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AI PLANNING FOR SPACE


NASA Jet Propulsion Laboratory
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JPL Mission Control Room

JPL Mars Yard

Why automate planning for space missions?

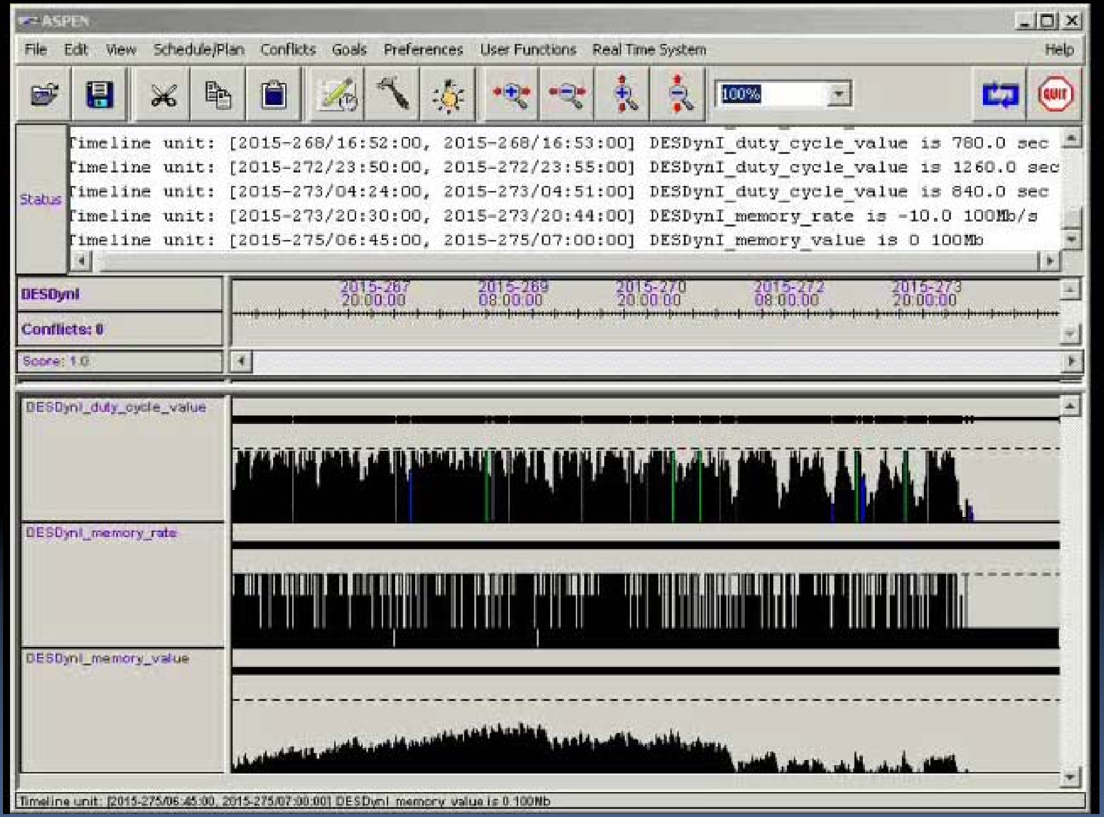
- Spacecraft have limited resources
  - cost limits mass
  - mass limits power
  - power limits communication bandwidth
- Many flight rules and constraints
  - Don't point the camera at the sun.
- Inefficiency is expensive.
- A mistake can end the mission.
- Missions need to work out details in advance.

How has artificial intelligence (AI) planning been used by space missions?

