The Role of Autonomy in Space Exploration

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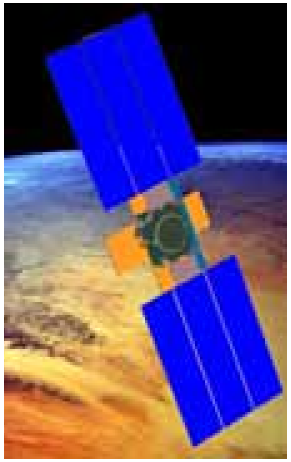
What is Autonomy?



sense

decide

act

Autonomous decisions

Autonomy software performs the sophisticated reasoning and decision making needed to accomplish user goals with limited human intervention.

Autonomous is much more than Automated

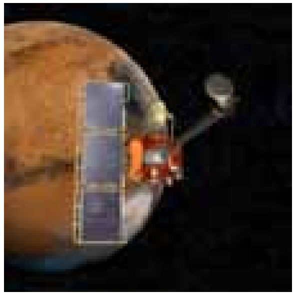
- automated: low-level, mechanical decisions (if-then, control law) designed for a limited class of situations.

- autonomous: sophisticated *system-level* decisions.
can deal with many situations, including the unexpected.
can deal with situations that *automated* systems cannot.

Challenges of Deep Space Missions

- Uncertain, hazardous environments
- Relatively long distances from Earth
  - long round-trip light-time delays
  - low data communication rates
  - infrequent communication

ballute



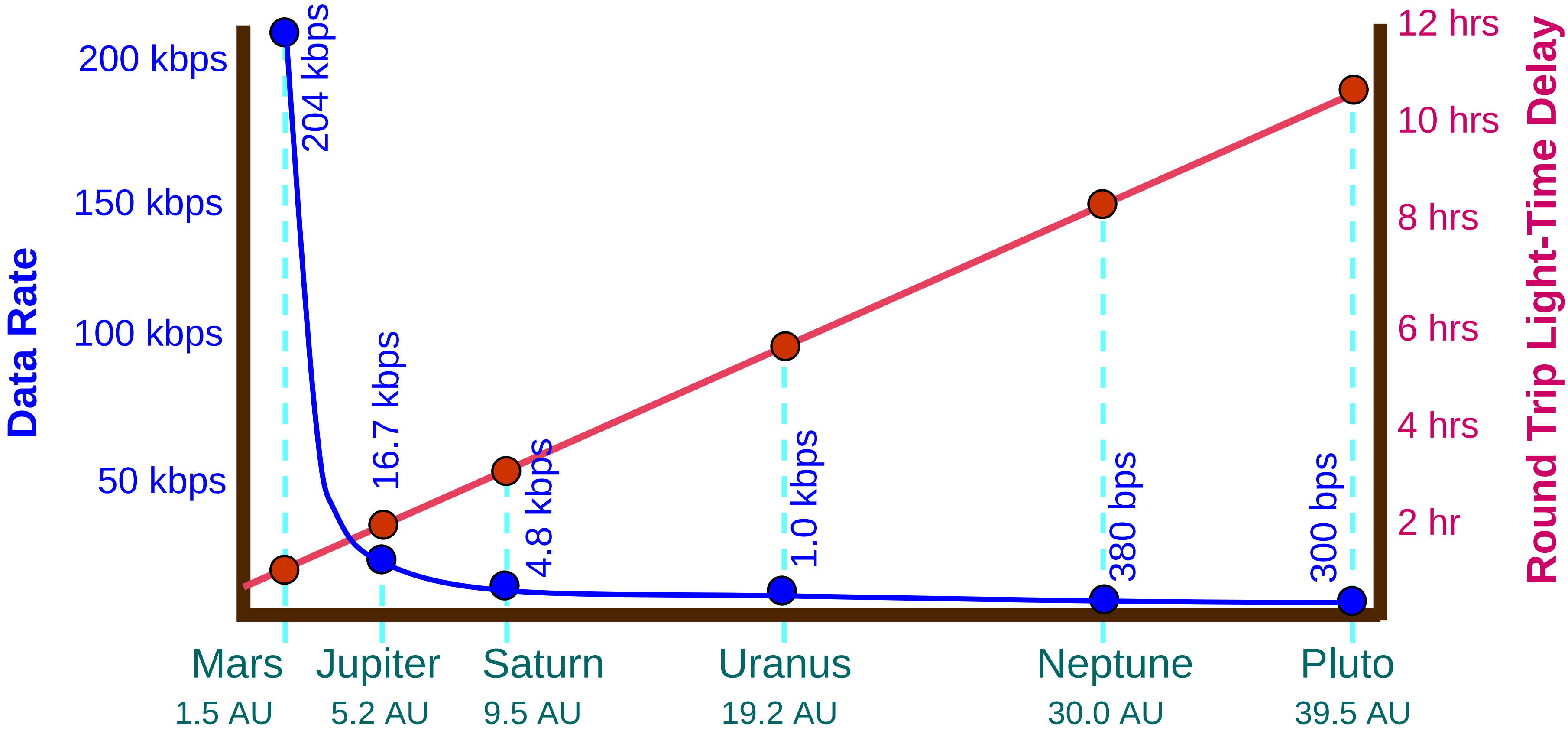
planetary orbiter

hydrobot in Europa ocean

Martian rover

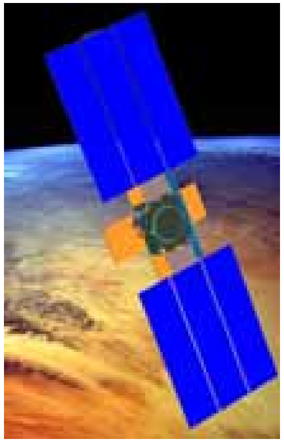
Distance, Data Rate, Time Delay

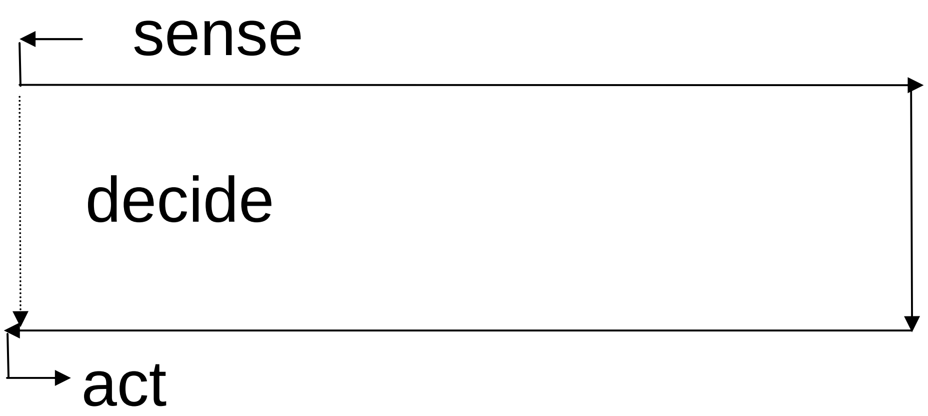
Effect of distance on data rate for X-band RF communication with 5 watts transmitted power from a 2-meter spacecraft antenna into a 70-meter ground antenna

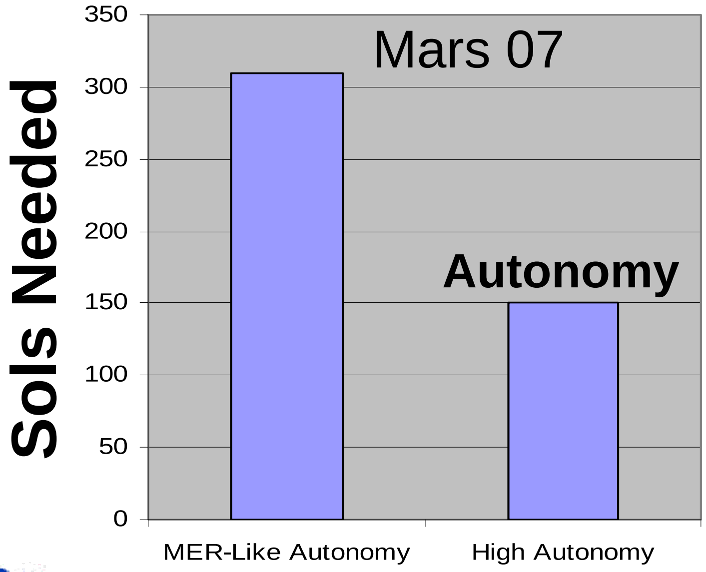


At orbit of Pluto it will take ~10 hours to send a command from Earth and receive acknowledgement!

