The Role of Autonomy in Space Exploration

Dr. Richard Doyle, Manager, Information Technologies and Software Systems Division, JPL

Material Prepared by Dr. Ben Smith
Manager, Autonomy Technology Program, JPL

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University of Southern California, USA

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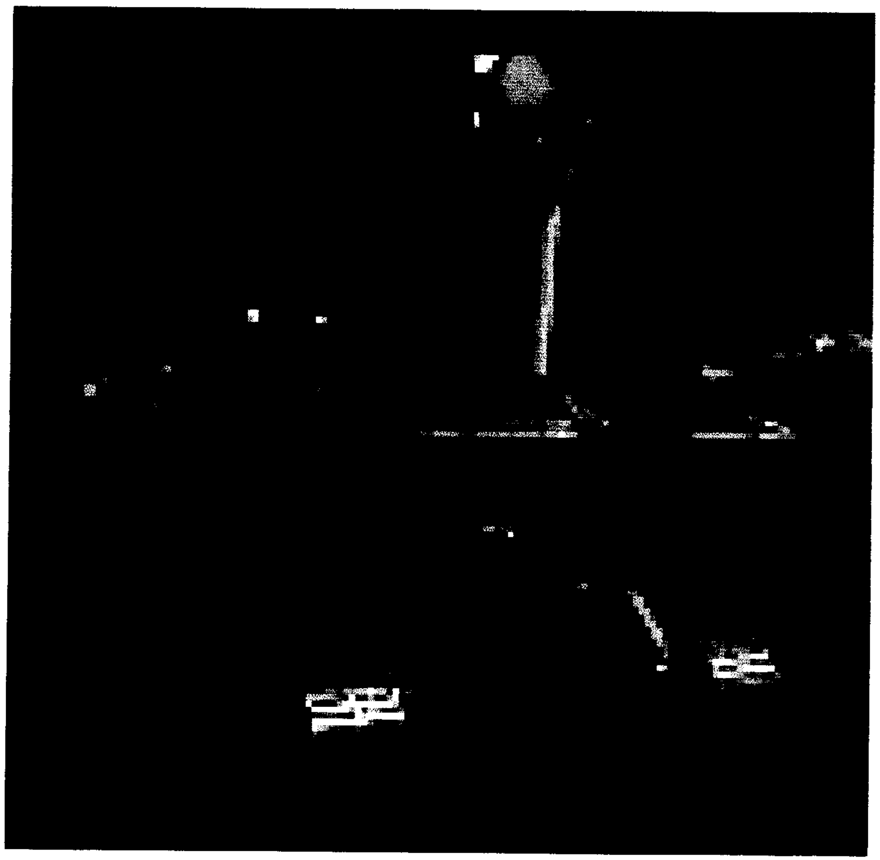
The Space Exploration Missions

Mars Exploration Rover

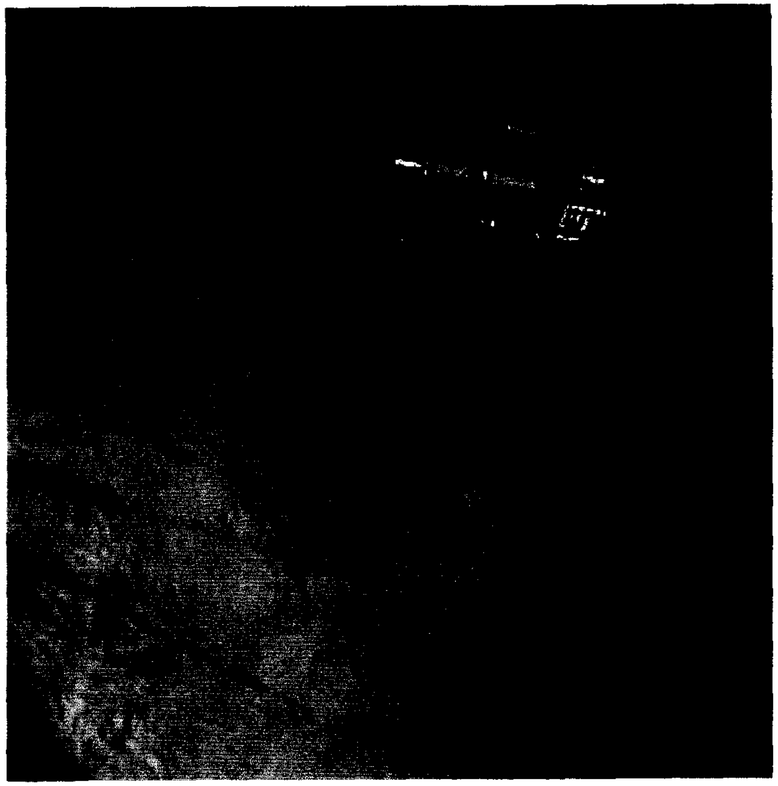


- Place two landed mobile science platforms on Mars
- Airbag landing approach
- Significantly upgraded science payloads - a half-dozen sophisticated instruments and tools
- Up to 100 meters traverse per sol (local Martian day)
- 90-sol nominal mission