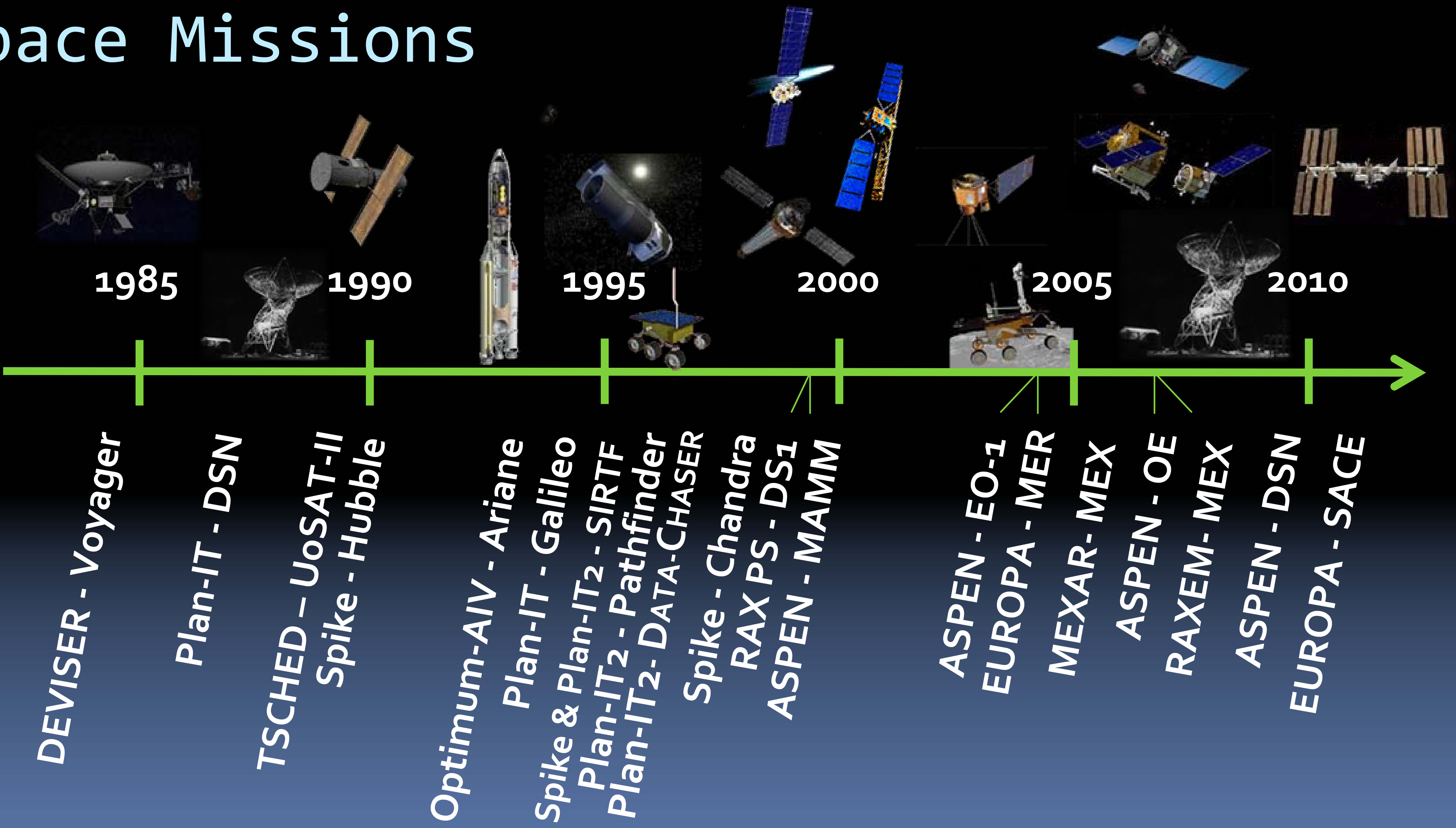
- Help science and operations planning
  - which targets
  - when to take images
  - when to downlink data
  - how to sequence commands
- Autonomous spacecraft commanding
- Generate schedules allocating ground antennas to spacecraft.
- Create plans for solar array manipulation on the International Space Station.
- Project management for the construction of rockets.

What’s challenging?

