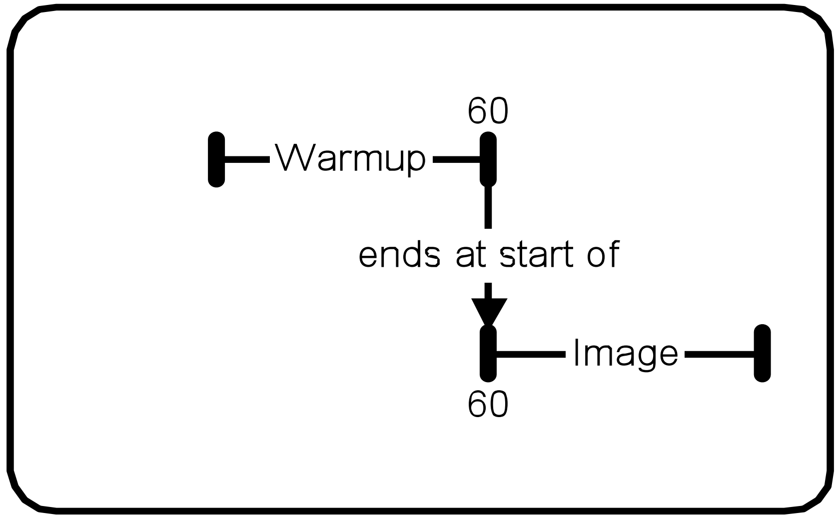
Choice Points

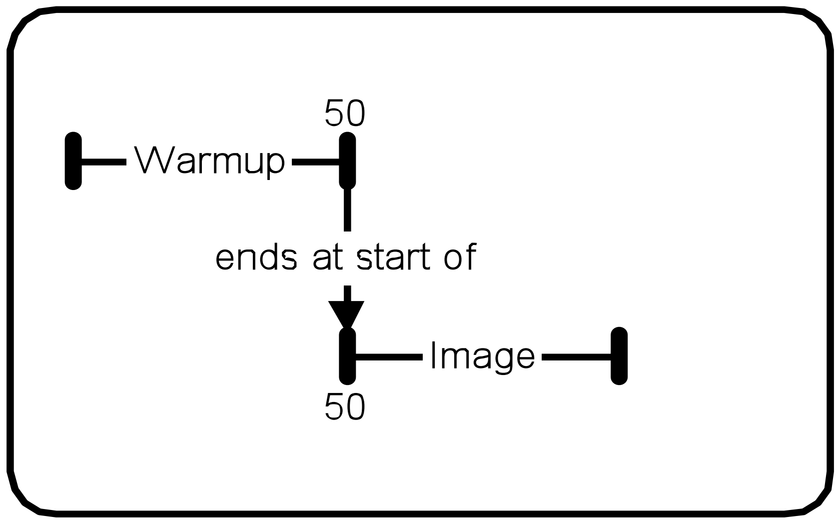
Choice points are the forks in the road to finding a solution.

At each point, we must choose among the options available.

Instead of keeping track of all of our choices, we opt to make choices quickly and keep moving forward, possibly causing other conflicts.

Move Choice Point Example





Delete Choice Point Example

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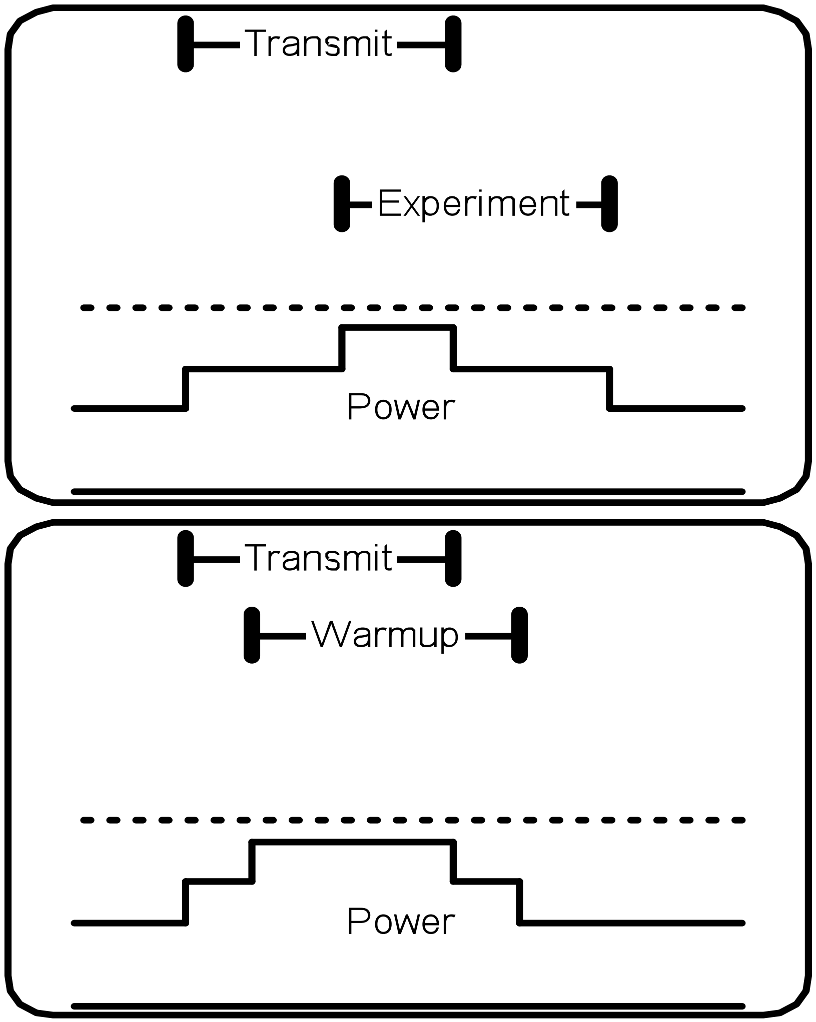

Heuristics

Heuristics guide the search for solutions by expressing a preference for one choice over others at each choice point

Move

- Earliest activity, latest activity

Delete

- Earliest activity, latest activity, least valued activity

The Repair Search Tree

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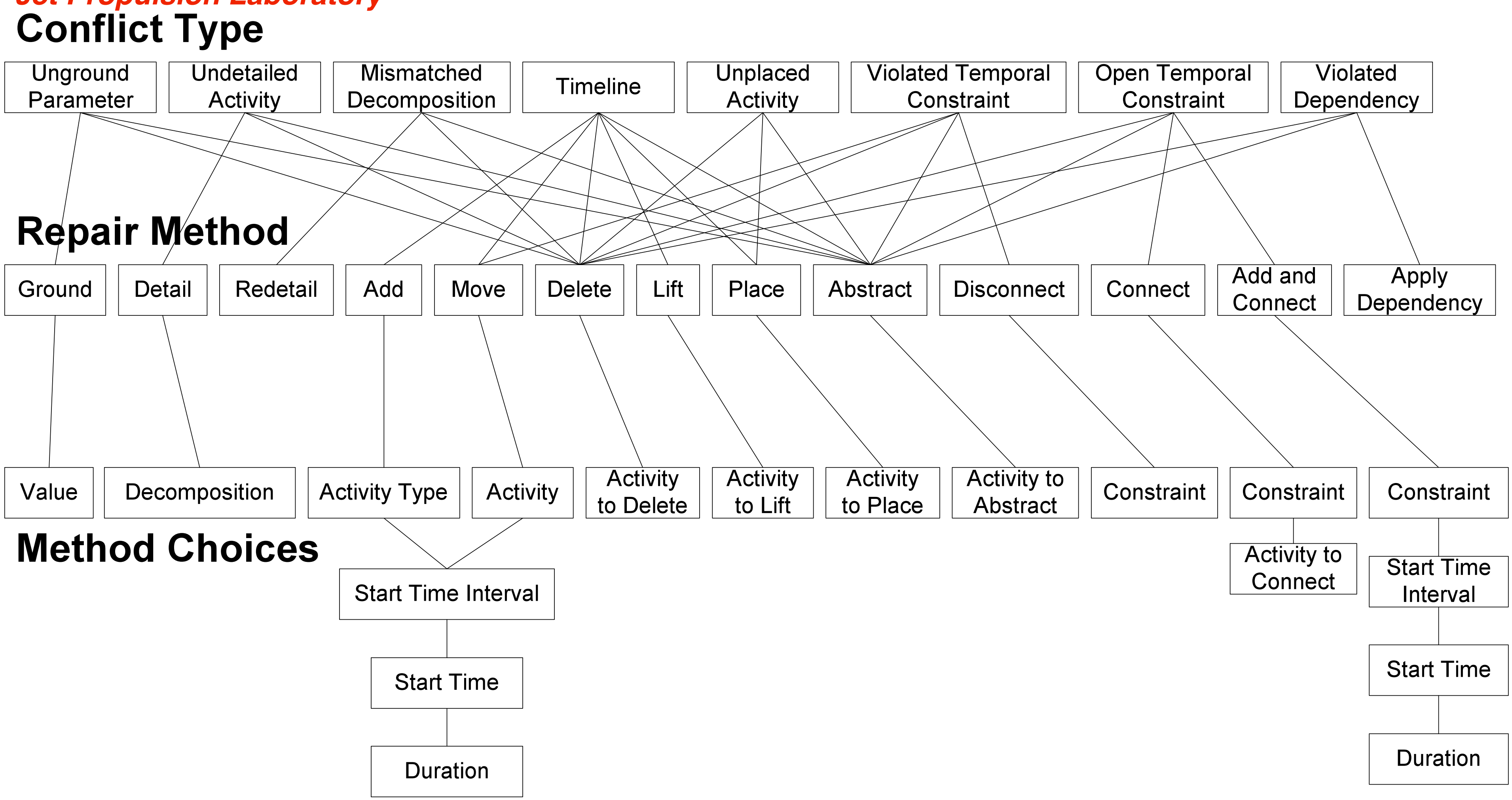

Packing

Allows for fitting more activities into the schedule or for making elbow room for existing activities.