Deep Impact

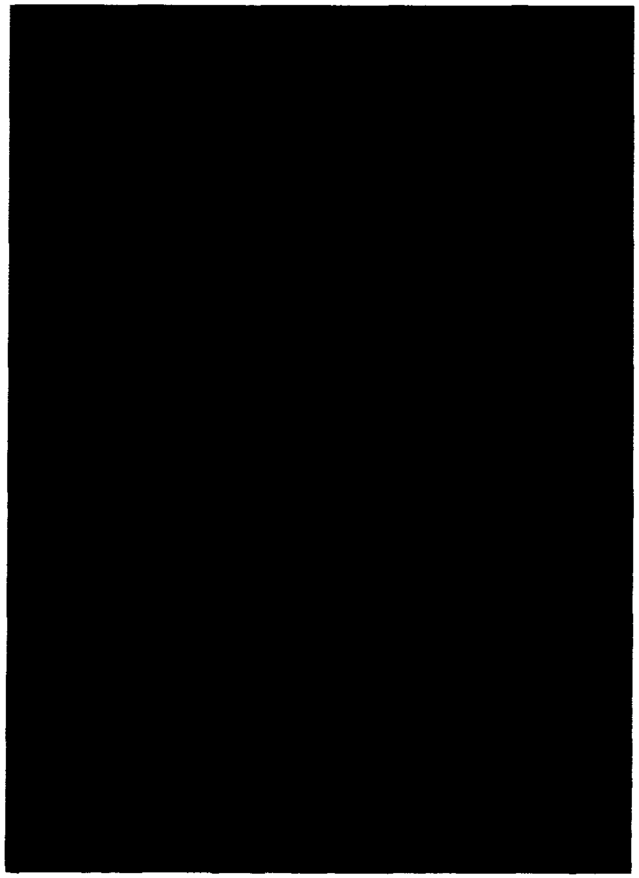
- Comets are primordial stuff -- unprocessed material from the time of origin of the solar system
- Flyby and Impactor spacecraft
- Impactor is a copper wrecking ball
- Flyby spacecraft observes crater and excavated material

Europa Orbiter



- Comprehensive mapping mission
- Radar sounder and altimeter will seek ice-water boundary and measure tides to resolve question of subsurface ocean
- Intense radiation environment
- 18-month cruise after arrival at Jupiter to achieve Europa orbit, followed by 30-day nominal mission

Mars Smart Lander



- Safe and precise landing
- Single-command-cycle traverse over the visible horizon
- Single-command-cycle robust instrument placement
- Onboard planning, scheduling and resource management
- Opportunistic science during traverse