- Scale
  - a week-long plan could have tens of thousands of actions
  - often tens or hundreds of state and resource variables
- Slow processors and limited memory
- Complex states and resources
  - power, battery, and solar arrays
  - temperature
  - file system
- Complex and unspecified goals
  - The plan is safe, but is it what the user wanted?
- Validation
  - Are all possible plans safe?
- Usability

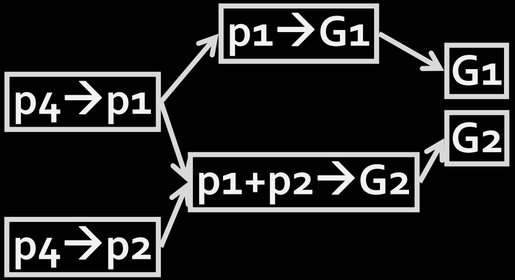


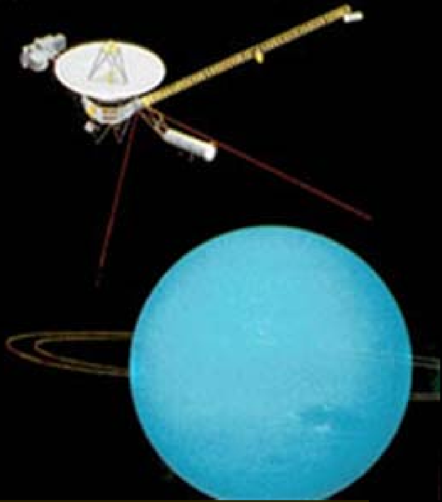
Deployments of AI planners for Space Missions



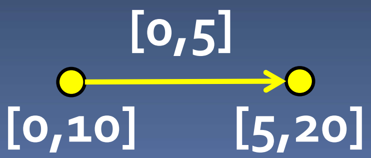
DEVISER – early 1980s

- NASA JPL temporal planner based on Nonlin, written in Lisp.
- Activity planning for Voyager mission in its encounter with Uranus
- Partial order planning, subgoaling, backward chaining
- Time windows
  - Metric time
  - Concurrency
  - Simple temporal constraints





```
(ROLL ACTION
     (CONTEXT
          (NEQ refstar.1 refstar.2)
          (AZIMUTH refstar.1 star1.azimuth)
          (AZIMUTH refstar.2 star2.azimuth))
     ((SC.AZIMUTH star1.azimuth)
          (LOCKED.ONTO refstar.1 )) →
          ((SC.AZIMUTH star2.azimuth)
          (LOCKED.ONTO refstar.2))
      (DURATION (84 + 5 * (SCOPE.0.TO.180
          (star2.azimuth - star1.azimuth)))))
```



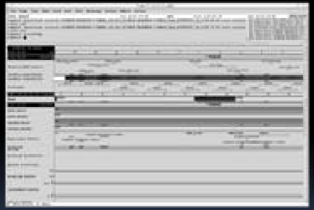

```
(GOALS ((A))
     ((WINDOW BETWEEN 15 300) (DURATION 1000) (B) (C))
     ((DURATION INFINITY) (D)))
```

Steven A. Vere. Planning in Time: Windows and Durations for Activities and Goals, IEEE Transactions On Pattern Analysis And Machine Intelligence, VOL. PAMI-5, NO. 3, MAY 1983

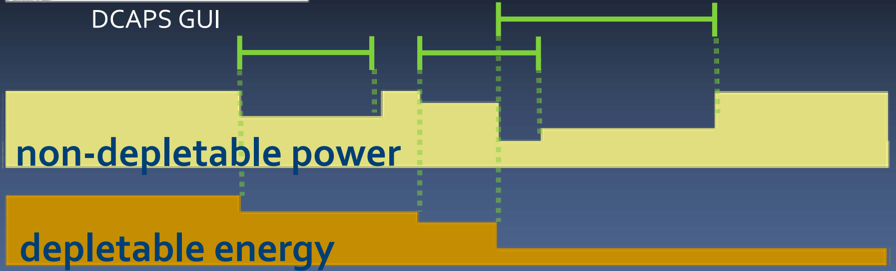
Plan-IT – 1987 to 2001

"Plan-IT" refers to both Plan-IT and Plan-IT-2.