Migrate Decision Loops Onboard



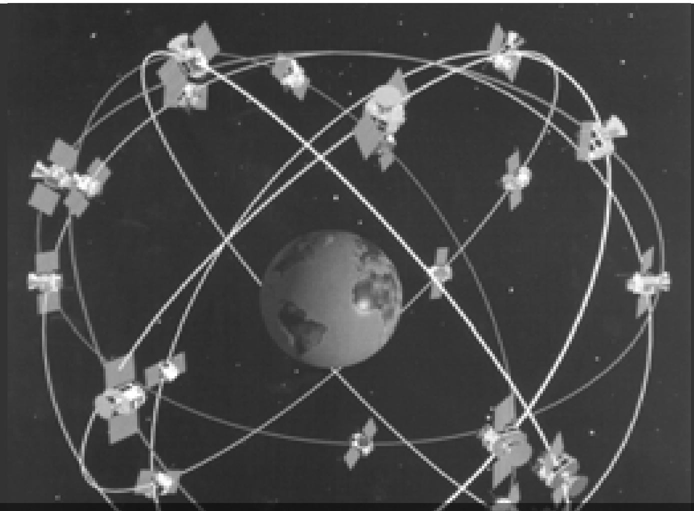




Close loops onboard
- planning
- execution
- fault diagnosis & response

Benefits
- Reduce operations costs
- Improved robustness to faults
- More time for science

Distributed Autonomous Systems



Autonomy Needs

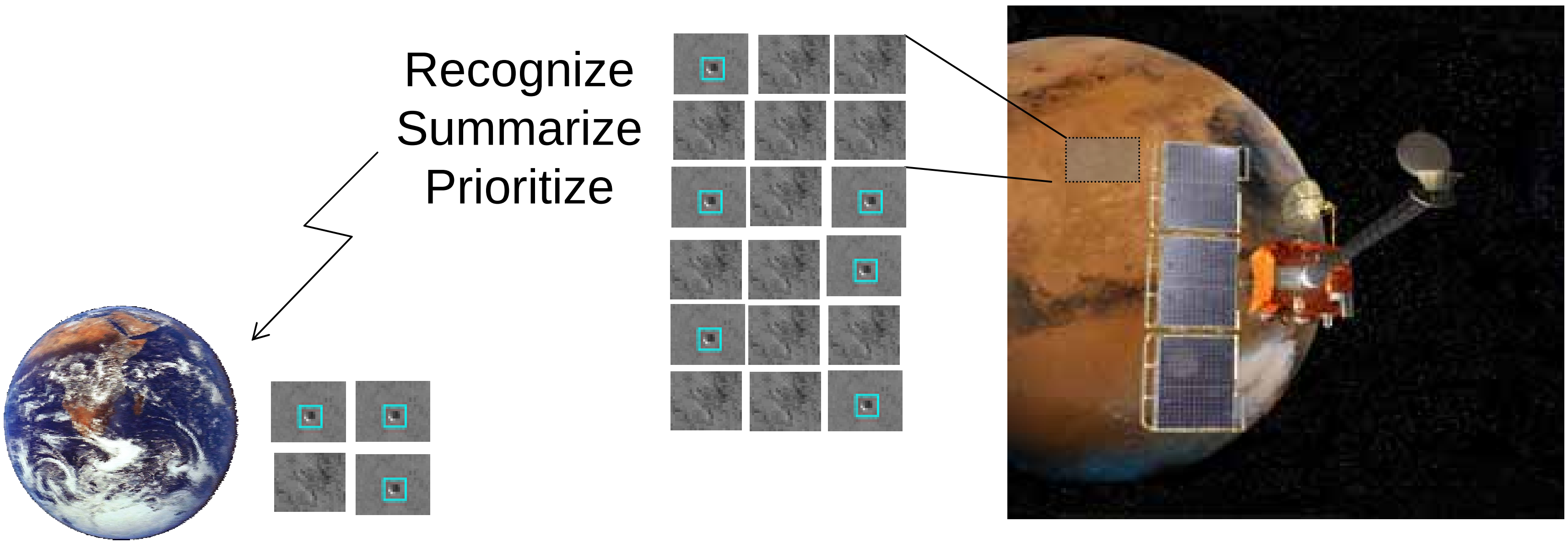
- Goal-based commanding of constellation as coordinated unit.
- Low-bandwidth approaches to coordinated execution & replanning.
- Collective fault detection & response

Challenges:

- Operations costs scale w/ # assets
- Coordinated activities
- Limited inter-asset communication
- Collective faults

Intelligent Science Data Analysis

- Maximize use of limited bandwidth
- Scan for hard-to-find features
- Respond to short-lived opportunities (eruptions, flares, . . .)



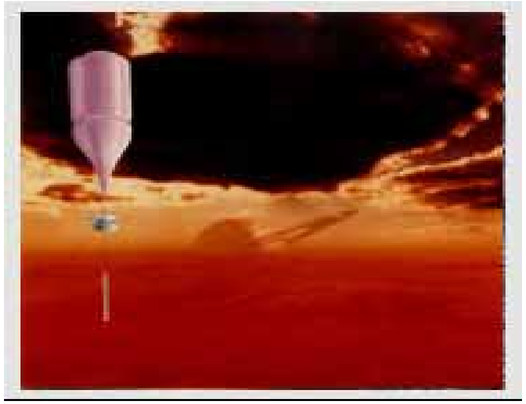
Acquisition rate far outstrips downlink capacity.

Explore Uncertain & Unknown Environments

Autonomy Drivers:

- Dynamic, unpredictable environment
- Unknown/poorly known environment
- Infrequent communications
- Uncertain navigation

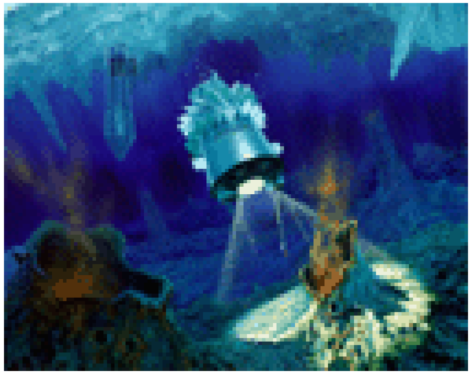
Comet Lander



Titan Aerobot

Autonomy Capabilities:

- Identify & evaluate science opportunities
- Onboard navigation, maneuver planning.
- Closed-loop planning, FDIR, science.



Europa Hydrobot

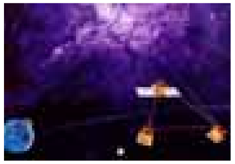
Autonomy Components & Goals

Autonomy Thrust	Near Term	Long Term
Onboard Planning & Execution		
Intelligent Science Data Analysis		
Distributed Autonomy		
Safe & Precise Landing		
Health Monitoring & Diagnosis		

Near Term

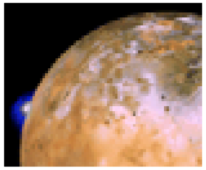
Opportunistic Science

Self-managing Explorers

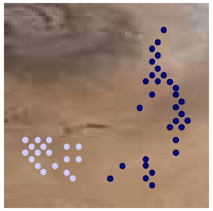


Coordinated Spacecraft Fleets

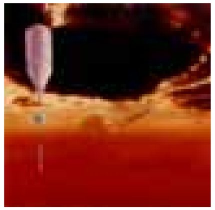
Long Term



Vigilant, Sustained Presence



Robot Colonies



Exploration of Uncertain Environments

Planning & Execution

Uses Model of Activities / Operating Constraints

Resources	uses 20 W power
States	requires camera to be "ON"
Other Activities	calibrate the camera 2-30s before pic
Decompositions	first cool the instrument
	then open the pod doors
	then unshutter the instrument

General planning algorithm reasons about model to construct a plan that achieves goals & meets constraints.

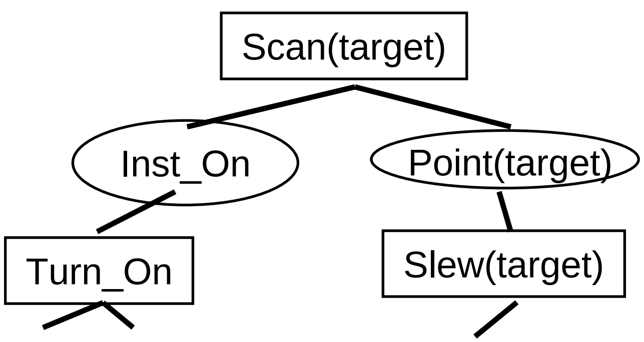
Types of Reasoning

Subgoaling: achieve pre-conditions for executing an activity

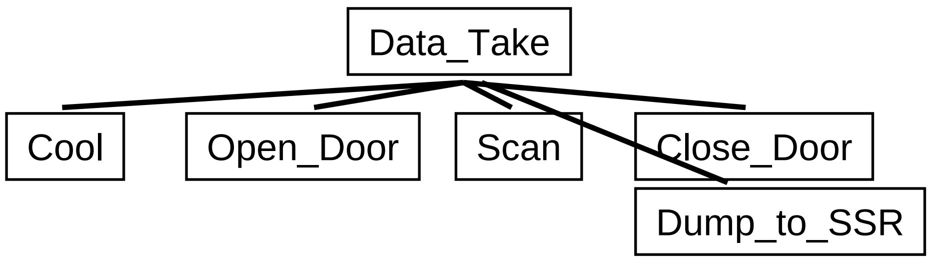
Task Reduction: expand a higher level activity into lower level activities