Earliest

- Pack activities as early as possible without causing a conflict

Latest

- Pack activities as late as possible without causing a conflict

Loosest

- Attempt to space out the activities evenly over time

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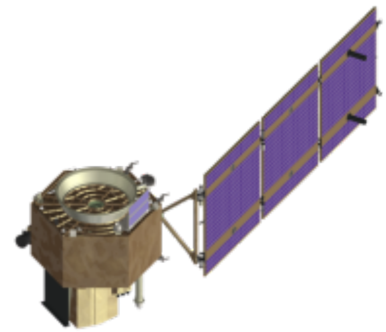
Case Study: Earth Observing One R5 Ground Scheduling

Steve Chien, Daniel Tran, Gregg Rabideau,
Steve Schaffer, Daniel Mandl, Stuart Frye

JPL and NASA/GSFC

Earth Observing One



Low earth orbit, 2000 launch

Repeat cycle 15 days

Point and shoot (slews to target)

Currently Two principal science instruments

- ALI – 30m/pixel multispectral, 28km swath
- Hyperion 30m/pixel hyperspectral, 7km swath
- Both 0.4-2.5 μm (SWIR, VNIR)

Onboard processing Mongoose M5

- 12 MHz, no FPU, 128MB RAM

EO-1 Operations Timeline

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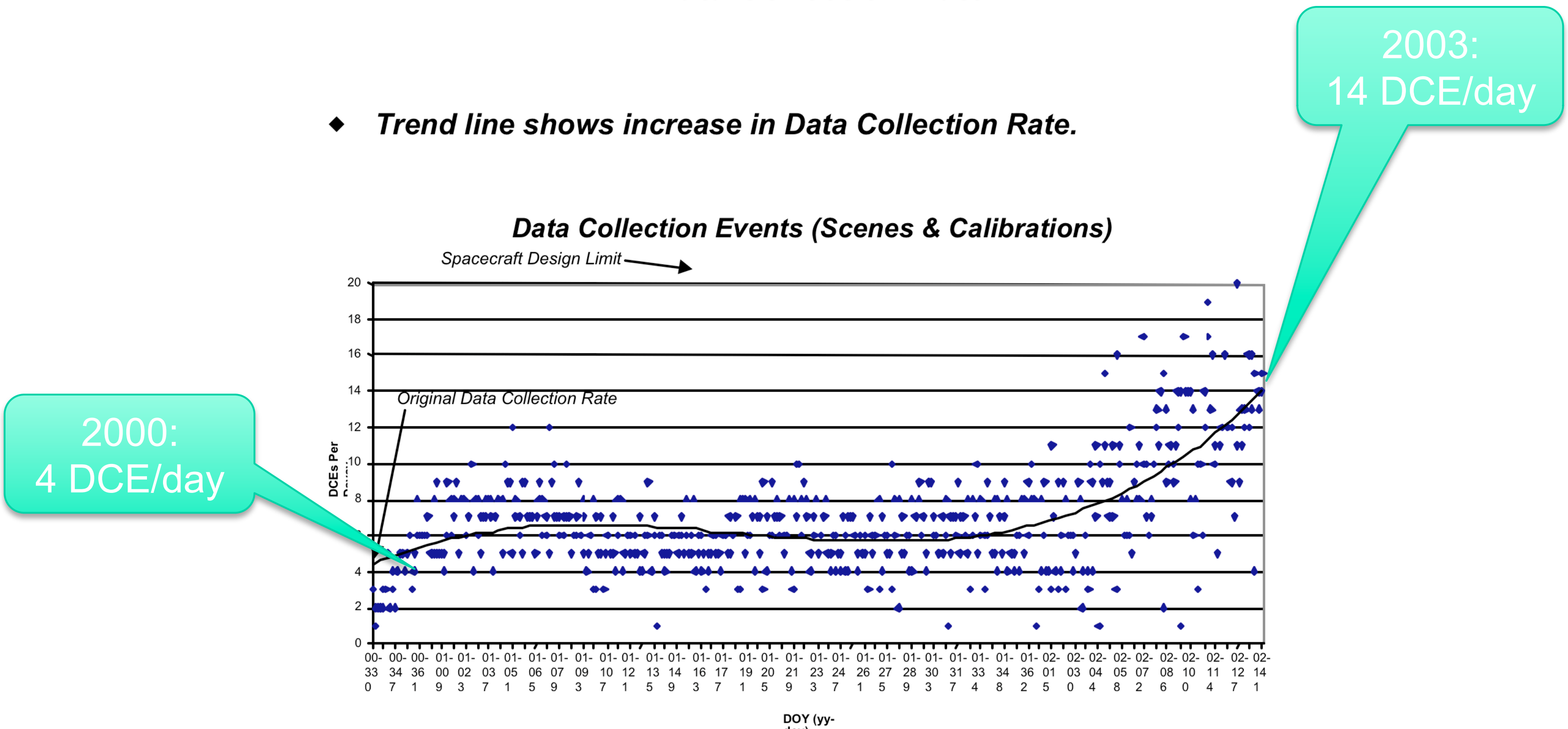
Data Collection Rate

- ***Trend line shows increase in Data Collection Rate.***



"The data collection rate was increased from four to 20 DCEs per day, which is essentially the design limit of the spacecraft ", EO-1 Flight Operations Team upon receiving NASA Continuous Improvement Award 7 March 2003

Automation of EO-1 mission planning

2000: ASPEN (ground) and CASPER (flight) R4 operational, 4 FTE's mission planning value created for > $1M/year savings.

- ASPEN/CASPER models constraints as stated in MOPSS (GSFC sequence generation tool)
  - Least costly and least Many constraints implemented as temporal constraints (thermal, power, …)
  - See Rabideau et al. 2006

2009: R5 upgrade, directly encoding many constraints: pointing, thermal constraints to improve

Focus of this talk

EO-1 Operations Constraints

Easy

- Scene and Downlink Overlap – scenes cannot overlap other scenes (instrument) onboard recorder cannot playback and record simultaneously (recorder)
- Onboard Storage – spacecraft has limits on # of files and total blocks (bytes) storage
- Sequence and Timing – setup sequences for instrument, data system, recording,…

Hard

- Priority – higher priority scenes pre-empt lower priorities
- Maneuver – spacecraft must be able to slew and settle from one scene to the next
- Thermal – instrument heats while taking scenes, must be allowed to cool before too many consecutive scenes
- Engineering and Housekeeping

EO-1 Operations Constraints

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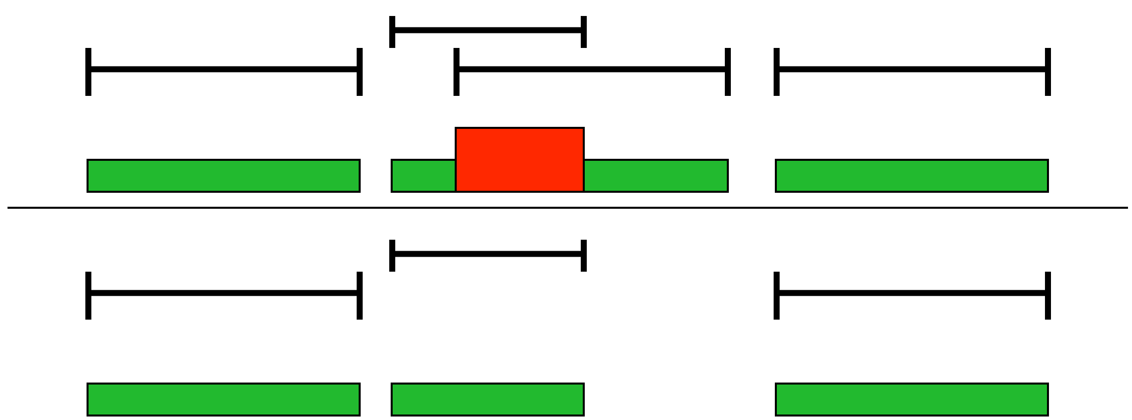
Scene and Downlink Overlap – scenes cannot overlap other scenes (instrument) onboard recorder cannot playback and record simultaneously (recorder)



EO-1 Operations Constraints

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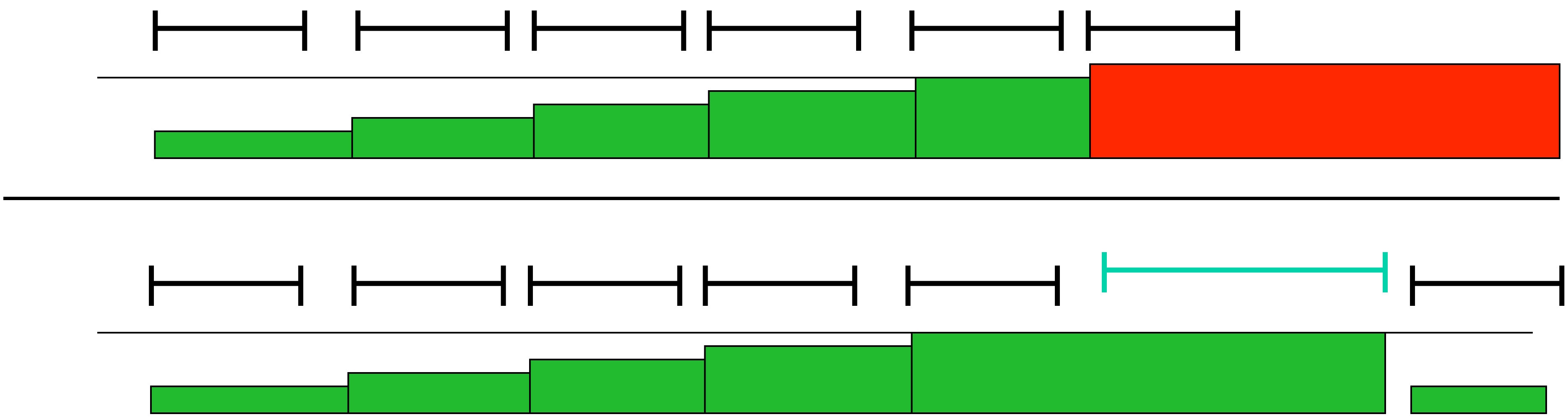
Onboard Storage – spacecraft can only store 5 scenes before needing to downlink