- JPL's Plan-IT is an iterative repair local search planner written in Lisp and improving on DEVISER.
- 1987 – Rescheduled Deep Space Network (DSN) ground antennas.
- 1994 – As MIRAGE, created activity plans for Galileo at Jupiter.
- 1995 – present, created long range plans for Spitzer along with Spike.
- 1996 to 1997 – Used for science and ops planning for the Mars Sojourner rover.
- 1997 – As DCAPS, Plan-IT generated commands for SCL executive onboard the DATA-CHASER shuttle payload.
  - 80% reduction in operations effort
  - 40% increase in science return
- 1998 to 2001 - Generated all command sequences for Deep Space 1.
- Domain modeling with depletable and non-depletable resources
- Heuristic iterative repair:
  1. select a conflict
  2. choose how to resolve: move, add, or delete
  3. select an activity
  4. pick start time and duration



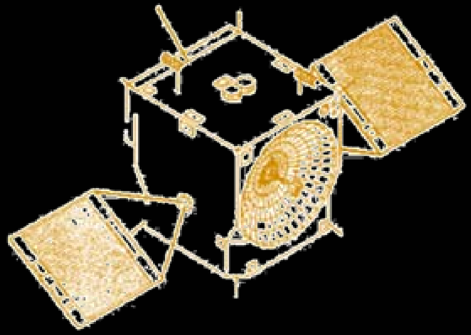
DCAPS GUI



MIRAGE = Mission Integration, Real-time Analysis, and Graphical Timeline Editor
SCL = Spacecraft Command Language
DCAPS = DATA-CHASER Automated Planner/Scheduler
DATA-CHASER = Distribution and Automation Technology Advancement, Colorado Hitchhiker and Student Experiment of solar Radiation

Shepperd, R.; Willis, J.; Hansen, E.; Faber, J.; Siewert, S.; Rabideau, G.; , "DATA-CHASER: a demonstration of advanced mission operations technologies," *Aerospace Conference, 1998 IEEE* , vol.2, no., pp.419-427 vol.2, 21-28 Mar 1998

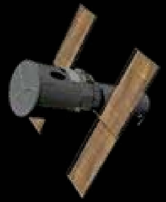
T-SCHED – 1989



T-SAT concept

- British National Space Center
- T-SAT Technology Proving Spacecraft Project
- T-SCHED generated a 24-hour plan that was uploaded and executed live onboard UoSAT-II.

Spike – 1990 to present

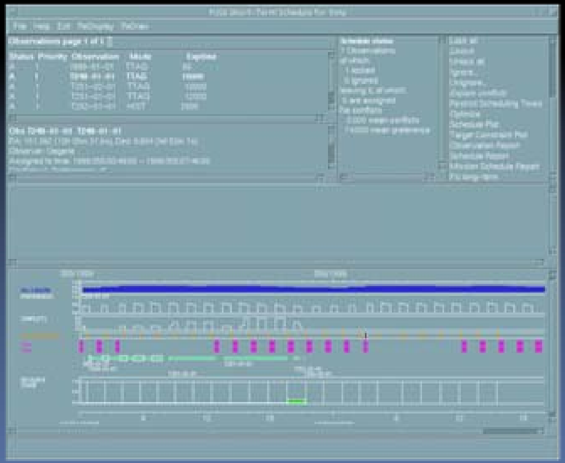


- Space Telescope Science Institute (STScI)
- Used to schedule long term observation schedules for the Great Observatories
  - 1990 - Hubble Space Telescope (HST)
  - 1998 - Spitzer Space Telescope (formerly SIRTF)
  - 1999 - Chandra X-Ray Observatory (CXC)
- Used by many others!
  FUSE, VLT, Subaru Telescope, German Space Operations Center, EUVE, ASCA, XTE
- Stochastic constraint-based schedule optimization in Lisp
  1. trial assignment
  2. repair
  3. deconflict – remove activities or relax constraints
- Constraints & preferences
  - Observations of the same target must be at least 2 months apart.
  - Target must be at least 50° away from the Sun.
  - Minimize change in attitude (rotation).