Europa Cryobot / Hydrobot

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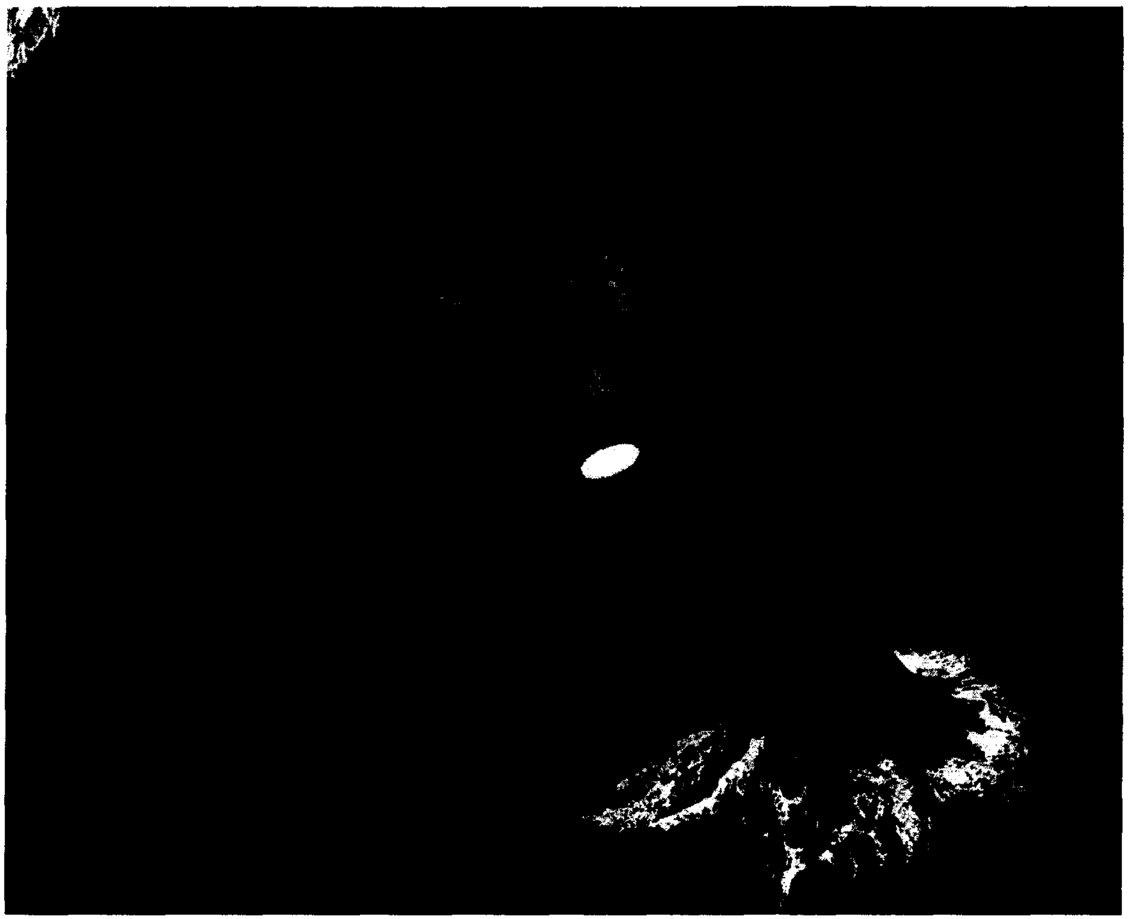
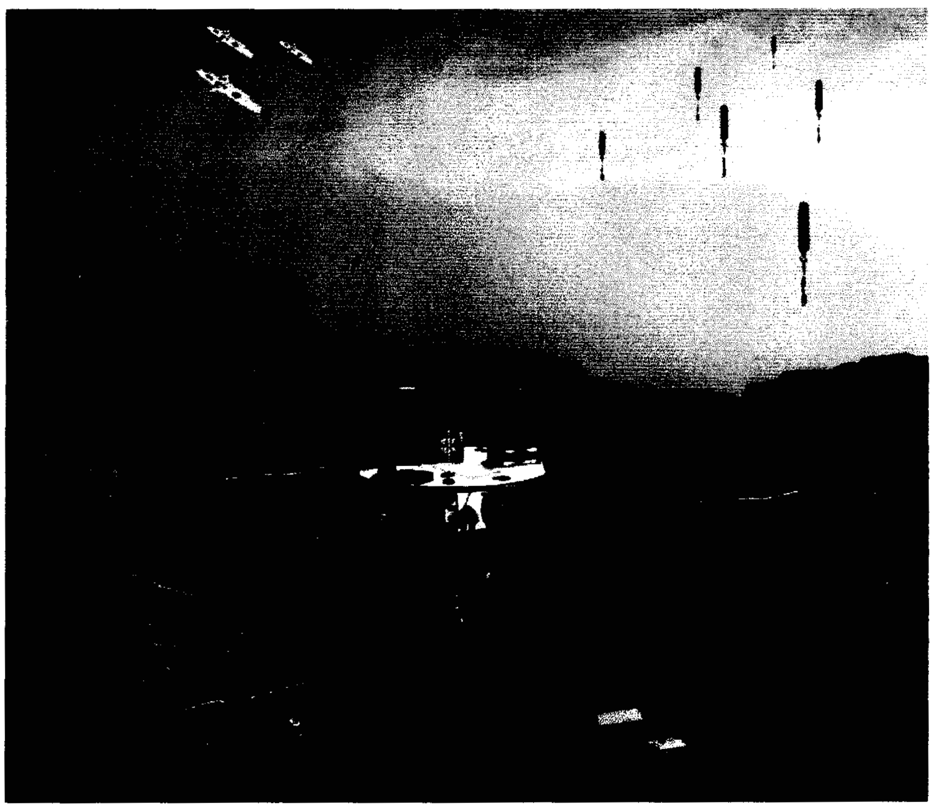


- Perhaps more than any other, a mission of discovery in a truly alien environment: How to know what to look for? How to recognize it?