Conflict Analysis: avoid/resolve negative interactions among activities

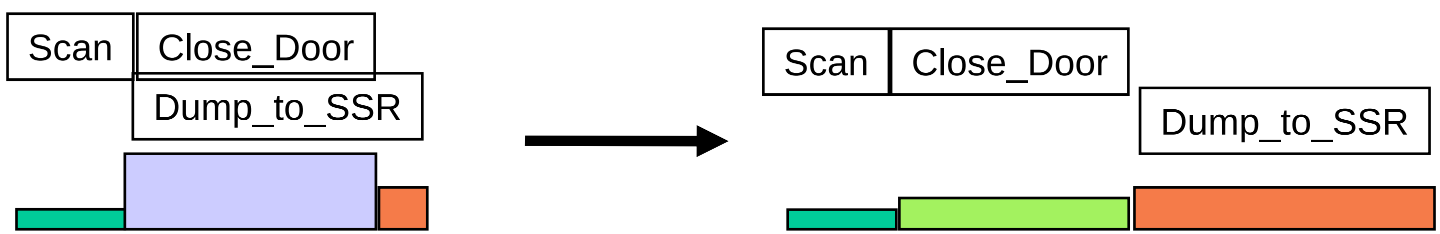
Subgoaling



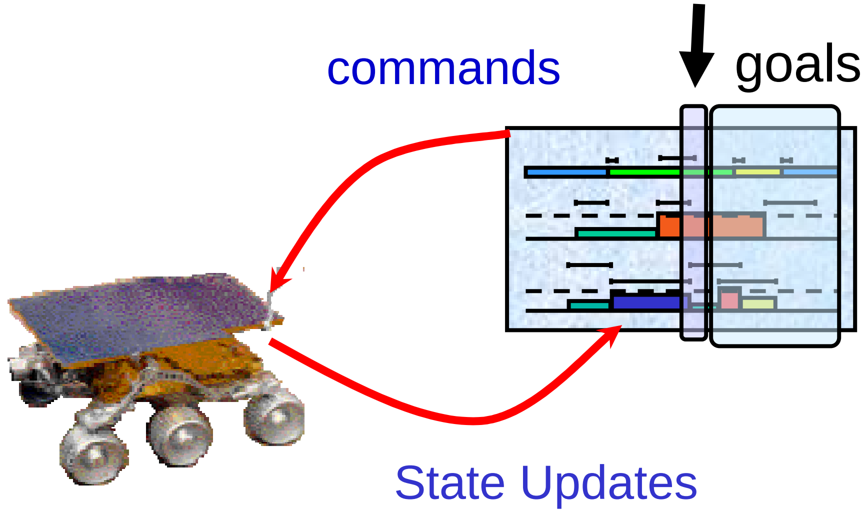
Task Reduction



Conflict Analysis



Continuous Soft Real-time Planning and Scheduling



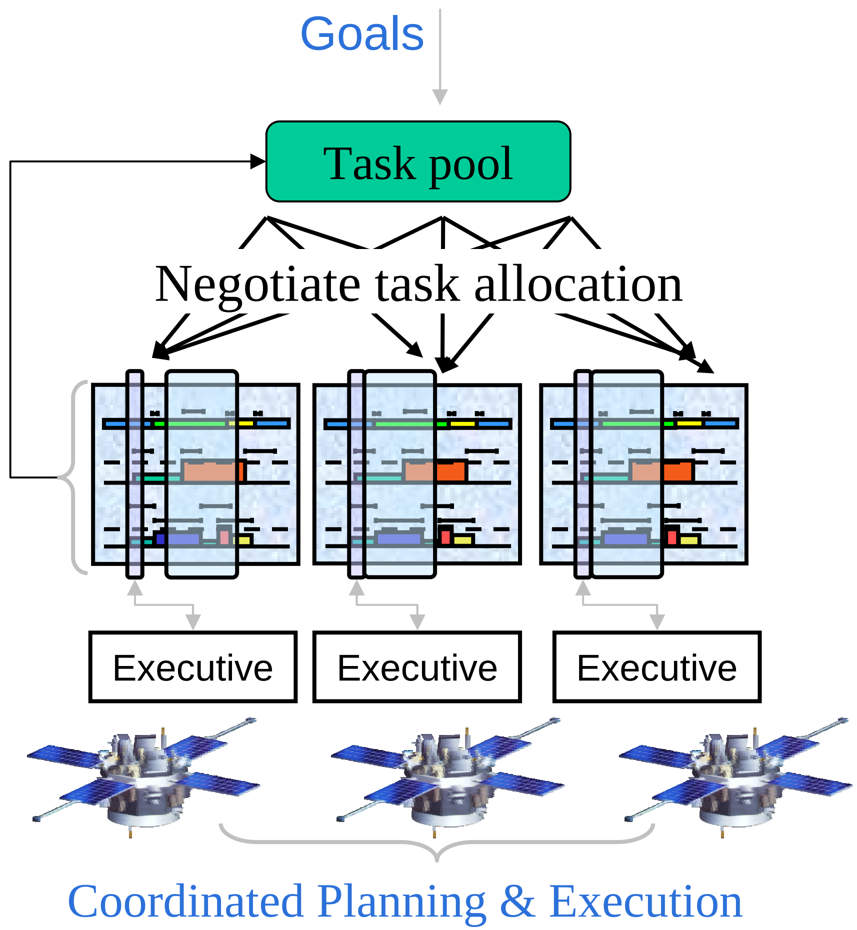
<u>Technology:</u> ASPEN/CASPER

- Automatically generate plan of action that achieves goals while obeying resource & operations constraints.
- Resolves *system level* interactions (resource contention, goal ordering, etc)
- Continuously revises plan in response to events (~10s)

<u>Benefits:</u>

- Continuous adaptation to execution-time uncertainties.
- Robust fault protection
- More efficient resource utilization
- Less accurate models OK (can adapt)

Onboard Planning for Constellations



Technology

- Planners on each spacecraft negotiate to best allocate goals & resolve conflicts among respective plans.
- Planners replan / reallocate as needed during execution to coordinate activities.

Approaches:

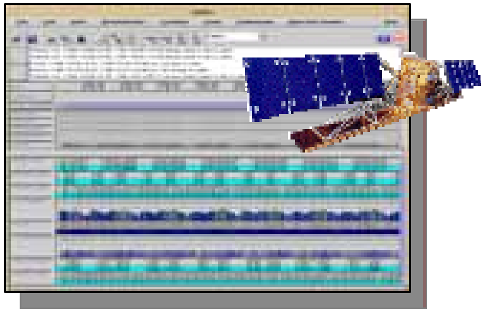
- Loose (goal distribution)
  - Centralized ‘distribution’ planner
  - Contract network
- Tight coordination

Scalable, coordinated commanding and execution will enable future constellation and fleet missions.

ASPEN & CASPER Deployments

Unpiloted aerial vehicles (w/ Lock-Martin Skunkworks, upcoming)

3 Corner Sat (3CS) Launch: 2002 (with CSGC)



Automated Mission Planning for MAMM
(reduced planning effort 10x wrt similar manually planned mission)

Ground station automation (CLEaR)

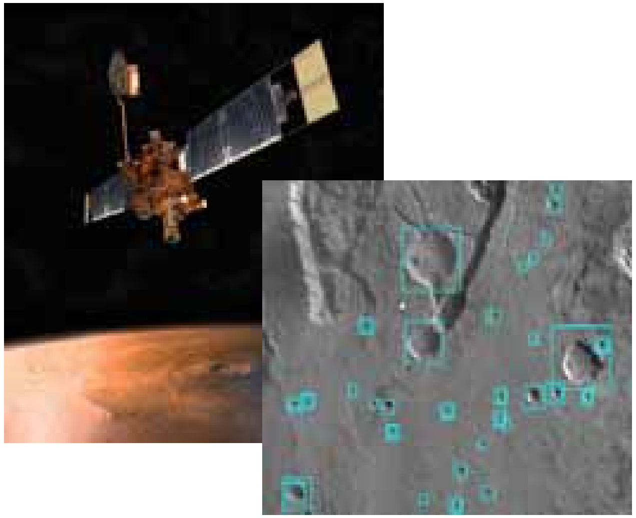
Autonomous rover control (Rocky7, Rocky8)

Intelligent Data Analysis

Onboard Science Analysis and Knowledge Discovery

<u>Technology:</u> DiamondEye

Automatically detect craters and other scientifically interesting features in image data.

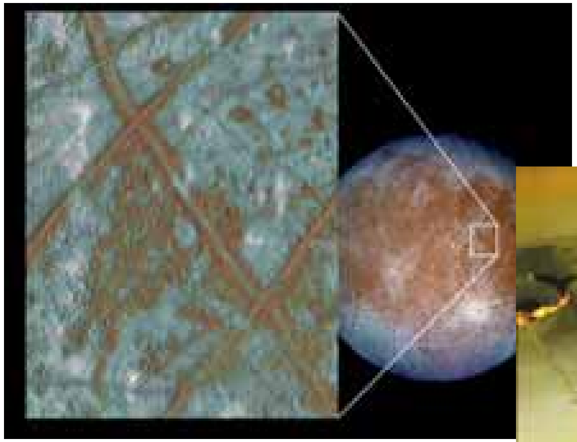


Craters detected in Viking data

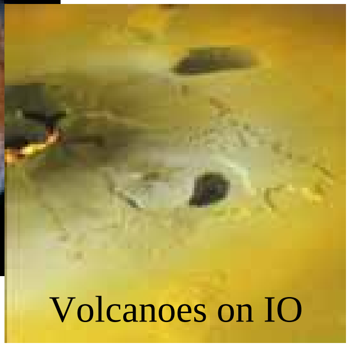
<u>Innovations</u>

Learns scale- and rotation-invariant pattern recognizers from a few examples

Discovers 'anomalous' features--these could be big science discoveries.