$$B_{i\alpha}(t;t_{j\neq i}) = \begin{cases} \exp[W_{i\alpha}(t;t_{j\neq i})] & W_{i\alpha}(t;t_{j\neq i}) > -w_0 \\ 0 & W_{i\alpha}(t;t_{j\neq i}) \le -w_0 \end{cases}$$

$$S_{i\alpha}(t) = \max\{B_{i\alpha}(t;t_{j\neq i}) \mid t_{j\neq i}\}$$

$$S_i(t) = R_i(t)\prod_{\alpha} S_{i\alpha}(t)$$



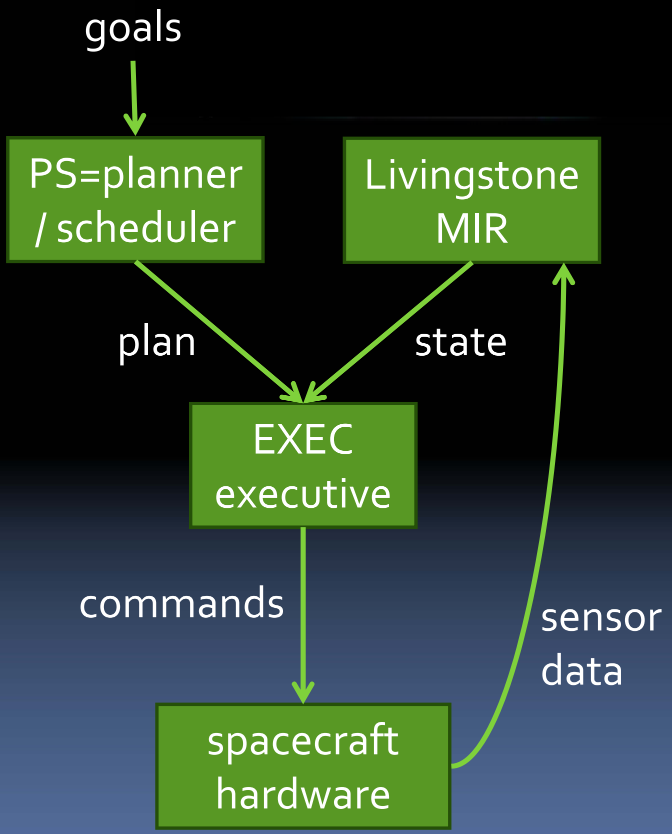
Mark D. Johnston and Glenn E. Miller. SPIKE: Intelligent Scheduling of Hubble Space Telescope Observations. Intelligent Scheduling. 1994

Optimum-AIV – 1993

- European Space Agency (ESA)
- Optimum-AIV automated planning for the project management of the assembly, integration, and verification (AIV) of the vehicle equipment bays of the Ariane 4 rockets.
- Inherits from the PlanERS-1 planner (built for the ERS-1 mission), Nonlin, and O-Plan.
- Integrated with the commercial ARTEMIS project management system.
- Rich plan representation
- Scheduling is solved as a constraint satisfaction problem involving resource and temporal constraints.