- Actual constraint on number of files and total bytes storage



EO-1 Operations Constraints

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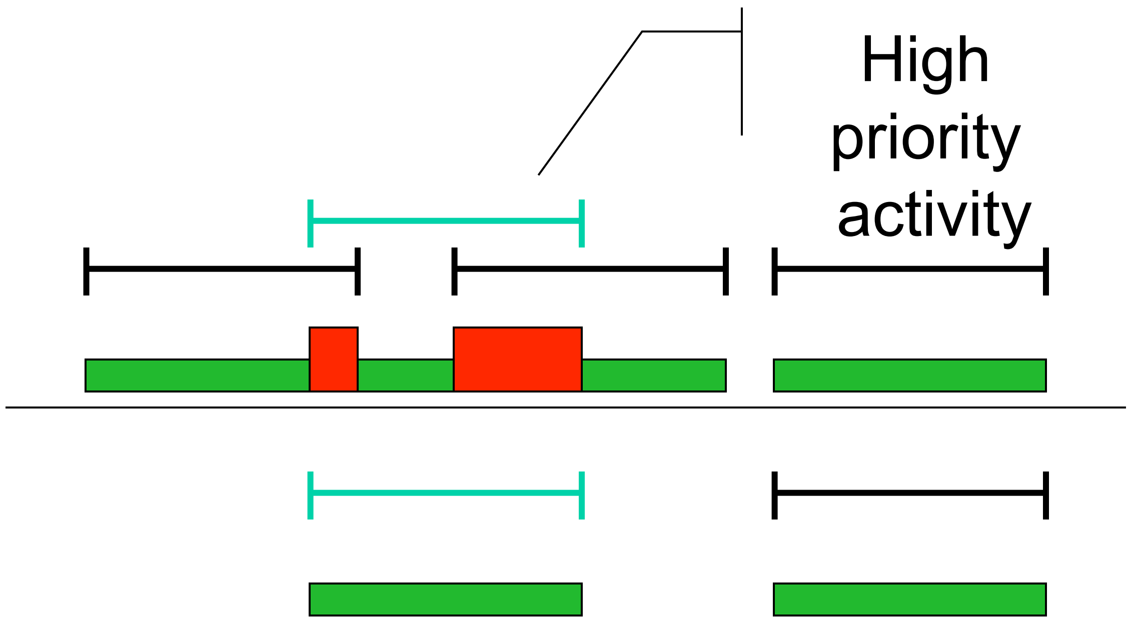
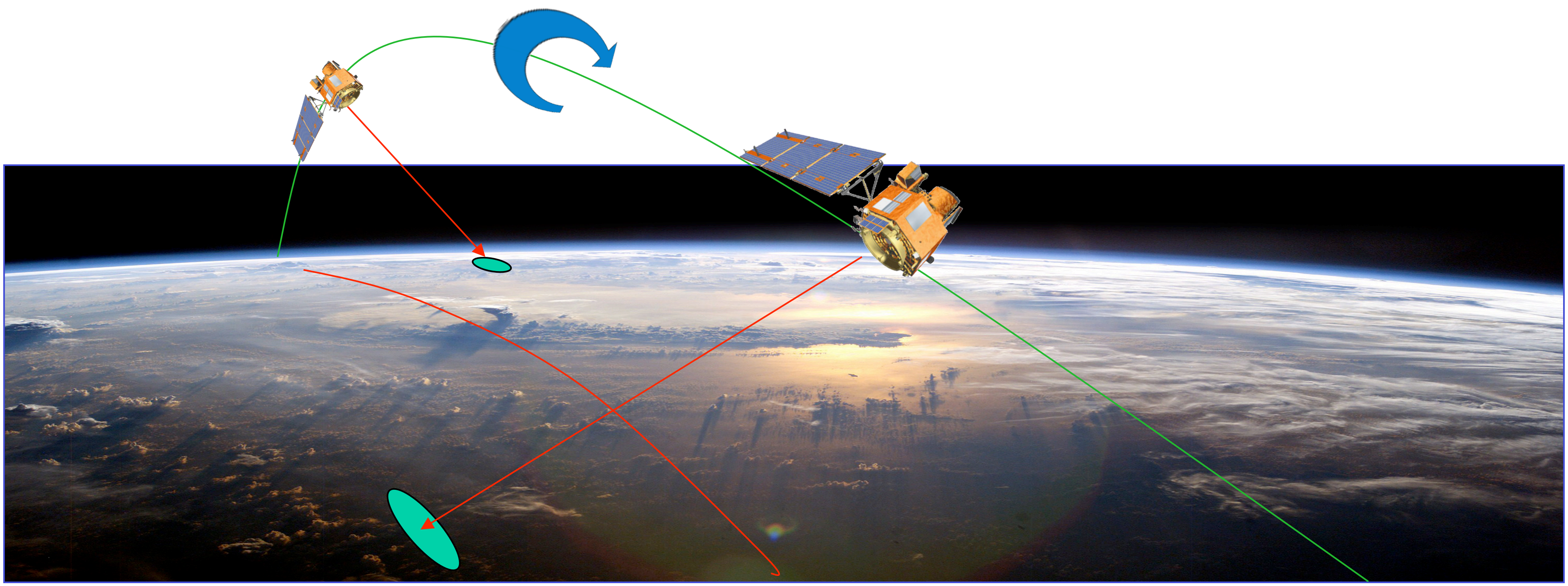
Priority – higher priority scenes pre-empt lower priorities



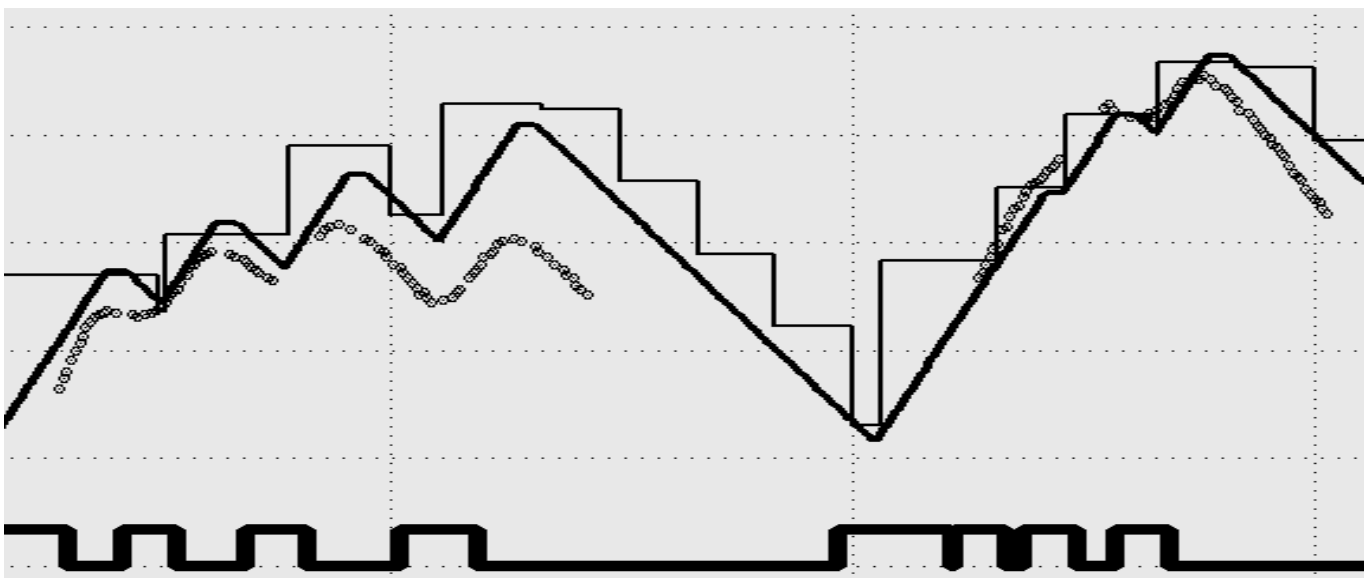
EO-1 Operations Constraints

Maneuver – spacecraft must be able to slew and settle from one scene to the next



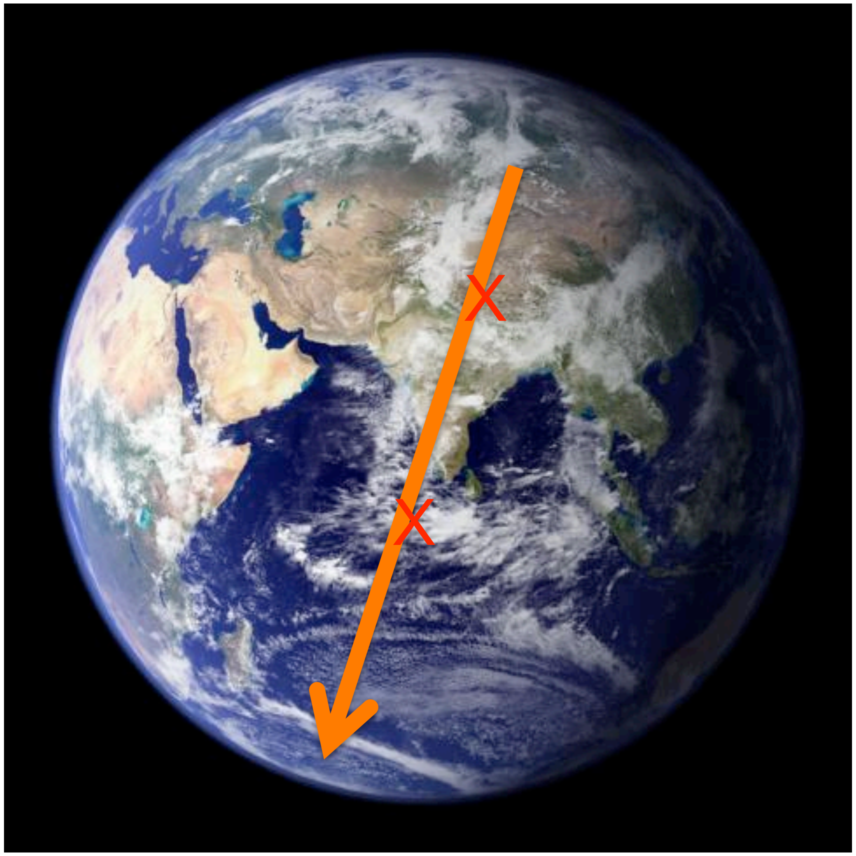
EO-1 Operations Constraints

Thermal – instrument heats while taking scenes, must be allowed to cool before too many consecutive scenes



Motivation for upgrade

- Originally EO-1 allowed one data collection event block with maneuver keepout before and after
- Practically speaking this meant 1 image per orbit
- Later dual collects would allow two DCE's without powering down instruments, e.g. two per orbit, with very limiting constraints



Analysis

Using basic timing information

- What are the closest duals we have ever done
- What are minimum setup times for instrument
- What are the fastest slew & settles we have ever done
- What is longest on-time ever executed for each instrument

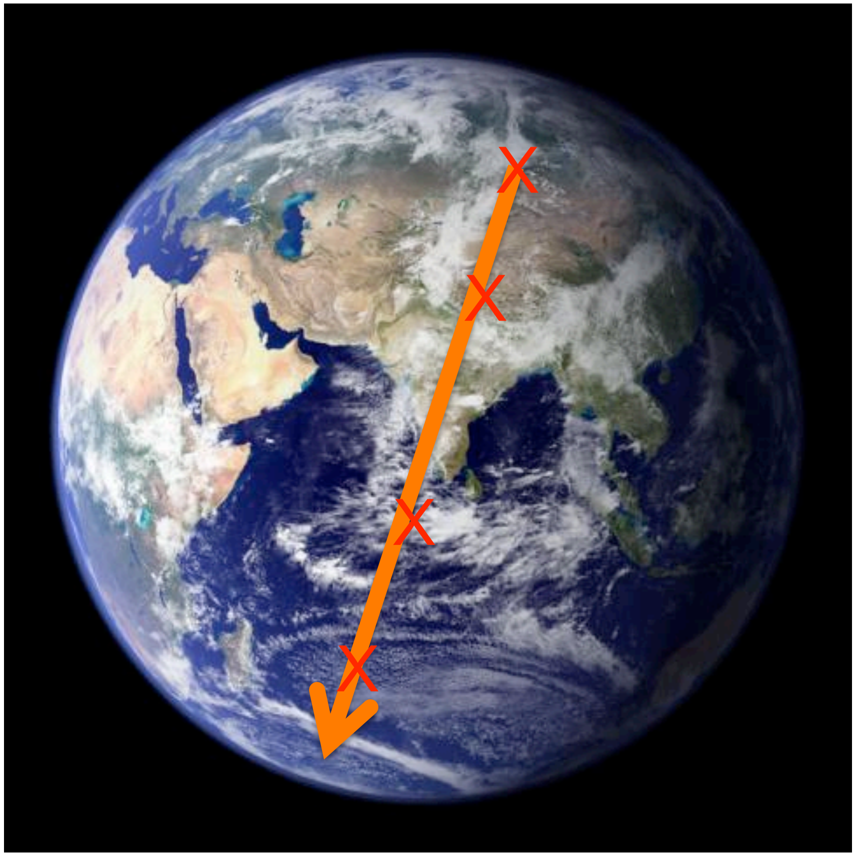
Analysis indicated that we might be able to observe four targets in an orbit ("quad")