Europan ice motion

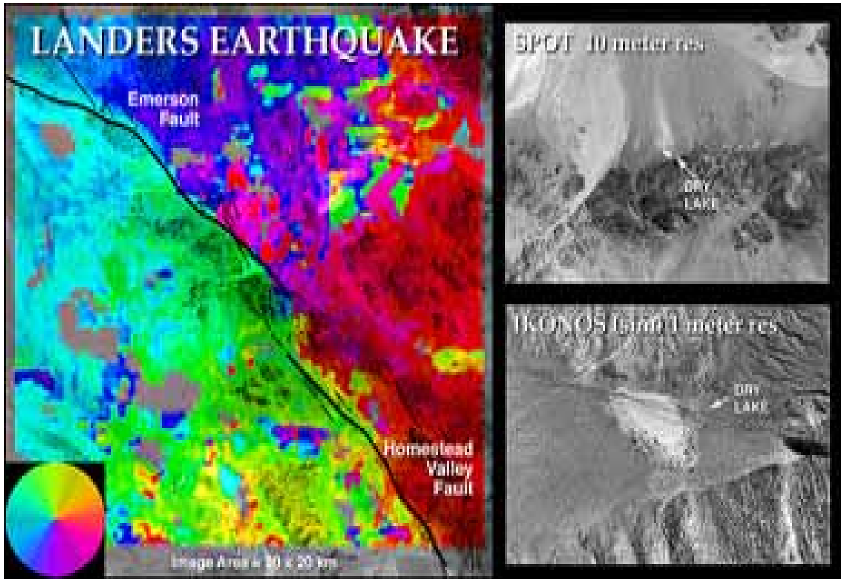


Volcanoes on IO

<u>Applications</u>

- Machine-assisted discovery of phenomena in vast datasets
- Opportunistic Science
- Data Prioritization & Summarization

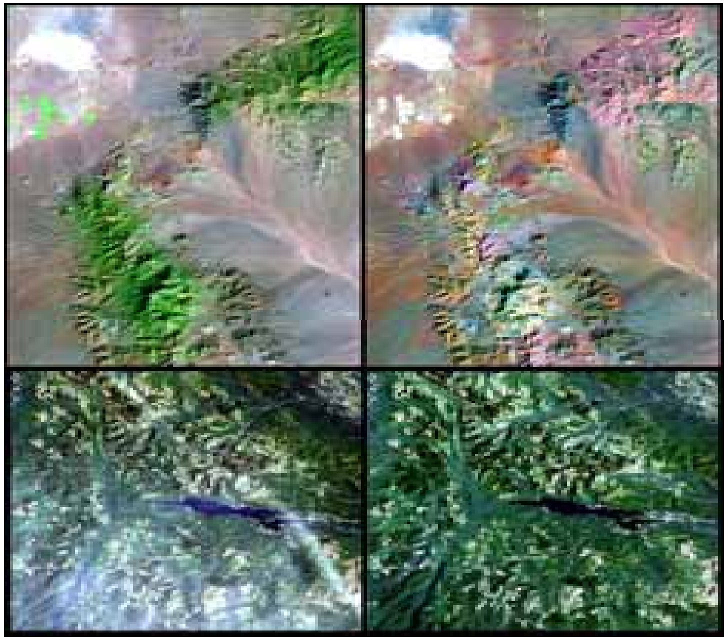
Temporal and Spectral Data Mining



Enhances thresholds of detection of dynamic planetary processes (<1/10 pixel)

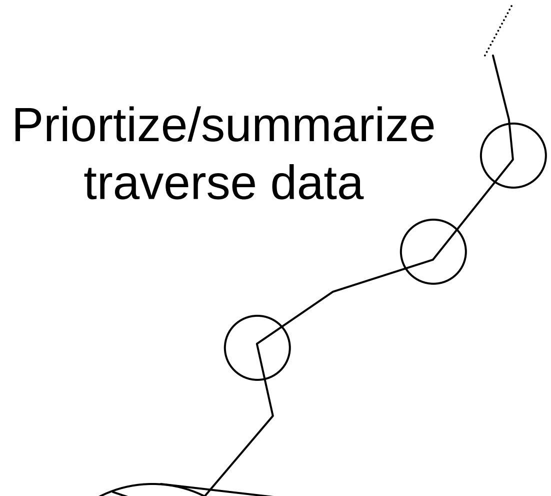
- Mining the vast 30m Landsat image archive for quakes with maximum ground motions as small as ~3m.
- Found evidence of possible earthquake precursory thermal signal. Would be of major importance if proven.

- **Temporal: sub-pixel displacement of surface features**
- **Spectral: unveil features of interest that are obscured by vegetation, haze bedrock, etc.**



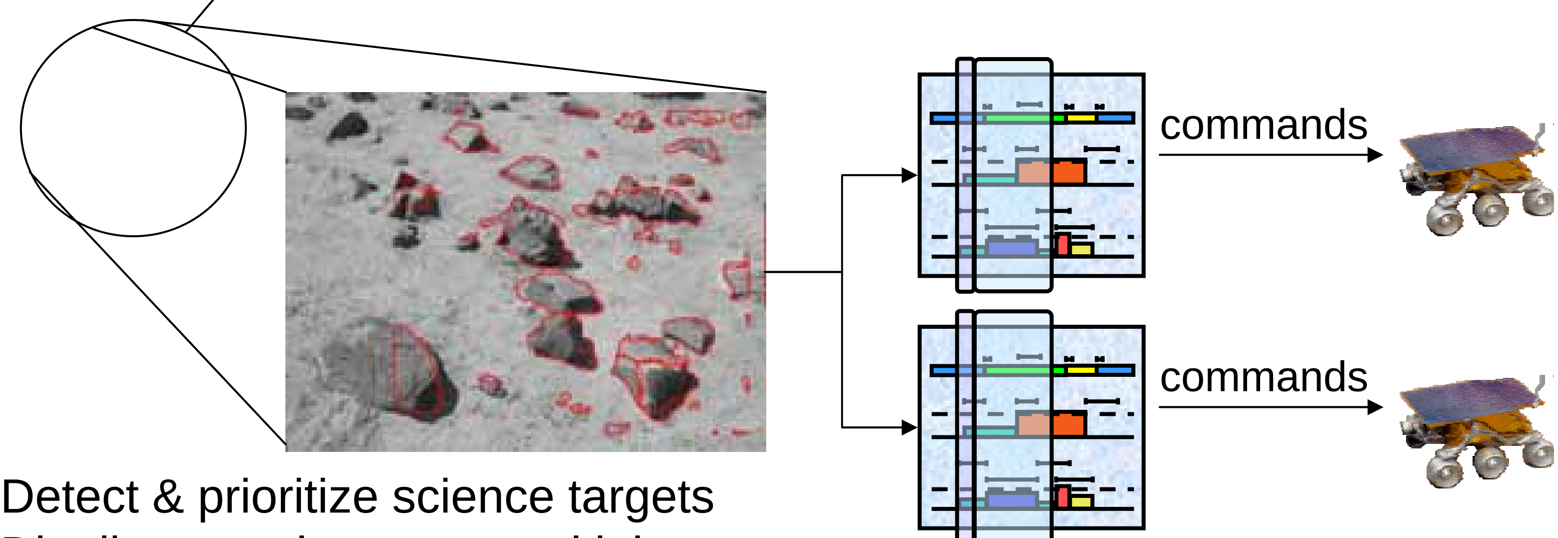
Project Contact: Robert E. Crippen, JPL

Rover Science Autonomy



Technologies:

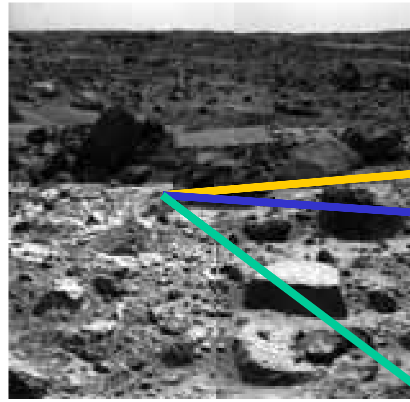
- geological data understanding
  - science feature recognition
  - geological process models
- onboard planning & execution

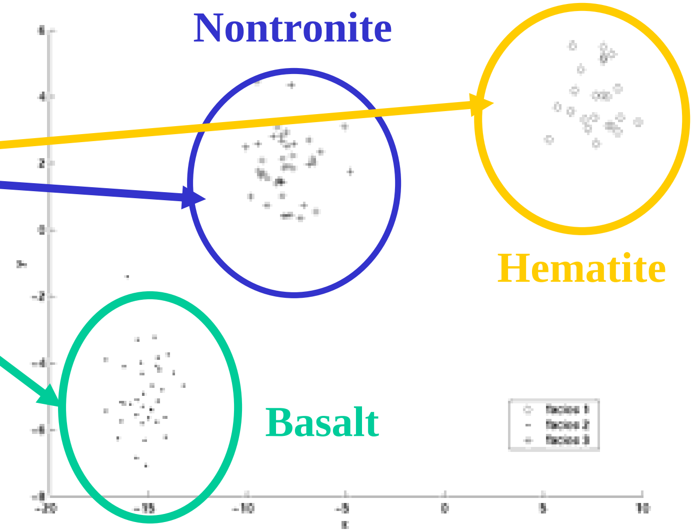


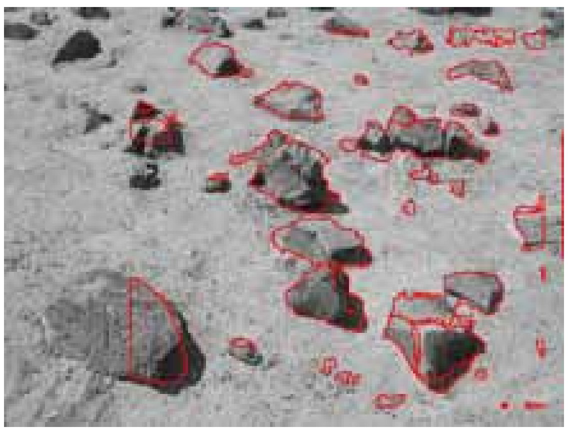
- Detect & prioritize science targets
- Distribute goals among multiple rovers
- Acquire science data, recover from failures

Geologic Science Analysis

Segment image into homogeneous regions based on texture (rock type)