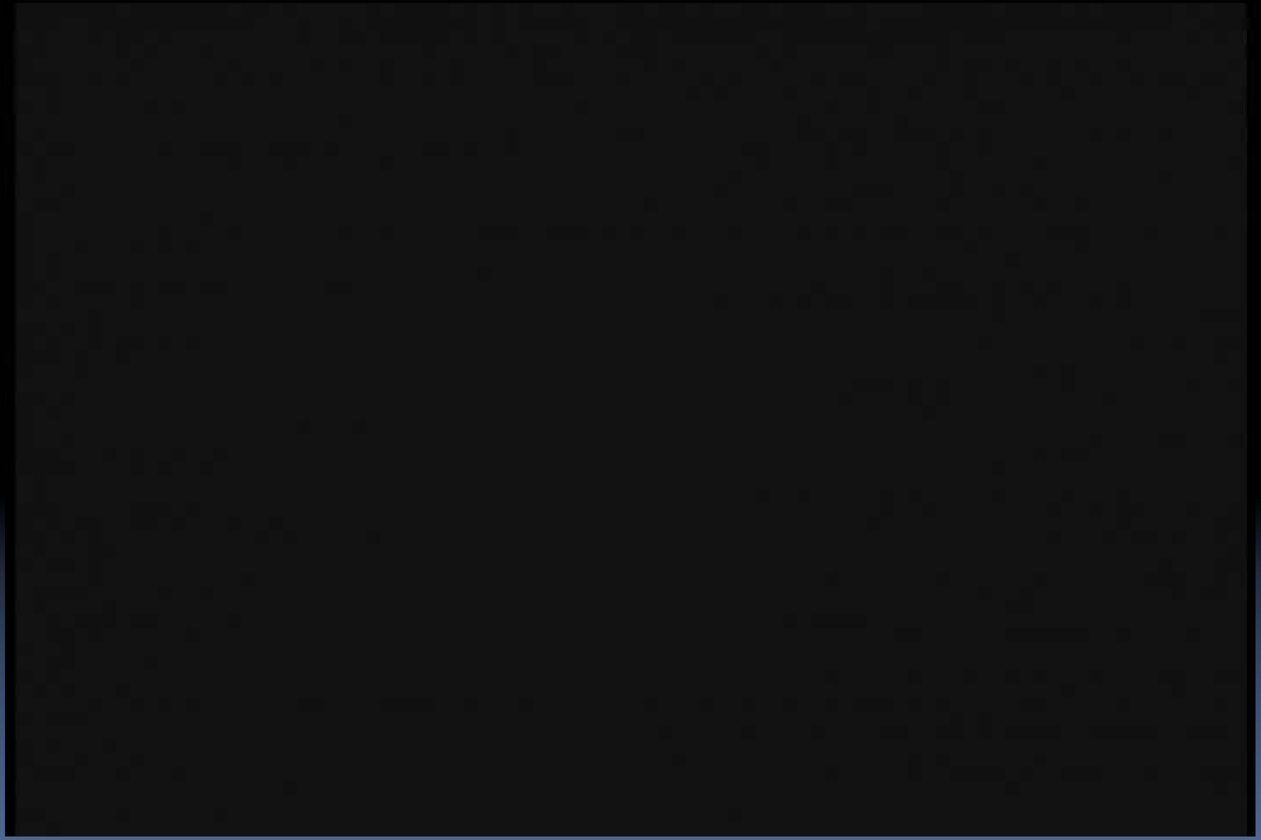
RAX, Remote Agent Experiment - 1999

- NASA Ames Research Center (ARC) and JPL
- Deep Space 1 (DS-1) technology demonstration
- Three main Lisp components autonomously operated DS-1 for two days:
  - Planner/Scheduler (PS) is a constraint-based temporal planner and resource scheduler
  - EXEC executive
  - Livingstone mode identification and reconfiguration (MIR)
- Also demonstrated response to unexpected events in simulation while onboard.
- Examples of constraints
  - Total power usage < 2600 watts.
  - Ion engine thrust uses 2300W.
  - During a thrust the Attitude Control System must not be turning the spacecraft.



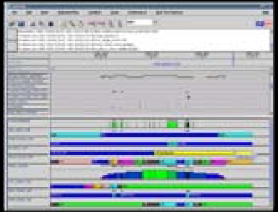
Autonomous Sciencecraft Experiment on EO-1

- Aqua downlinks images.
- Sensor web ground software detects changes since last image.
- Requests high resolution image from EO-1.
- ASE replans operations onboard EO-1 for the new high priority target.
- Autonomous planning enables quick response to forest fire.



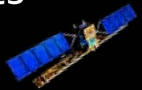
ASPEN/CASPER – 2000 to present

Automated Scheduling and Planning Environment
Continuous Activity Scheduling Planning Execution and Replanning



```
Activity fire_engine {
  constraint =
    starts_after end_of catbed_htr_on
      by [1800, infinity];
  reservation engine_sv change_to “firing”;
}*
```

- JPL stochastic iterative repair planner written in C++
- Similar to Plan-IT, adding hierarchical task network (HTN)
- Intuitive language designed for (and by) non-AI experts
- 2000 - Modified Antarctic Mapping Mission (MAMM)
  - reduced planning effort by 80%; saved > $1M



- 2004 - present - onboard EO-1 satellite as part of the Autonomous Sciencecraft Experiment
  - Integrated with SCL executive
  - 55% reduction in operations costs
- 2007 - ground planning for DARPA Orbital Express
  - saved more than $10 million
  - natural language processing to generate model
- 2009 - present – DSN Service Scheduling Software (S^3)
  - generates schedules and aids negotiation among 20+ missions