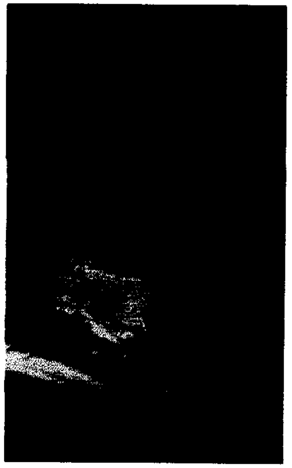
Mars Fleets



- Orbital assets
  - High-sensitivity observing instruments
- Surface assets
  - Mobile rovers
  - Science stations
- Airborne assets
  - Balloons
  - Air platforms

The Need for Autonomy

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.

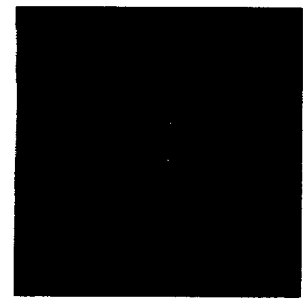
Autonomous is much more than Automated

- 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

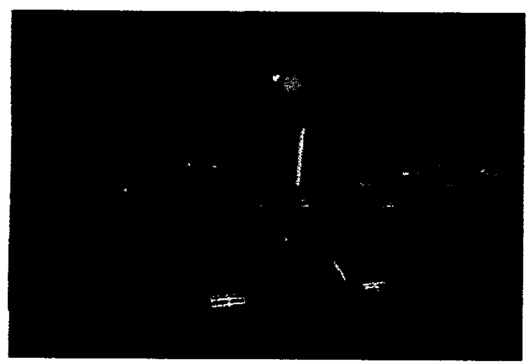
- Uncertain, hazardous environments
- Relatively long distances from Earth
  - long round-trip light-time delays
  - low data communication rates
  - infrequent communication

ballute



planetary orbiter

hydrobot in Europa ocean



Martian rover

Distance, Data Rate, Time Delay

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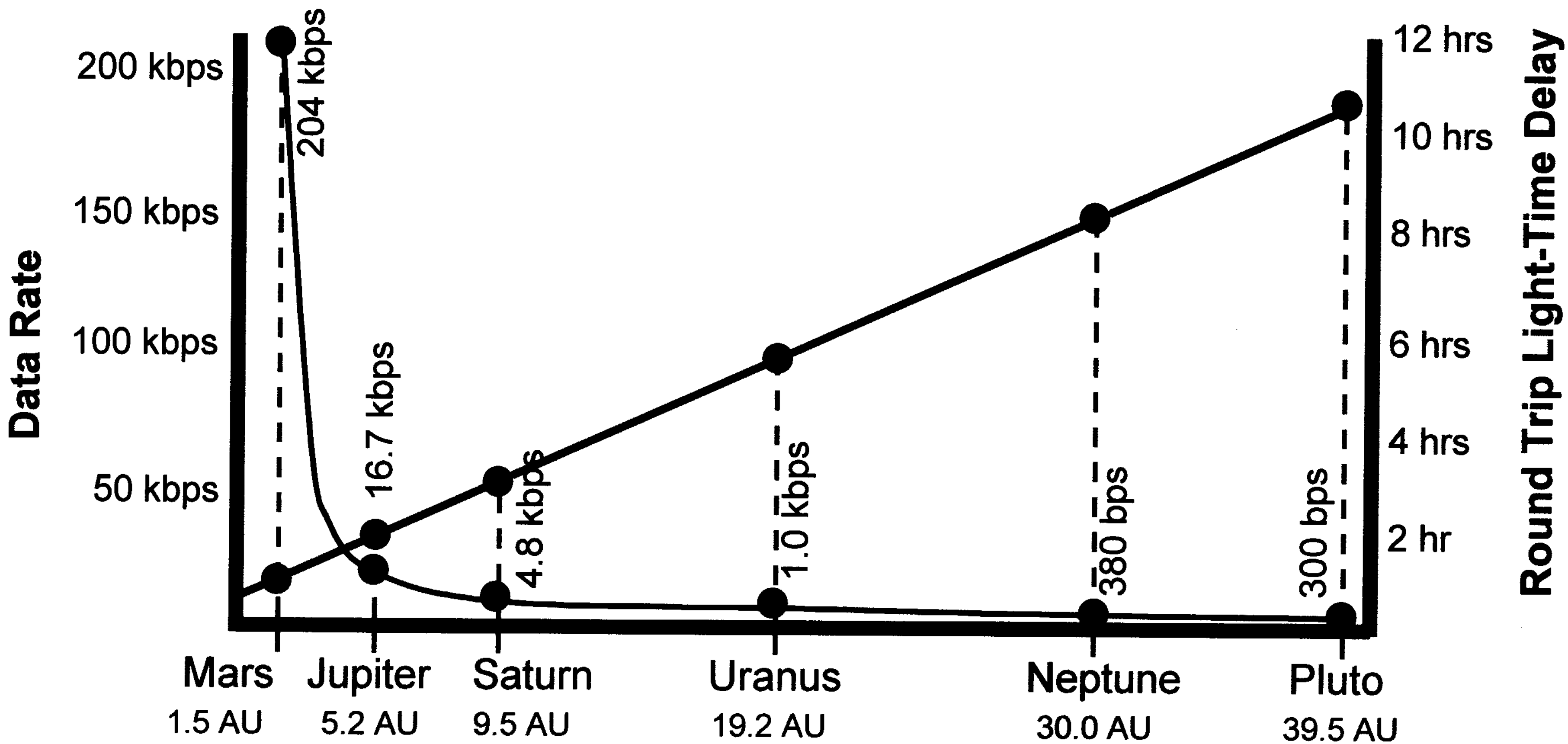
Effect of distance on data rate for X-band RF communication with 5 watts transmitted power from a 2-meter spacecraft antenna into a 70-meter ground antenna