Motivation for upgrade (2)

Analyzing hard timing constraints it appeared possible to take up to 4 images per orbit, subject to maneuver, thermal, …

- Based on 45 minute descending node, minimal setups, maneuvers
- 1 of 4 may be a night scene

This was our target for the R5 upgrade



Flight Test

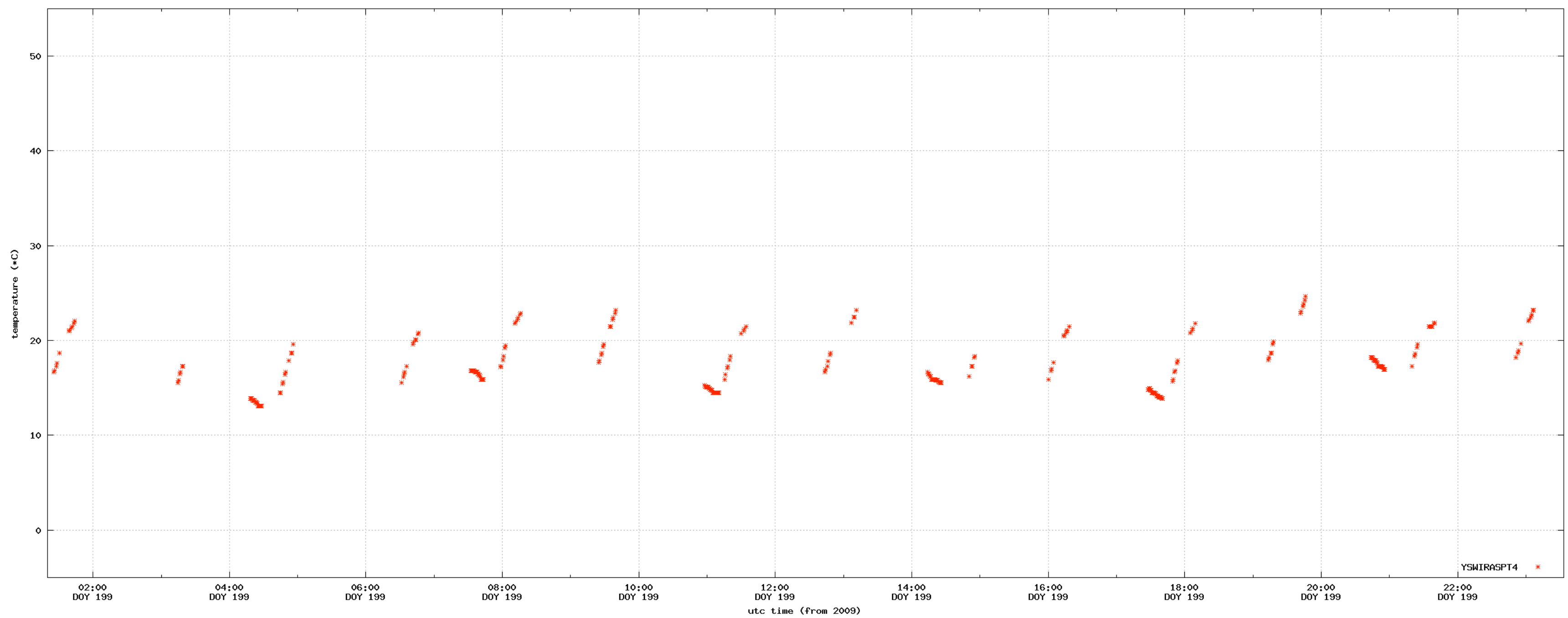
- To gather further information (mostly temperature) we executed a flight test consisting of three quads (date)
- Purpose of test was to gather more detailed thermal modeling data
- Tests occurred with abnormal TDRSS coverage for telemetry data

- Surprise – tripped Hyperion FPGA TLM point (didn't even have a TSM)

Refinements to thermal model

Model thermal cycle (increase, decrease) as two linear temperature ramps with delay offset

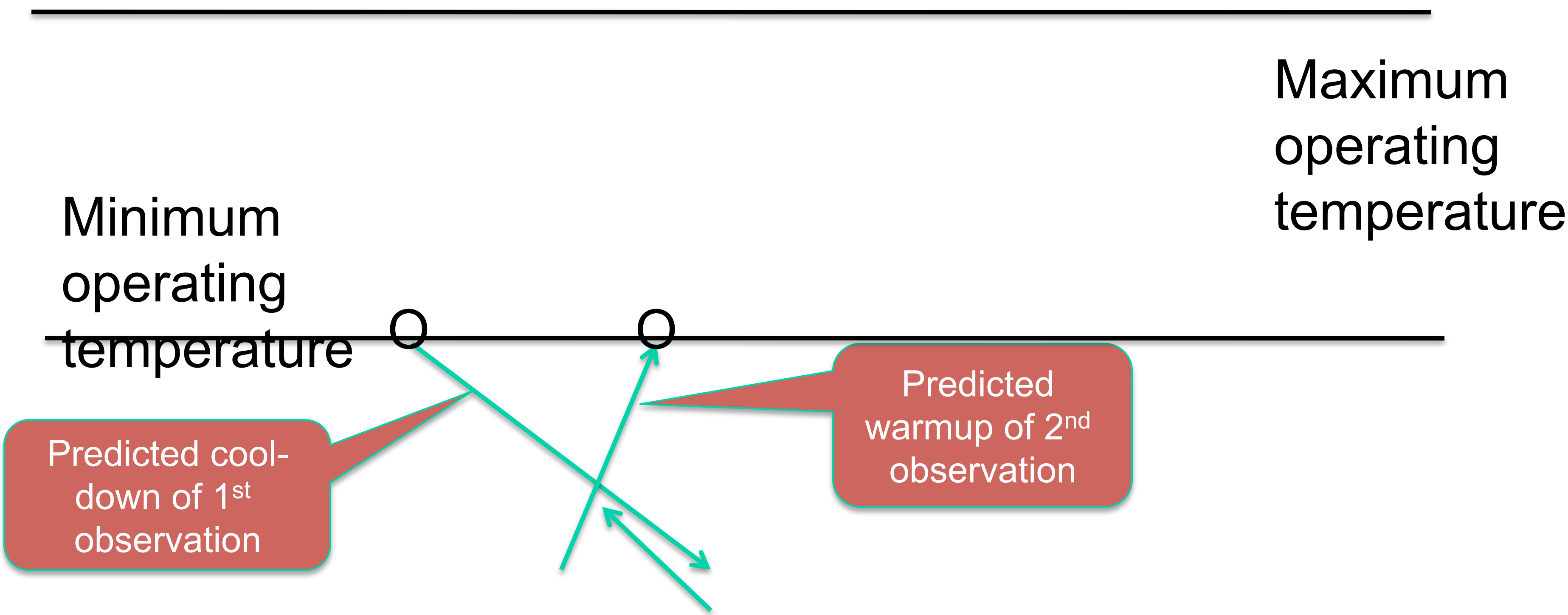
- Currently tracking SWIR, VNIR, FPGA temperature
- Constants inferred by statistical analysis of large numbers of observations (100’s) but only few triples examples prior to start of checkout



Thermal model

HTN Expansion of the model computes the ideal time to turn-on instrument

- based on temperature (to achieve minimum operating temperature) and
- minimum setup time



Maneuver Calculation

- Uses GSFC developed Maneuver planning tool (Matlab)
- 1st rev of tool took as input a ground target and computed slews to (from nadir)
  - Point to target
  - Point back to nadir
    - Provide predicted wheel speeds at observation time
- 2nd rev of tool allowed specification of a secondary scene
  - Nadir, point to target (primary), point to secondary, point back to nadir
  - Primary must be 1st scene in dual
  - Report predicted wheel speed for 1st and 2nd scenes (reject secondary?)
- 3rd red of tool allowed construction of up to quads with a primary anywhere in the quad (e.g. 1st, 2nd, 3rd or 4th)
  - Software attempts to optimize wheel speeds for primary
  - Rejects if any other scene is out of limits

Tuple construction

Grow scenes from temporal groupings

Produce all singles, duals, triples

Because of heuristic maneuver planning algorithm, tuples are not monotonic. E.g., A, B, C, legal as singles, AB legal, BC not legal, but ABC legal…even though if ABC is legal BC should be achievable…

Checkout process

- 1st schedule singles only
- Then add dual collects
- Then add small numbers of triples
- Finally, run with unlimited triples
- Consecutive weeks observation count

Upgrade approval process

Approval for upgrade concept

- EO-1 Mission Science Office rejected onboard maneuver computation
- Ground-based maneuver computation but with flexible instrument power approved for implementation
- Instrument team approved operations concept
- Implementation of new model and validation against telemetry
- Flight test to gather additional thermal data
- Operational checkout begins

EO-1 R5 Scheduling algorithm

Generate tuples by searching space of adjacent requests (maneuver)

- 100s scenes → 1000s tuples

Sort tuples by decreasing lowest priority scene

Insert, allowing only bumping with scene subsumption

Effectively starts with highest priority scenes, then grows by adding more of lower priority