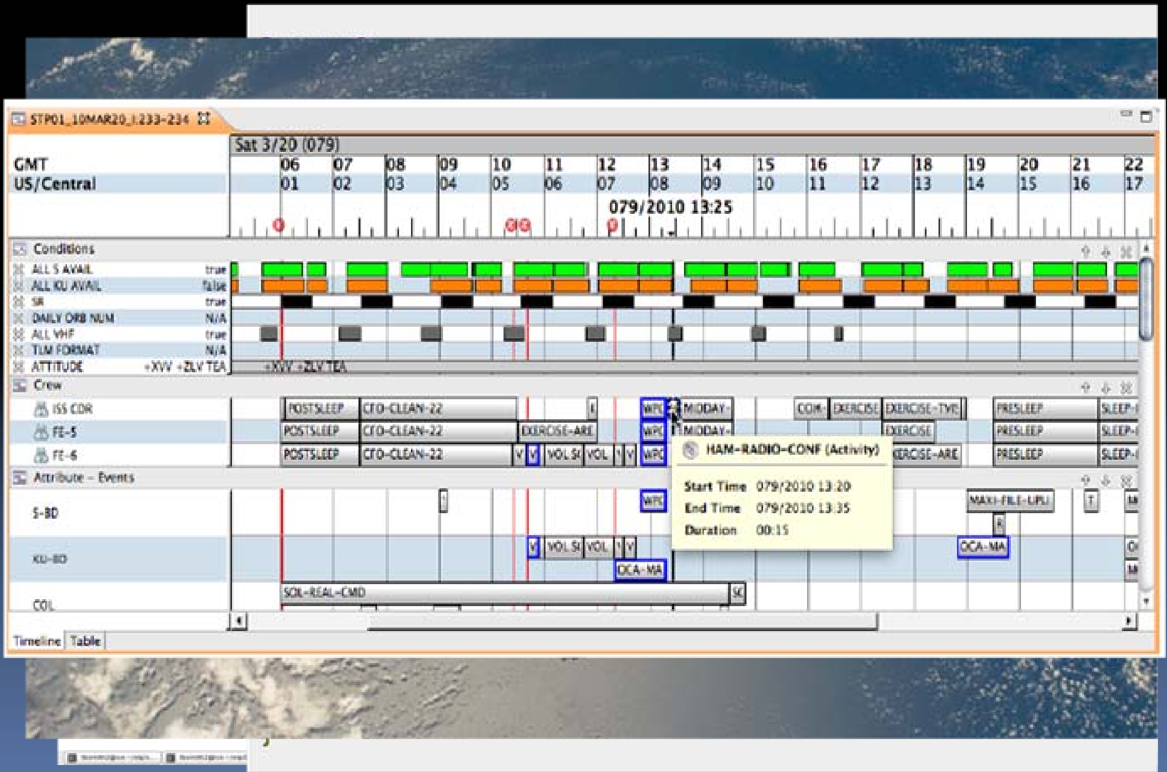
* B. Smith, G. Rabideau, R. Sherwood, A. Govindjee, St Chien, D. Yan, and A. Fukunaga. Representing Spacecraft Mission Planning Knowledge in ASPEN. In Proc. of *Artificial Intelligence Planning Systems Workshop on Knowledge Acquisition.* 1998.

PROBA – 2001

- ESA Project for On Board Autonomy series of spacecraft
- PROBA-1 launched in 2001
  - Demonstrated onboard scheduling and resource management.