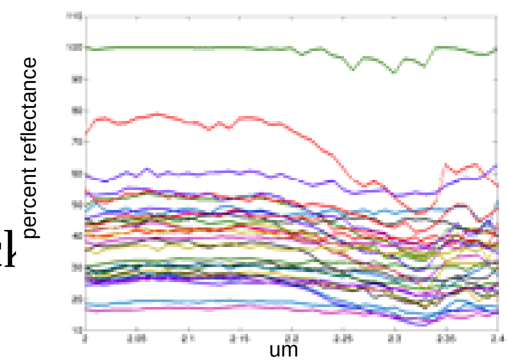


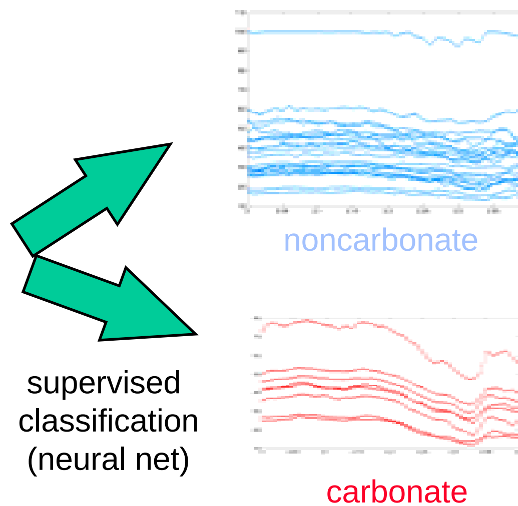




Locate rocks from range and grayscale image data

Trained neural network discriminates carbonate rocks from non-carbonate rocks



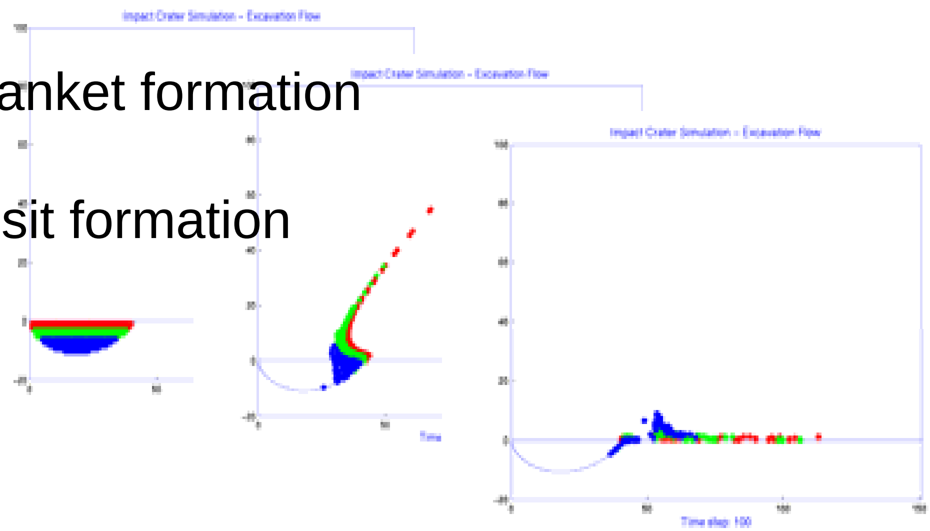


Hypothesis-directed Science

Forward model:

impact(params)->ejecta blanket formation

hydrologic(params)->deposit formation



Inverse Modeling:

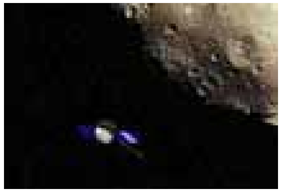
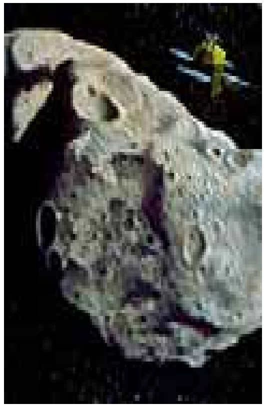
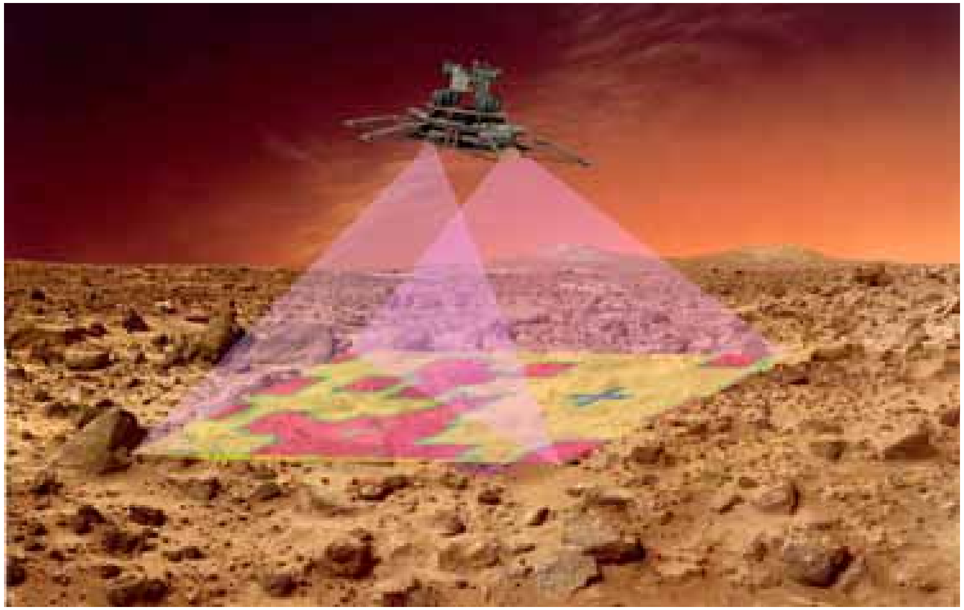
observed rocks --> formation process, params

What new observations will provide most information about emerging hypotheses?

Safe & Precise Landing

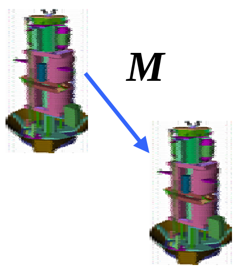
Machine Vision for Safe & Precise Landing

- Comet Nucleus Sample Return
- Large Asteroid Sample Return
- Europa Safe and Precise Landing
- Mars Safe and Precise Landing

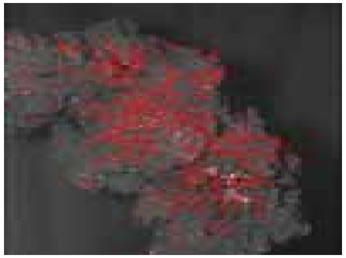





Machine Vision for Safe and Precise Landing

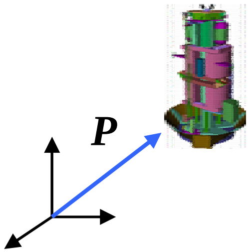
Motion Estimation Through Feature Tracking



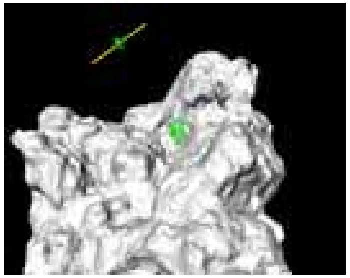
Features tracked during descent to comet analog. Motion estimation from imaging only is accurate to 1% of distance traveled.



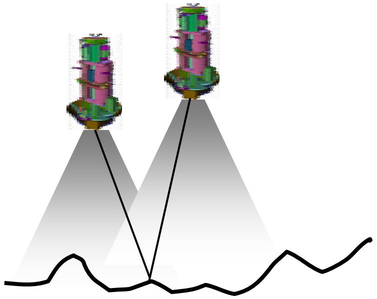
Landmark-Based Absolute Position Estimation



Crater landmarks automatically detected in NEAR Imagery. Crater center accurate to 10 m from 100 km orbit.

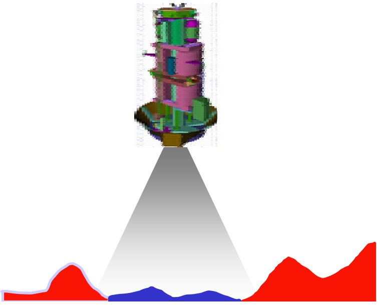


3-D Structure Recovery From Stereo Imaging



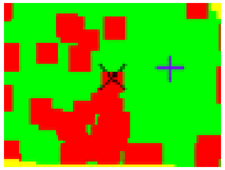
Surface reconstructed from pair of images acquired from single camera mounted on helicopter. Surface relief is accurate to 3 cm from altitude of 7 m.

Hazard Detection and Avoidance



Hazards detected in terrain map generated from passive imagery. Safe zones (green) have a surface roughness less than 10cm and a local slope less than 10 degrees.