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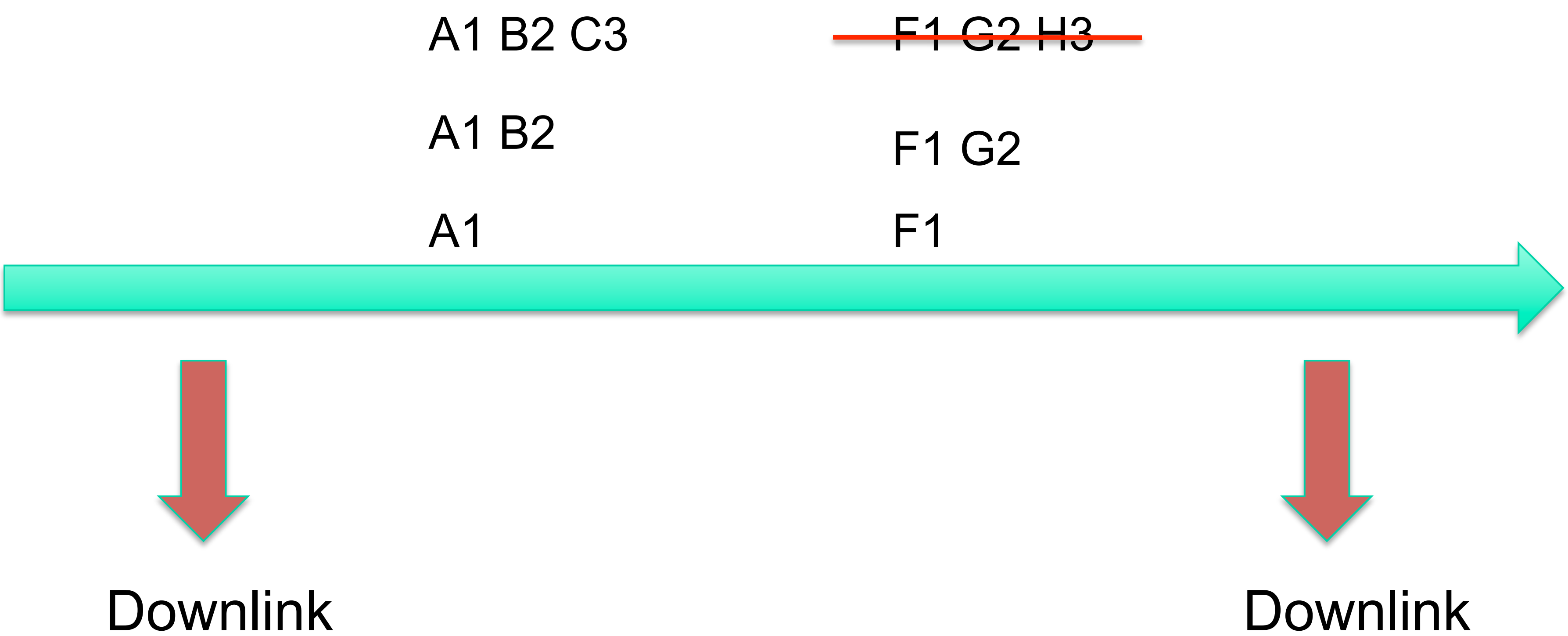
Scheduling algorithm



Evaluation

Ran on four weeks operations data with NO engineering activities.

Algorithm	X-bands	Scenes scheduled	Priority Score
R4	32	130	N/A
R5	51	214	1226
O1: Optimal no thermal, no maneuver, R5 X-bands	51	243	1286
O1A: O1 removing onboard storage	51	419	1286
O1B: O1 ignoring scene overlap	51	252	1422
O2: O1 but choose all X-bands not in conflict with high priority	48	229	1246

Status

Operational and in checkout for past month+

Only recently removed restrictions on number of triples, spacing of triples

Recent weeks observation counts are: 186, 171, 180

Estimated value added of additional scenes for remainder of mission is ~$3M U.S.

Conclusions – EO-1 R5

Representing and reasoning with spacecraft constraints is challenging

- A deep understanding of the constraints is needed to structure their representation
- Out of the scheduler computations always occur
  - How to integrate with planning/scheduling
- The constraint representation goes hand in hand with the scheduling algorithm
- Often when problem Is properly represented, relatively simple algorithms can provide strong performance

Glider Mission Planning in a Dynamic Ocean Sensorweb

David R. Thompson, Steve Chien, Yi Chao, Peggy Li — Jet Propulsion Laboratory

Matthew Arrott, Michael Meisinger — UCSD CalIT2

Arjuna Balasuryia, Stephanie Petillo — MIT Mech. Engineering

Oscar Schofield — Rutgers University

 US Government Support Acknowledged.

Agenda

Overview: a network of underwater gliders

The cartographic plan

- Current-sensitive path planning

The detailed plan

- Plan elements, dynamic simulations

Future development, open problems

Ocean Observatories Initiative (OOI)

Integrate assets: moorings, AUVs, gliders

Incorporate numerical forecasts

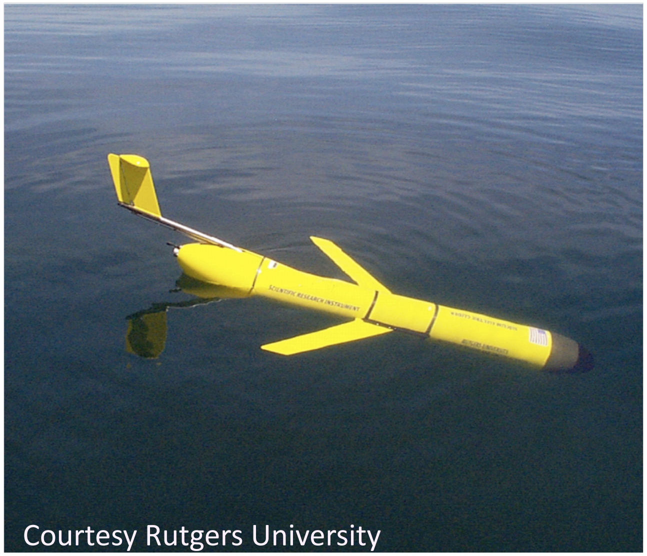
Real-time multi-sensor tasking and adaptive sampling

Mission planning must:

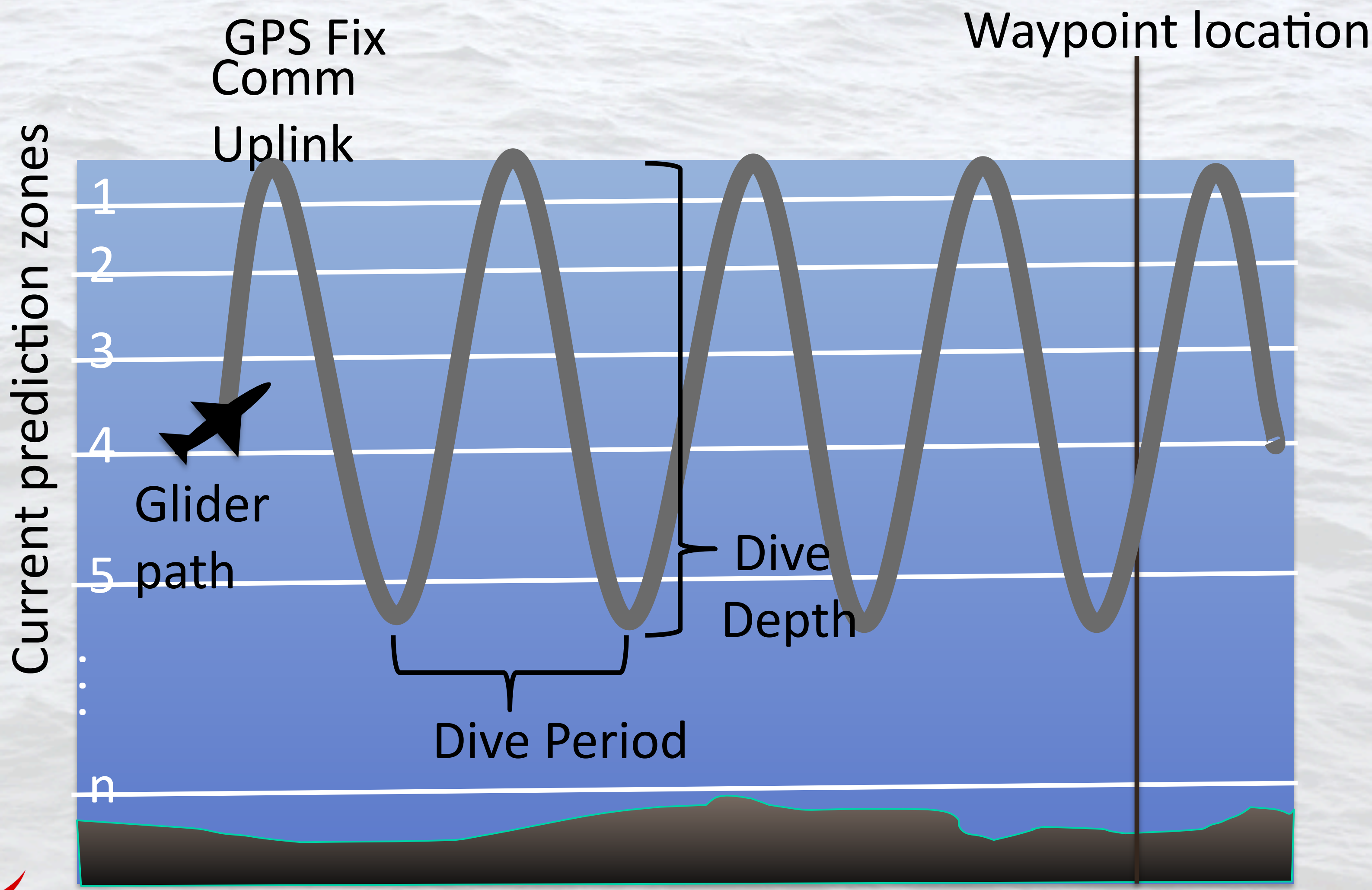
- Coordinate multiple assets
- Permit fast planning turnaround
- Integrate science data