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

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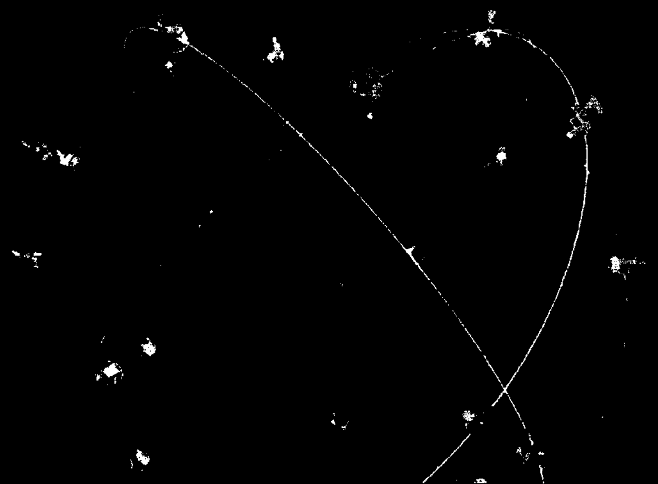
Distributed Autonomous Systems



Autonomy Needs

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

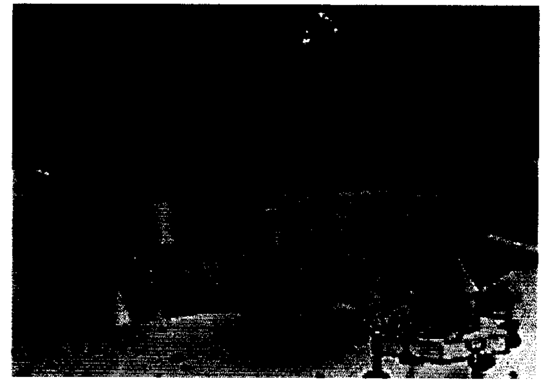
Challenges:

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

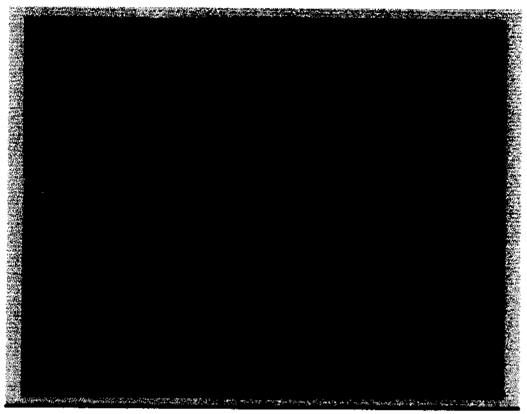
Explore Uncertain & Unknown Environments

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

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Autonomy Thrust

- Onboard Planning & Execution
- Intelligent Science Data Analysis
- Distributed Autonomy
- Safe & Precise Landing
- Health Monitoring & Diagnosis