Image


Hazard Map

Health Monitoring & Diagnosis

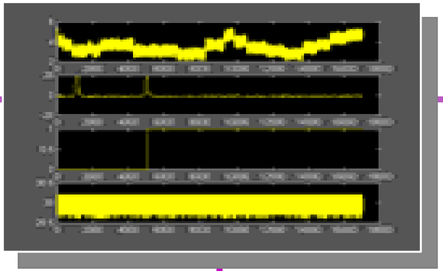
Health Monitoring & Diagnosis: BEAM

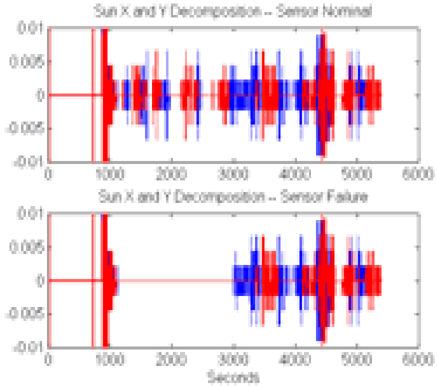
JPL

Cassini

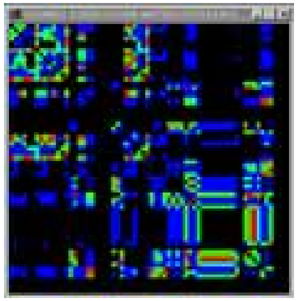
DSN

Space shuttle
Main Engine



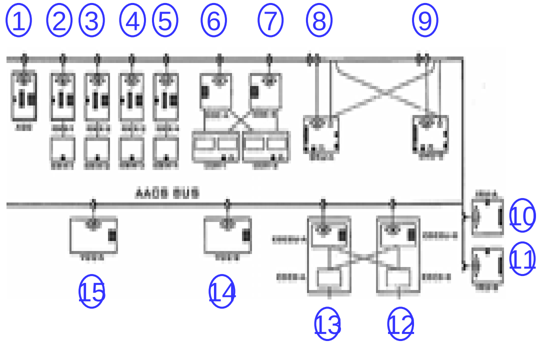


Trending



ζ -plot

Cross-signal Fault Detection



Fault Isolation

ADVANCES

- Low false alarm rate and high precision detection
- Can detect and isolate unmodeled faults
- High-precision Trending
- Cross-signal methods provide very high accuracy

BEAM Applications

- **DSN DSS-14 70m Antenna Hydrostatic Bearing**

– **Outperformed human analysts by detecting**
  - **Detected onset of failure faster than the operators**
  - **Isolated anomalies that expert operators failed to correctly identify**

– **Demonstrated predictive detection capability: 2-week lead time in predicting onset of failure**

- **CASSINI AACS / JPL MSAS**

– **BEAM able to detect errors beyond the AACS FSW design envelope and provide quantitative degradation assessment**

– **Ongoing work to integrate BEAM tools with MSAS (Cassini, DS1, SIRTF)**

Space Shuttle Main Engine

- **Successfully distinguished and identified all faults**
- **Exceeded existing fault protection**

Ongoing work with MSFC

- **Develop engineering tools to monitor engine tests and track degradation**
- **Scale up for in-flight experiments**

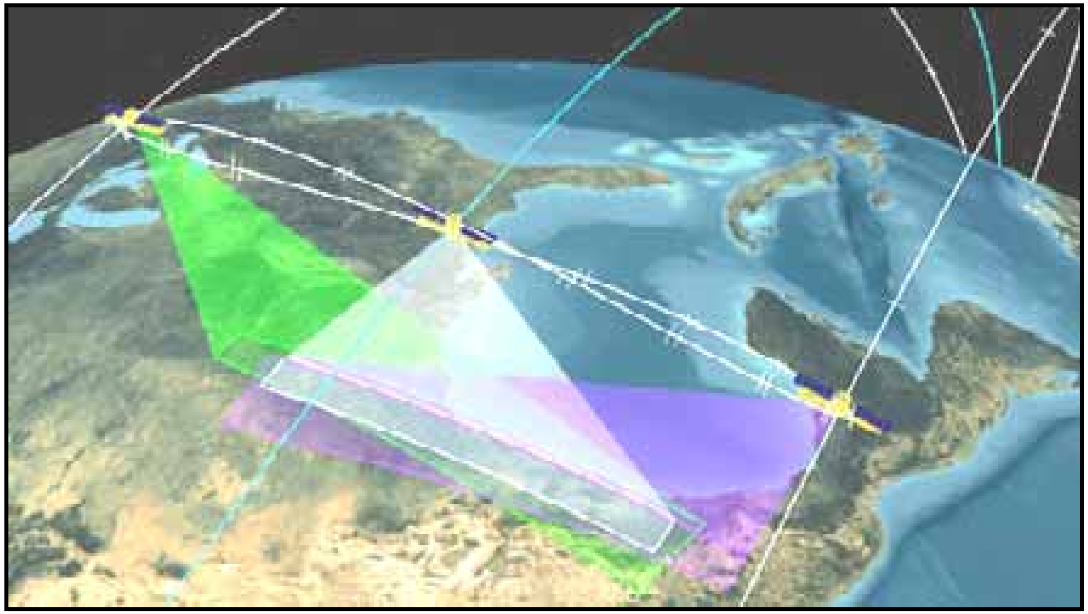
X-33 Aerospike and LOX Tank

Conducted shadow experiment on Aerospike Power Pack

- **Perfect fault detection and identification**
- **Exceeded operator false-alarm performance**