Underwater gliders

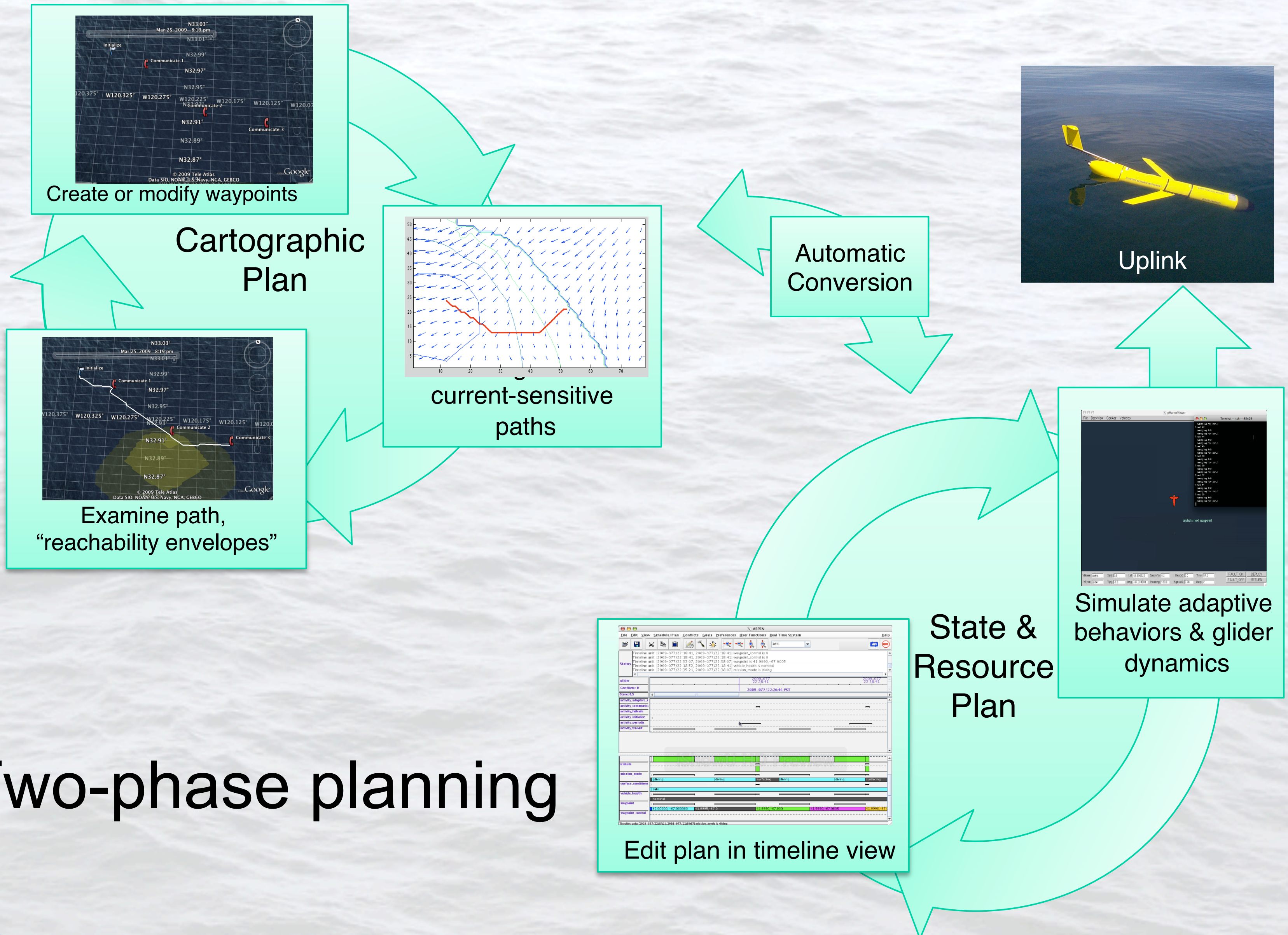
- Long mission durations
- Sensitive to time-varying currents
- Payload includes Current Temperature Depth (CTD) sensors
- Autonomous operations for ~ 6 hours


Courtesy Rutgers University

Underwater gliders: flight profile



Two-phase planning



The cartographic plan

Defines glider location in space and time

One activity at a time

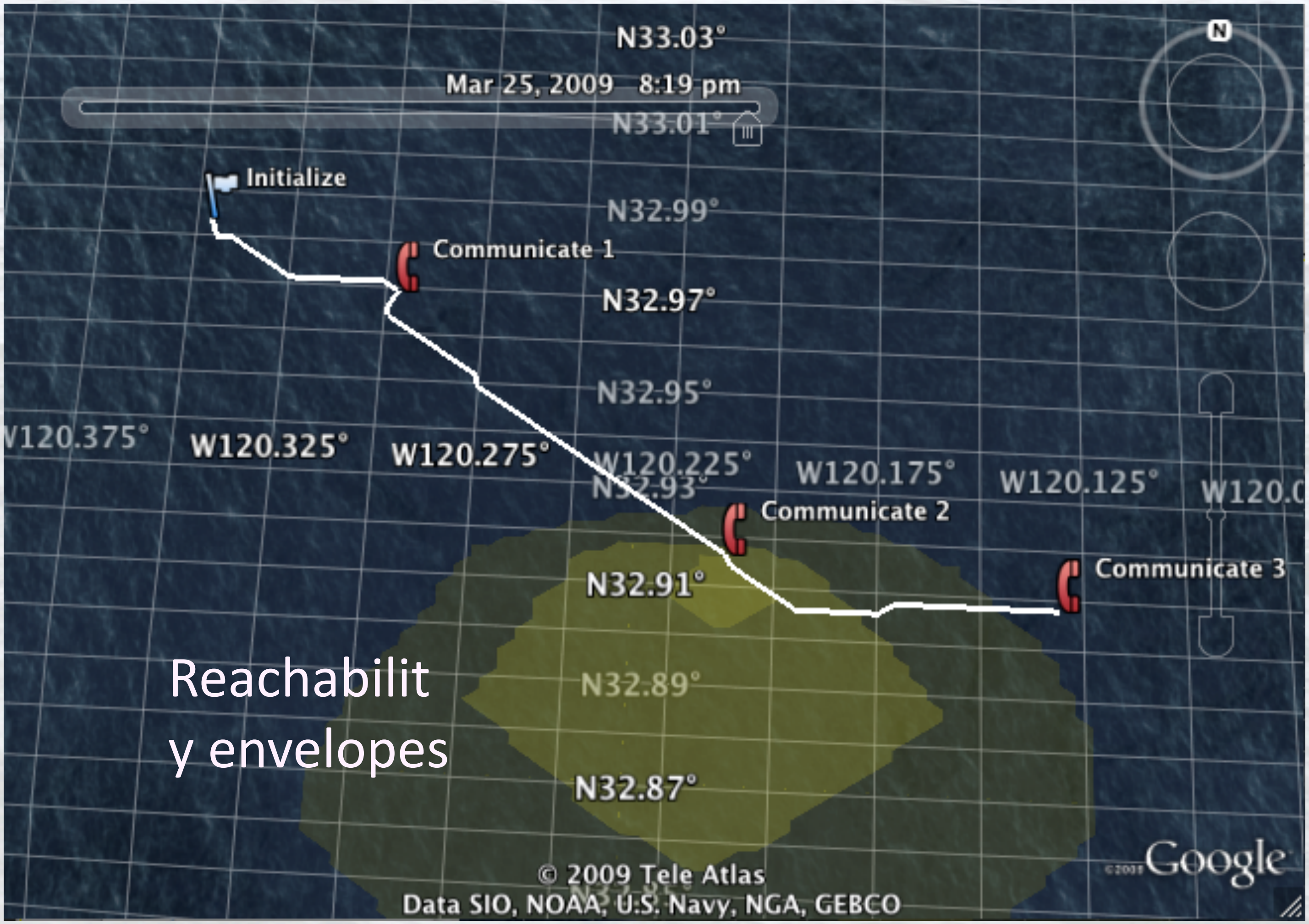
Intuitive map-based visualization

Models basic glider activities:

- Goto Waypoint [destination, fallback destination]
- Communicate [location]
- Initialize [location]

Current-sensitive path planner computes reachability polygons, interpolated paths

The cartographic plan



Reachability envelopes

Path planning

Interpolates communications actions, waypoints

Accounts for depth- and time-variable currents

Defines destinations with location *and* time of arrival

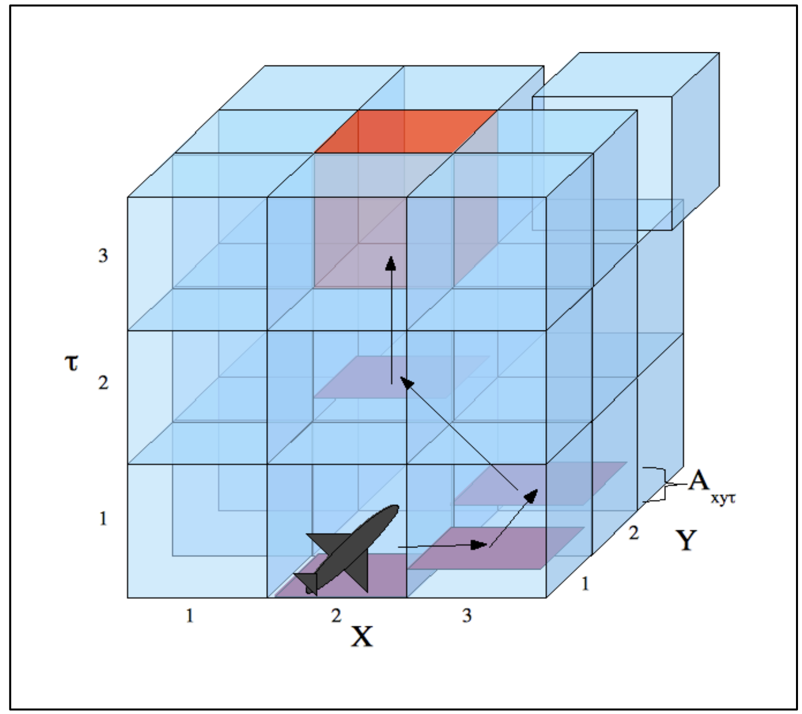
- Can track time-variable phenomena
- Can time-coordinate multiple OOI assets

Optimizes for *earliest valid arrival*

- Arrives as soon as possible such that the glider can hold position until goal time