Near Term

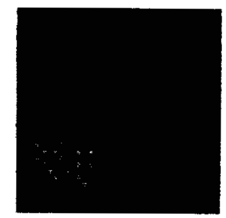
Opportunistic Science

Self-managing Explorers

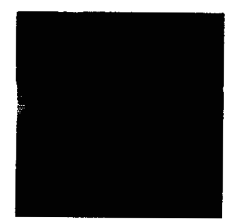
Coordinated Spacecraft Fleets

Long Term

Vigilant, Sustained Presence



Robot Colonies



Exploration of Uncertain Environments

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Planning & Execution

Onboard Planning for Constellations

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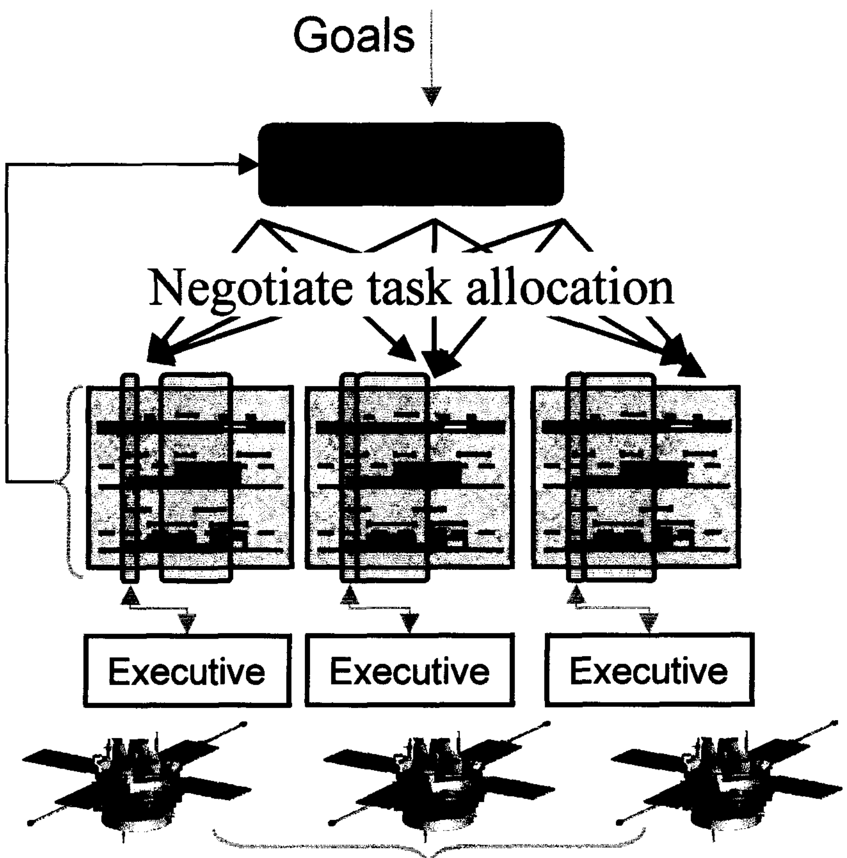


Coordinated Planning & Execution

Technology

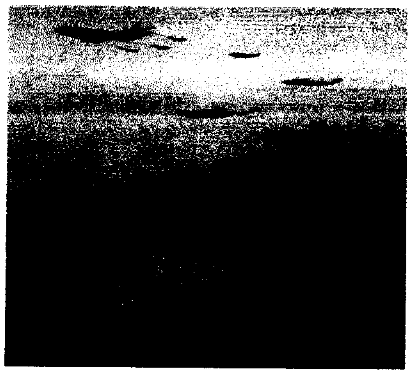
- Planners on each spacecraft negotiate to best allocate goals & resolve conflicts among respective plans.
- Planners replan / reallocate as needed during execution to coordinate activities.

Approaches:

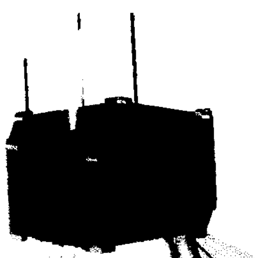
- Loose (goal distribution)
  - Centralized 'distribution' planner
  - Contract network
- Tight coordination

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

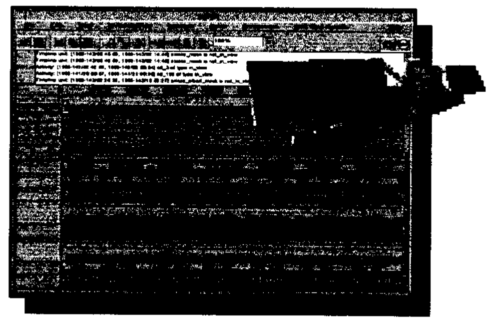
ASPEN & CASPER Deployments



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



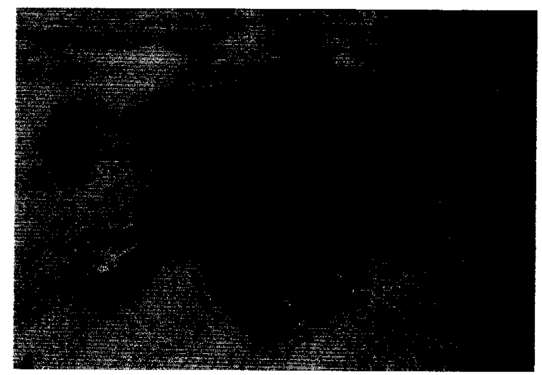
3 Corner Sat (3CS) Launch: 2002 (with CSGC)