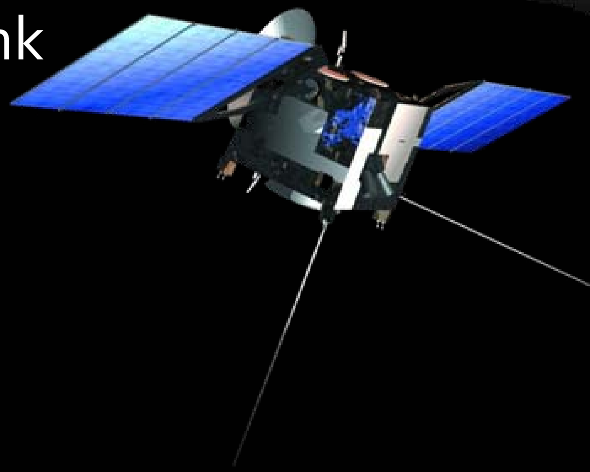
EUROPA – 2004 to present

- NASA Ames Research Center planner inheriting from RAX PS, written in C++
- 2004 - MAPGEN (Mixed Initiative Activity Planning Generator)
  - Increased scientific return, estimated between 20% and 30%
- 2011 - SACE – Solar Array Constraints Engine
  - Used to plan the orientation and movements of the International Space Station's eight large solar arrays.
- Constraint programming approach to planning and scheduling.
- States and actions are both represented as temporal variables, called "tokens."
- SPIFe and an Eclipse-based IDE are often used as user interfaces.



Mike McCurdy, Arash Aghevli, Alfredo Bencomo, *Scheduling and Planning Interface for Exploration (SPIFe), Demonstrations ICAPS 2011.*

MEXAR and RAXEM – 2005 to present



- ESA planners for Mars Express (MEX) downlink and uplink
- 2005 - present – MEXAR (Mars EXpress ARchitecture)
  - Data downlink planning for MEX
  - Constraint-based planner employing max-flow algorithm
  - Saved 50% of time for producing plans
  - Minimized data loss (due to the ability to generate plans for multiple days quickly)
- 2007 - present – RAXEM
  - Uplink planning for MEX to help with the limited buffer size for commands
  - Shortened planning from hours to minutes

AI Planning for Space – the Future
Autonomous rovers

What about the Mars Science Laboratory (MSL) mission's Curiosity rover?

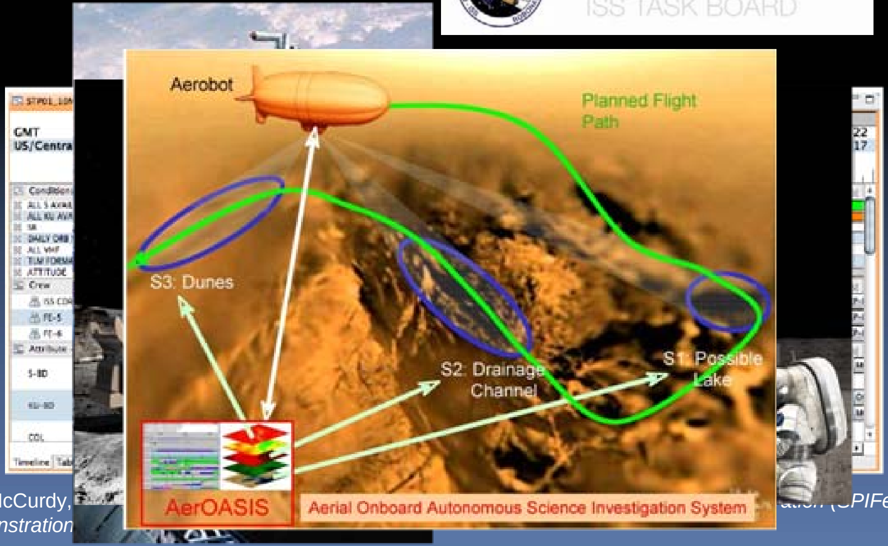
- The MER and MSL rovers use D* path planning.
- 2009 – present – AEGIS

(Autonomous Exploration for Gathering Increased Science)

  - Opportunity autonomously investigates rocks while on long traverses.
  - Machine learning employed for onboard image processing, but no planning, yet.

AI Planning for Space – the Future

- Autonomous and teleoperated robots for the space station and crew exploration missions
- Automated scheduling for crewmembers
- Space mission and spacecraft design
- Planetary and in-space construction
- Testing, verification, and validation
- Planetary exploration with aerobots or hydrobots.



Mike McCurdy, ... ation (SPIFe),
Demonstration

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