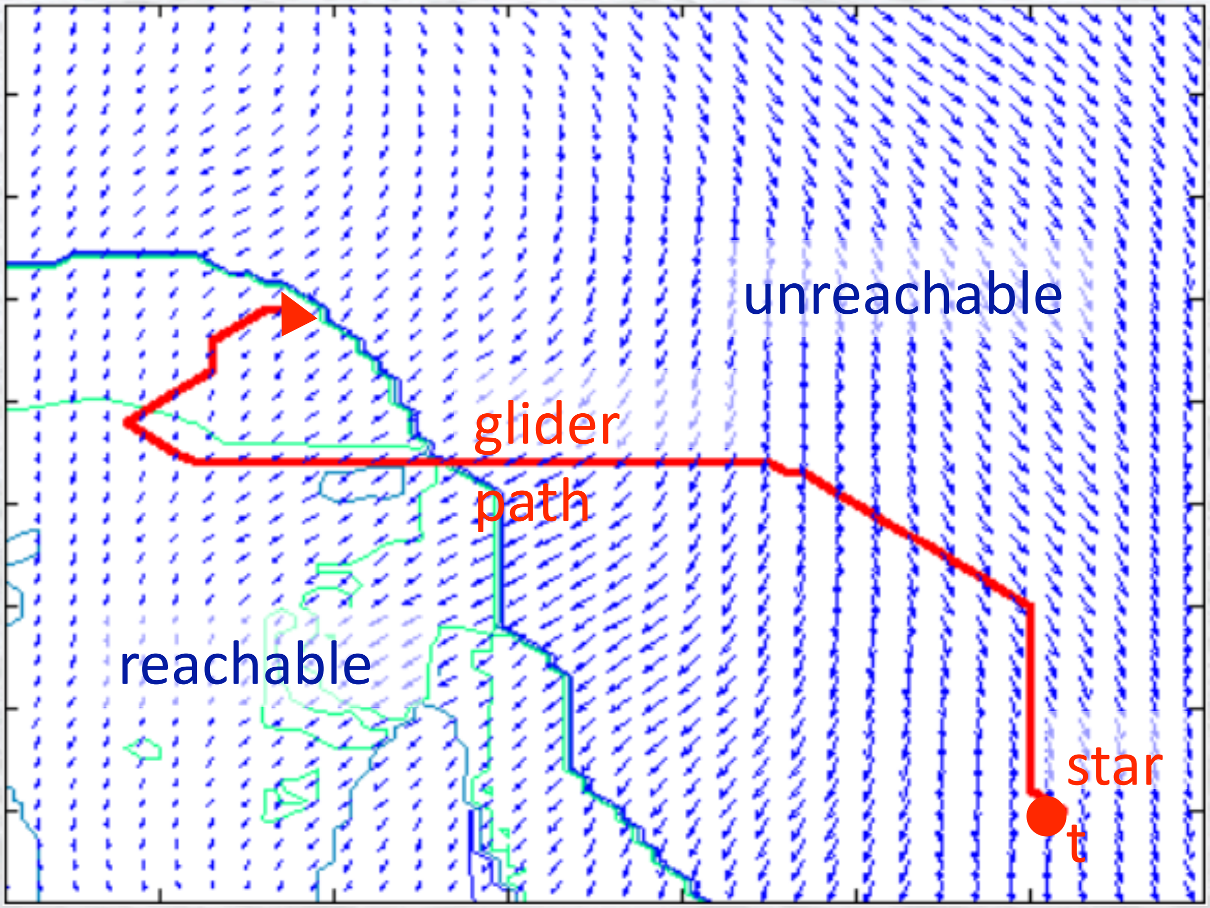
Path planning: algorithm

- 3D spatiotemporal grid indexed by x,y,T
- Recursively compute earliest arrival times A_{xyT}
- Retain the "best parent" for each reachable node
- After all nodes visited, follow parents back to start

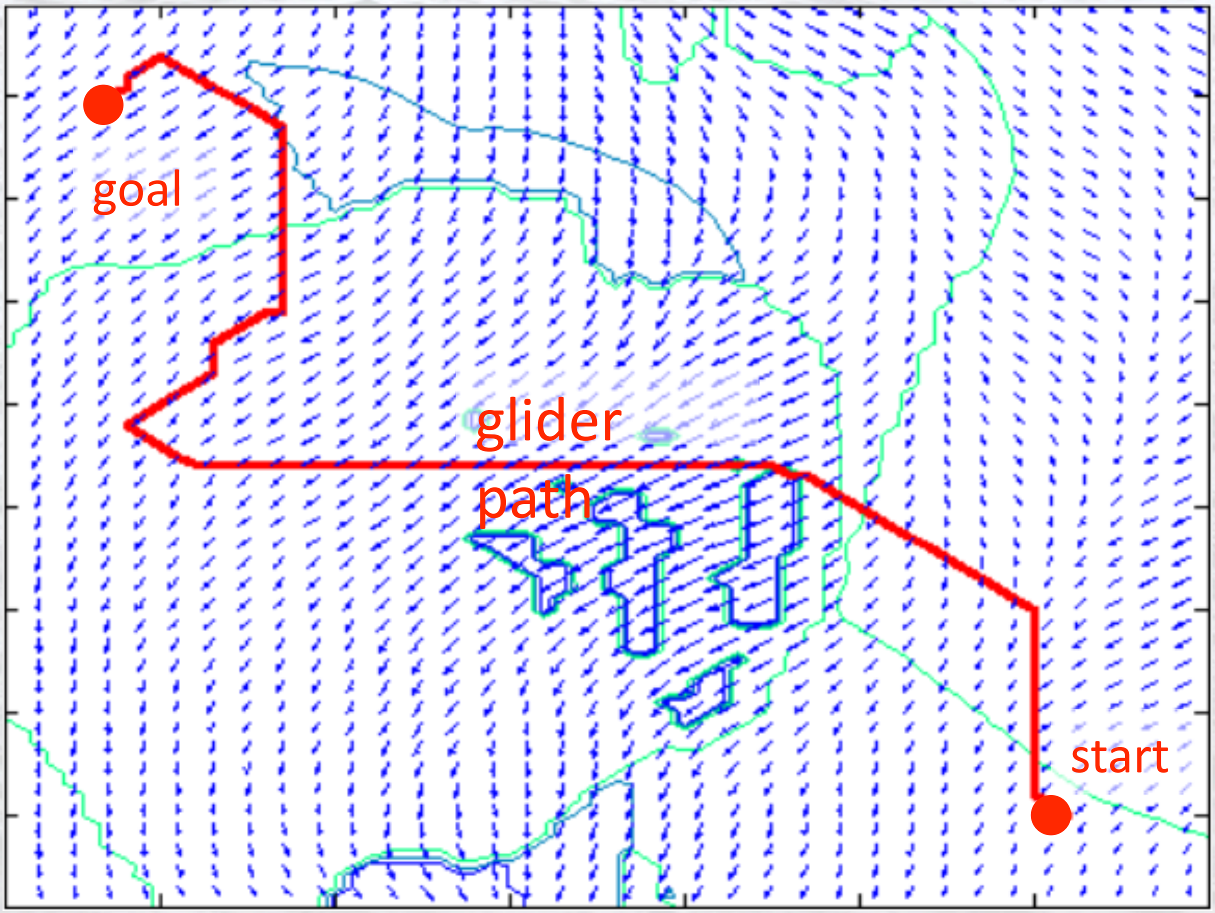


(Glider moves continuously in time dimension)

Path planning: example



Path planning: example



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Path planning: experimental results

Tested predictive vs. locally greedy path selection

- ROMS data from Southern California
- Random start and goal locations
- 48-hour maximum path length

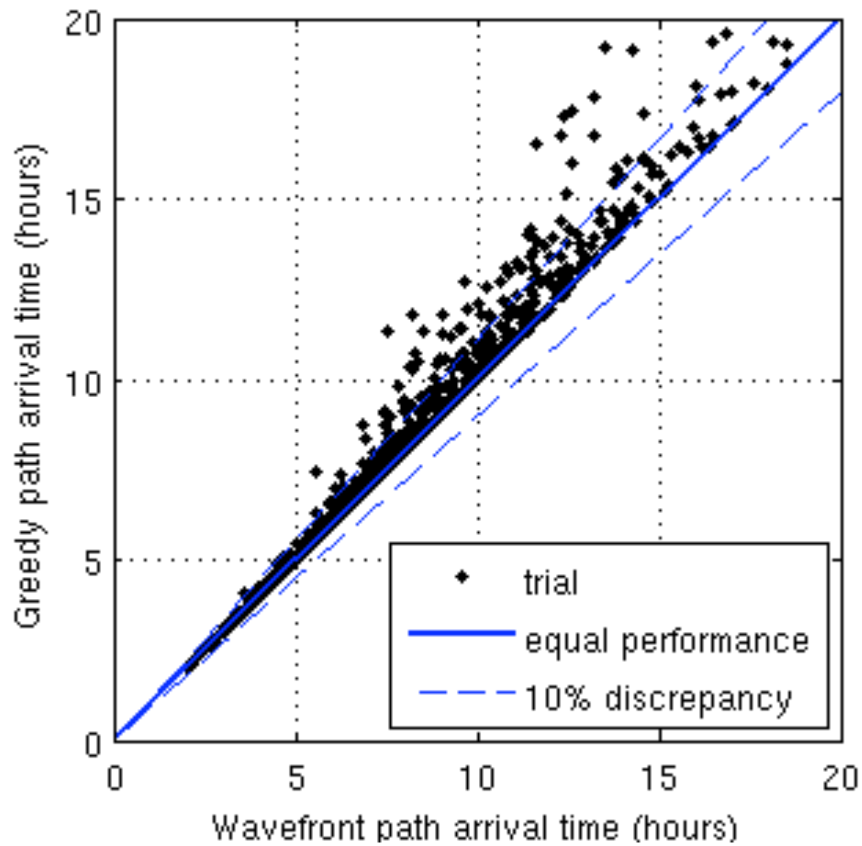
Predictive method finds significantly more valid paths

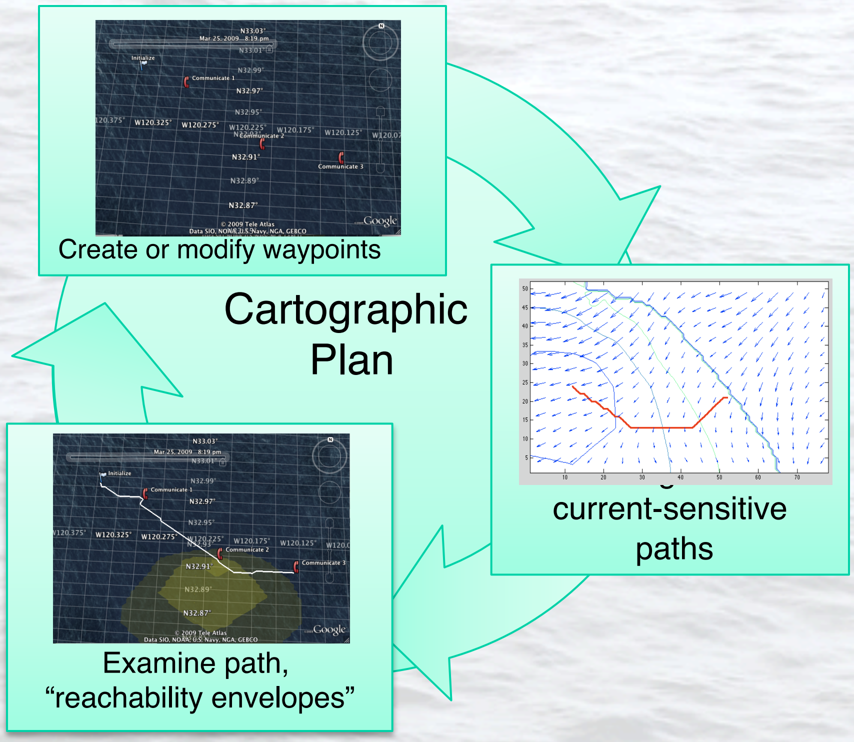
	0-5 km	5-10 km	> 10 km
Predictive	53.3%	50.7%	46.0%
Greedy	33.7%	33.1%	26.1%