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

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Onboard Science Analysis and Knowledge Discovery

Technology: DiamondEye

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

Innovations

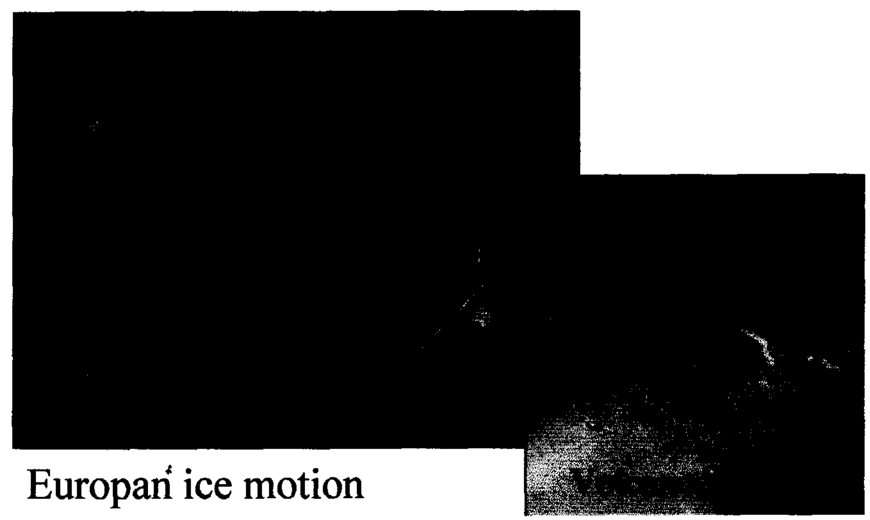
Learns scale- and rotation-invariant pattern recognizers from a few examples

Discovers 'anomalous' features--candidates for science discoveries.

Applications

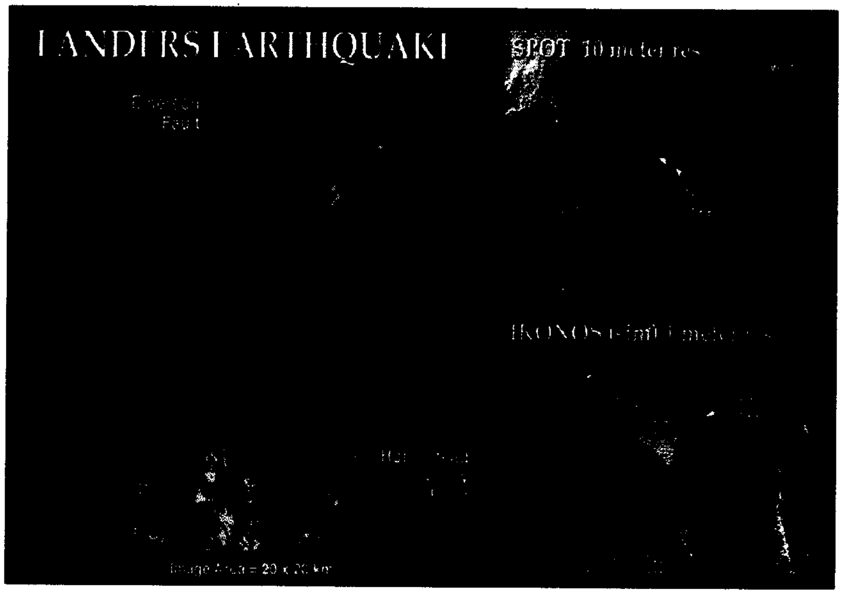
- Machine-assisted discovery of phenomena in vast datasets
- Opportunistic Science
- Data Prioritization & Summarization