The Techsat-21 Autonomous Sciencecraft Constellation

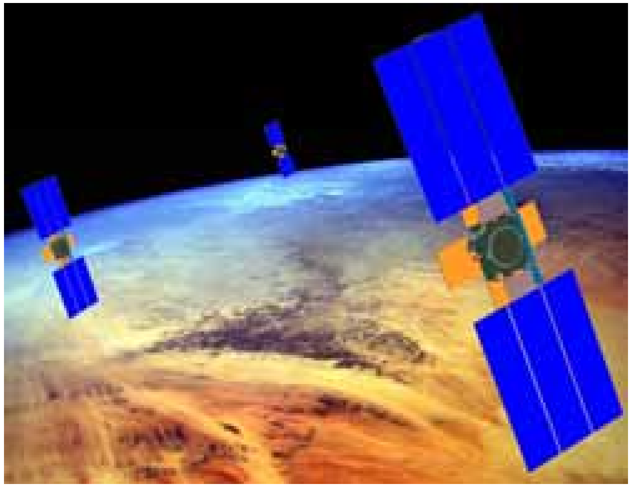
Steve Chien
Jet Propulsion Laboratory

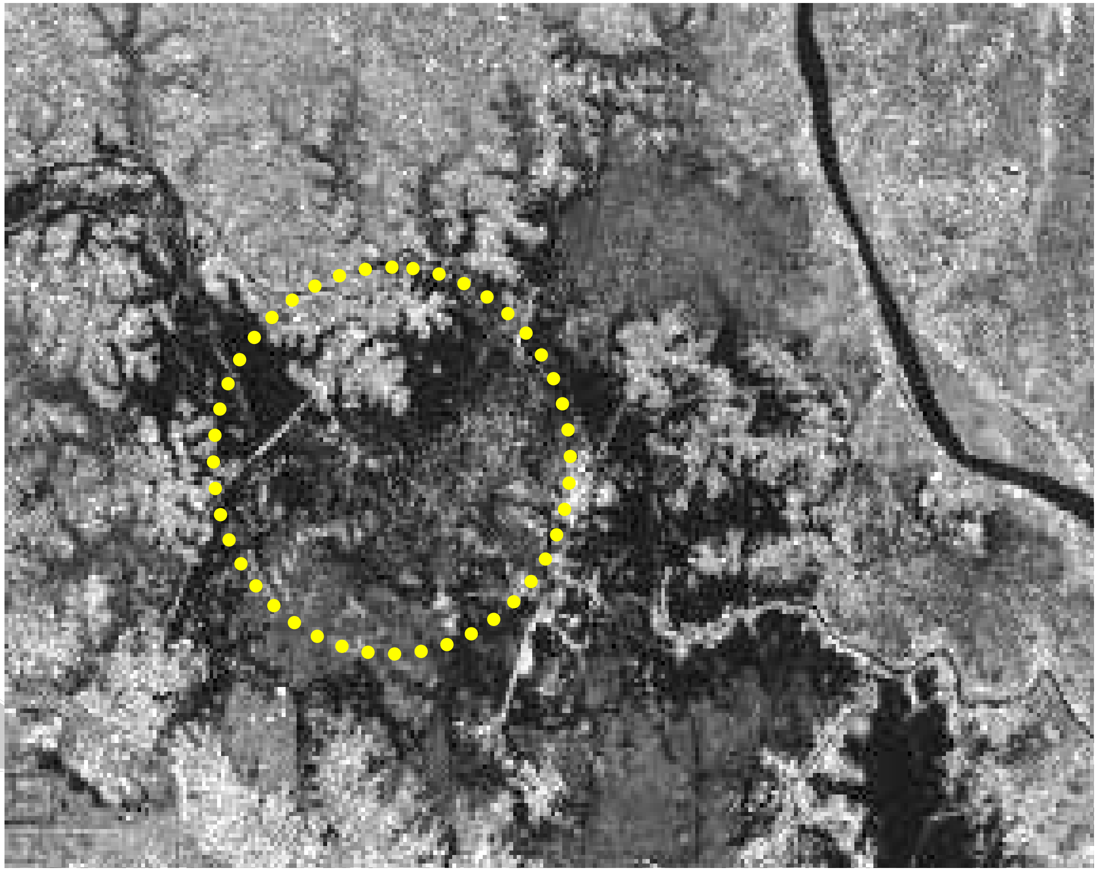


ASC Mission Scenario

Cluster Management: Constellation Reconfiguration

Onboard Replanning

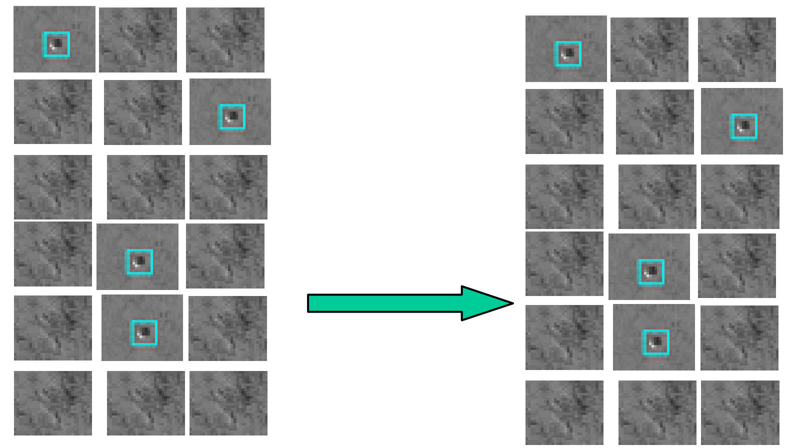




Motivation: Maximize use of limited downlink resource

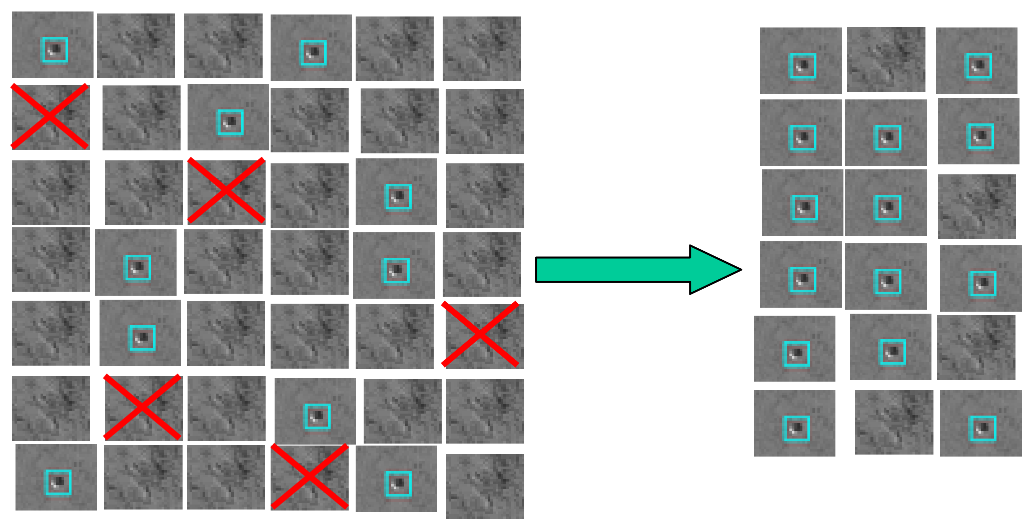
Old Way:

- Take 200 images
- Downlink 200 images



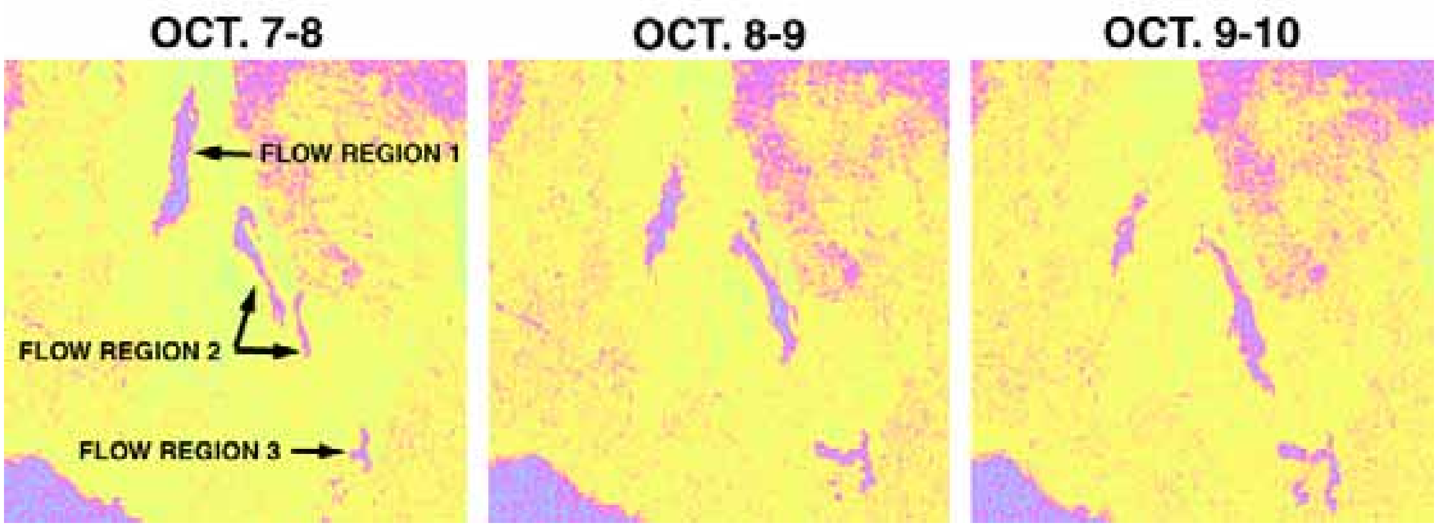
New Way:

- Take 2000 images
- Downlink best 200
  - only most scientifically interesting portions



Change Detection

- Algorithms detect feature changes in X-SAR data
- Science team analysis derived a >20 fold compression rate on subsequent images by downlinking only changed portions



C-SAR radar images indicating lava flow on Kilauea volcano, Big Island, Hawaii

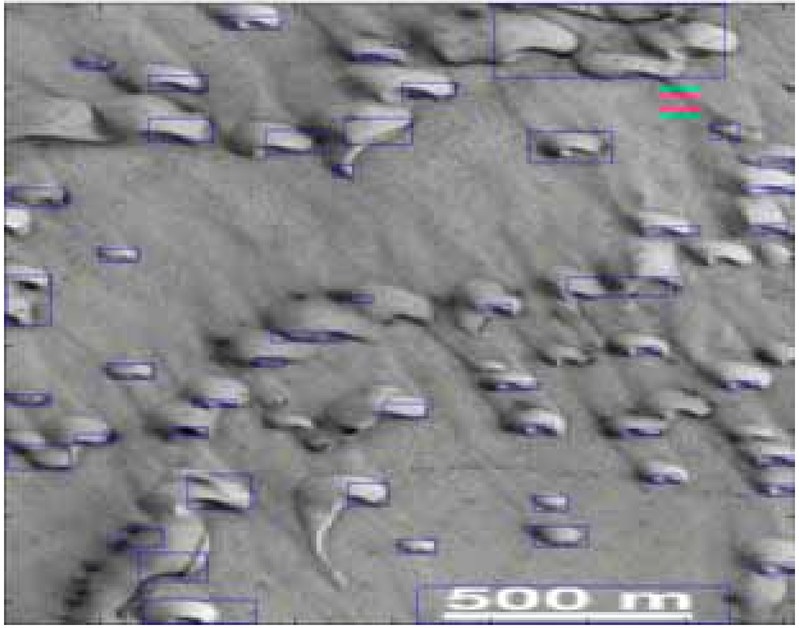
Feature Recognition Algorithms

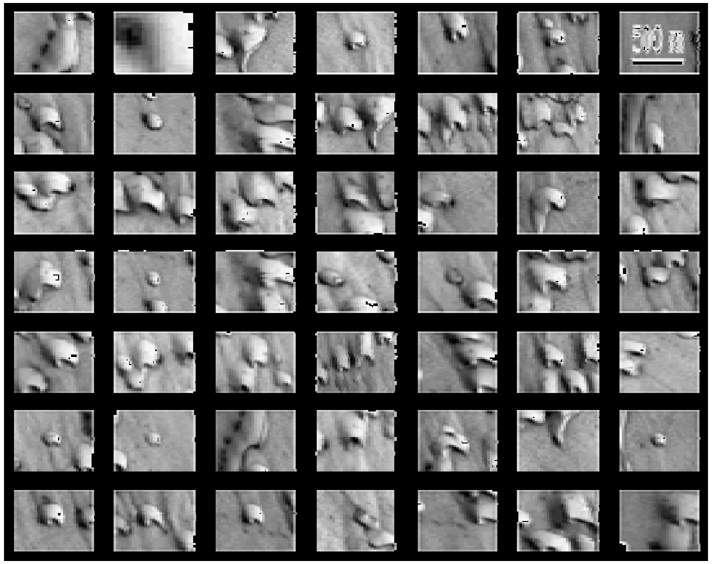
- Preliminary feature detection algorithms already being tested on lava cone X-SAR data
  - Circles indicate identified lava cones
  - Blue circles indicate highest confidence matches
- Dowlink higher resolution imagery of features or target features on repeat passes

X-SAR image of Lava Beds National Monument, CA, USA
image taken with X-SAR instrument from Space Shuttle on Oct. 09, 1994

Discovery Algorithms

- Prototype visual discovery algorithm
- Identifies regions of an image that differ significantly from the local background
- Has successfully identified impact craters, volcanoes, sand dunes, ice geysers from sample image data





Mars Global Surveyor image – many of the identified regions are sand dunes

Autonomous Sciencecraft Summary

- Techsat-21 will be flying on-board software for planning, science data analysis, and fault detection/recovery developed by the NASA research programs.
- This software will increase mission value by:
  - Returning only the most important science data
  - Requiring less engineering data
  - Moving the labor-intensive spacecraft and science data analysis functions onboard the spacecraft
  - Allowing the spacecraft to be commanded with high-level goals
  - Allowing quick response to opportunistic and dynamic science events