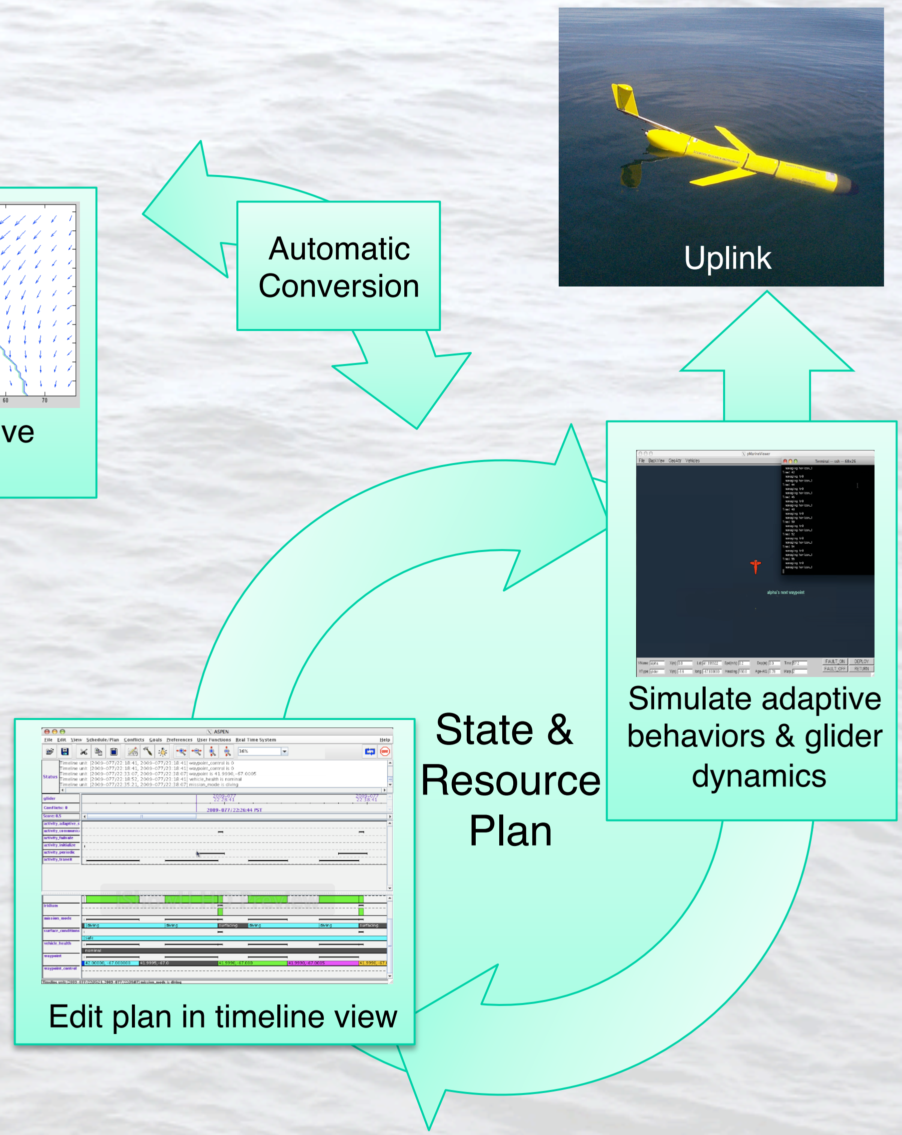
Fraction of random trials with successful paths

Path Planning: experimental results

- For all valid paths, wavefront method arrives faster
- Discrepancy increases for long paths







Two-phase planning

The State & Resource Plan

Models concurrent activities

Tracks limited resources

- Control of onboard processes (helm)
- Iridium phone
- Battery power

Defines *fallback destinations* if glider is out of position

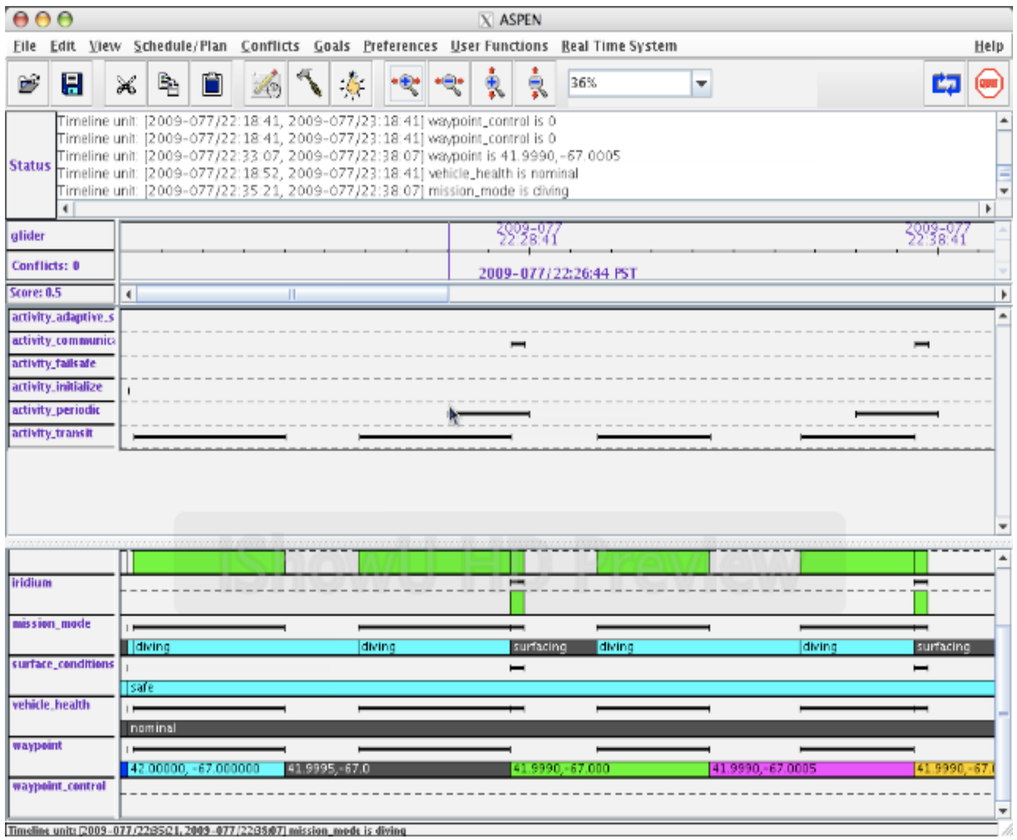
Additional user options

- Engage/disengage instrument packages
- Adjust glider flight parameters

Model element	Cartographic plan	State & resource plan
Initialize activity (start, duration)	X	X
Location	X	X
Communicate activity (start, duration)	X	X
Location	X	
Goto waypoint activity (start, duration)	X	X
Destination	X	X
Fallback destination	X	X
Energy required		X
Flight parameters (depth, pitch)		X
Loiter activity (start, duration)		X
Sample activity (start, duration)		X
Failsafe activity (start, duration)		X
Vehicle health		X
Payload health		X
Battery energy		X

Timeline interface

ASPEN planning system



Conditional activities

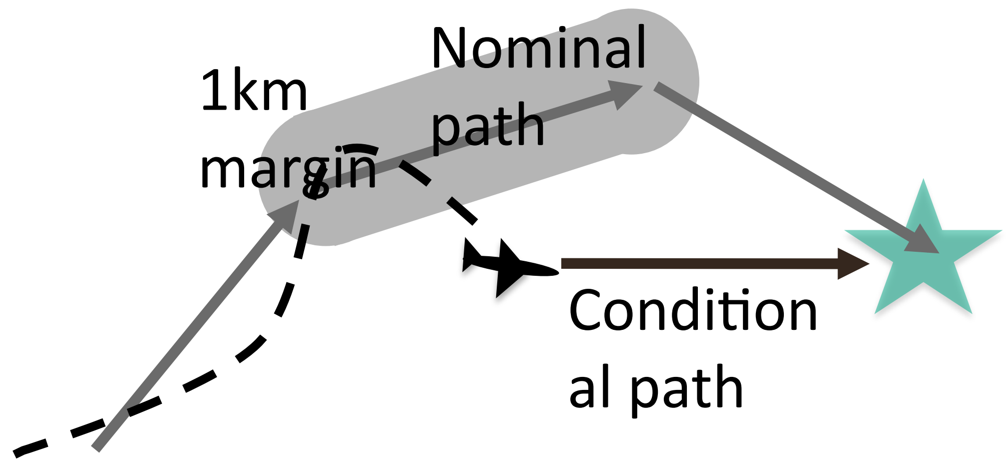
Fallback locations for timed waypoint sequences

Prevents backtracking, orbiting, etc.

Add robustness to execution or current prediction error

Conditional plans suitable for onboard execution

- Don't require updated current estimates
- Reactive (simple to compute)



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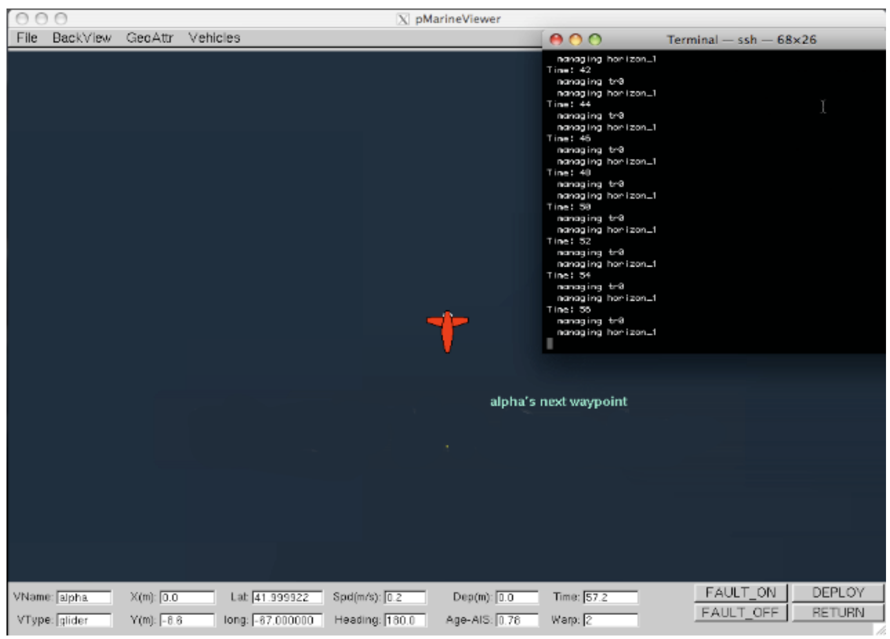
Moos-IvP simulation (future)

Simulates detailed plan with glider dynamics

CASPER onboard executive executes scheduled activities

Vehicle health, position monitoring



Conclusions / Open problems

Glider Planning uses two stage planning process

- Cartographic/path planning
- State/resource planning
- Similar to other routing problems such as Unpiloted Aerial Vehicle Control and Rover planning

Shore-based Glider planning to be deployed to support October/November 2009 Glider deployment to Mid Atlantic Bight

Onboard glider planning pending adaptation of glider hardware

Acknowledgements - Gliders

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ORION

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OOI

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