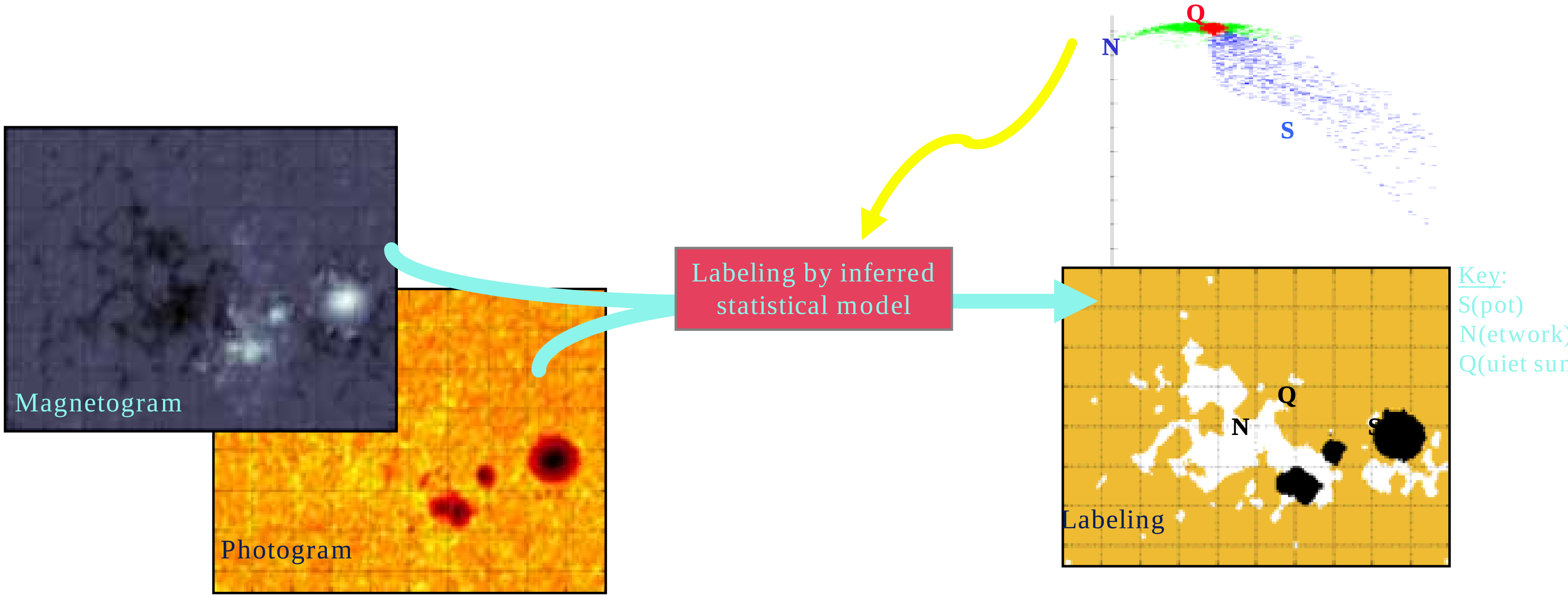
Future missions will benefit from TS-21's use of integrated onboard autonomy

Summary

- Deep space exploration of space continues to drive autonomy requirements
- Autonomy is an enabler for exciting future missions.
- Autonomy is already making an impact:
  - MAMM automated mission planning
  - Closed-loop science & planning (ST6 / 3CS)
  - SSME Automated fault monitoring
  - Data mining
  - Position estimation for NEAR

BACKUP

Startool: Solar Feature Identification



1: Experts identify classes in sample images

2: Learned model performs classification automatically

- Identifies solar features (e.g., sunspots) in solar data with high accuracy.
- Accuracy enables scientists to automate analyses that would otherwise require an army of graduate students
- Applicable to very different instruments & data sets with almost no modification.

Motion Estimation from Optical Sensors: A Comparison

Scanning Laser Radar

- + complete 3-D shape sensing
- + efficient algorithms (10 Hz)
- + no ground processing
- + dark side landing possible
- - low resolution (100x100)
- - short range (~2km)
- - continuous data acquisition
- - slow frame rate (1 Hz)
- - possibly moving parts
- - unproven sensor

Imager and Altimeter

- + high resolution (1000x1000)
- + long range (50 km)
- + instantaneous data acquisition
- + rapid frame rates (30 Hz)
- + no moving parts
- + no ground processing
- + efficient algorithms (4 Hz)
- + proven sensors
- - requires target illumination
- - shape requires processing
- - requires two sensors

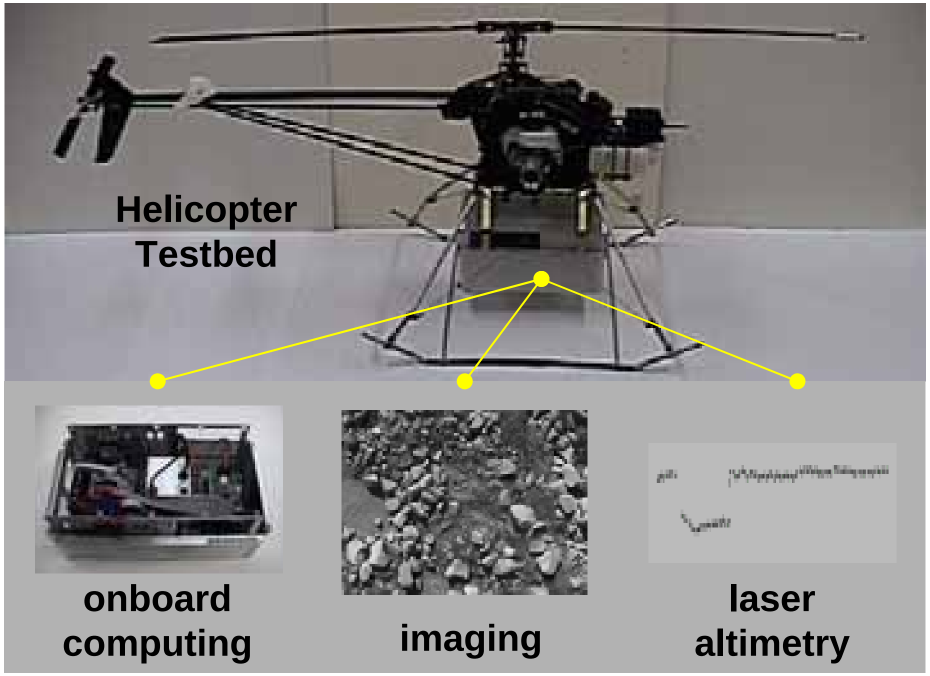
Safe & Precise Small Body Landing: Related Work

- Near Earth Asteroid Rendezvous
  - s/c position from orbital imagery
  - manual landmark identification on ground
- Deep Space 1
  - Autonomous position estimation
  - flyby only
- Muses-C
  - autonomous landing
  - large sensor suite

EDL Helicopter Testbed

Investigators: Dr. Andrew Johnson and Dr. James Montgomery

Section 345 : Machine Vision Group



CUSTOMER RELEVANCE

–The EDL helicopter will enable collection of data unobtainable with ground-based systems.

–The EDL Helicopter provides a platform for testing real-time safe and precise landing algorithms.

NASA MISSION RELEVANCE

Mars '07 Smart Lander

Comet Nucleus Sample Return

Mars Scouts: Aerobot and Airplane

Europa Lander

Titan Organics Explorer

TESTBED USERS

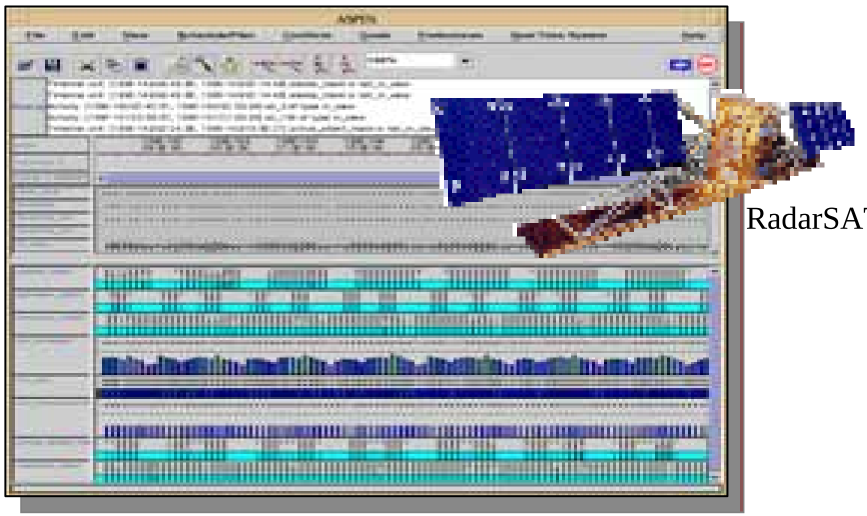
Intelligent Systems Program: Vision Guided Safe and Precise Landing Task

Mars Technology Program: Passive Image-based Hazard Detection Task

Thinking Systems Program: Visual Methods for Small Body Exploration Task

Antarctic Mapping Mission Deployment

ASPEN automated mission plan development & verification for the Modified Antarctic Mapping Mission (MAMM), which operated from Sept - Nov 2000.



RadarSAT

Mission plan in ASPEN

– ASPEN automatically scheduled downlinks, and checked mission plan for consistency with operational constraints

– ***ASPEN enabled over order magnitude reduction in time to develop mission operations plan.***

– ***ASPEN enabled mission planners to quickly generate "what-if" mission plans that were instrumental in s/c resource negotiations with CSA.***

"ASPEN has already reduced acquisition plan development and constraint checking time … because of the severely constrained schedule ***without ASPEN AMM-2 could not happen***."

John Crawford, MAMM Project Manager