Craters detected in Viking data



Europan ice motion

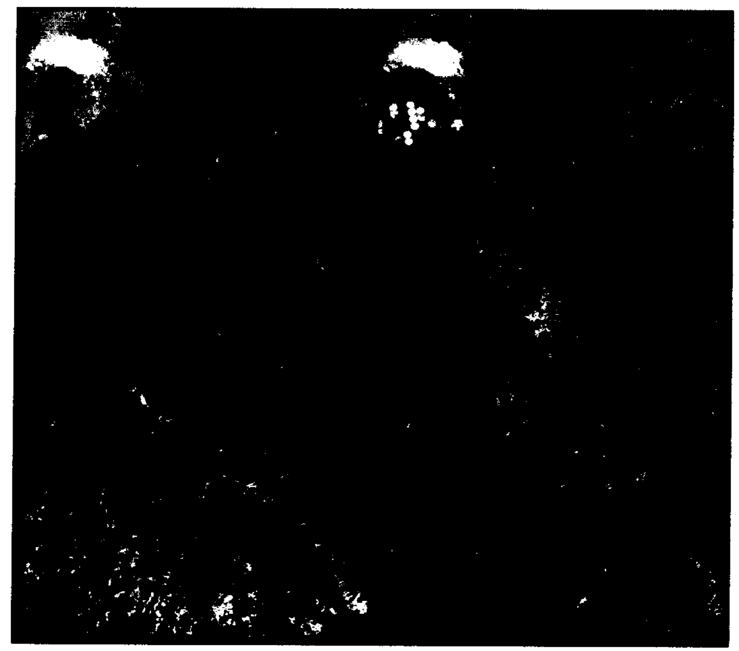
Temporal and Spectral Data Mining



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

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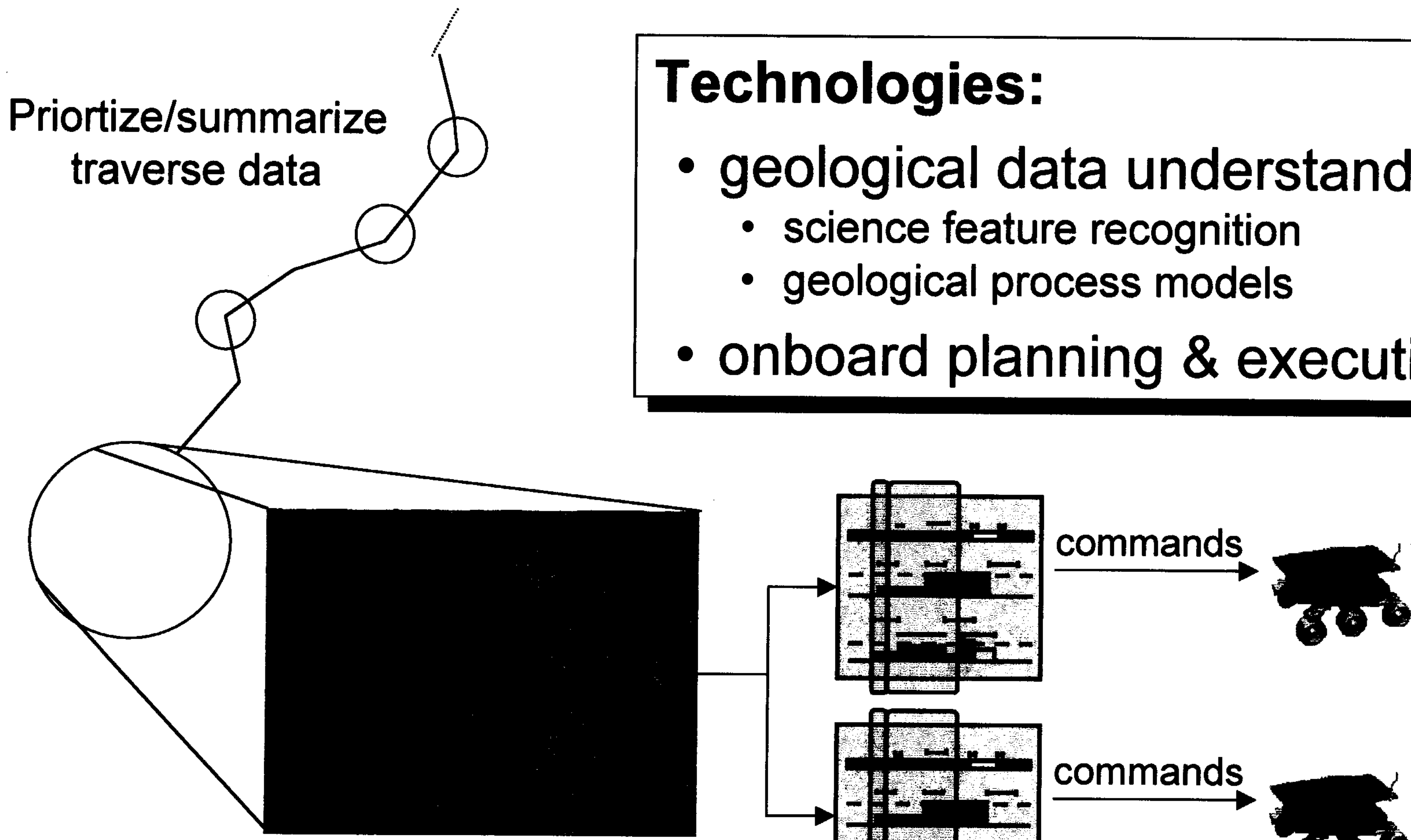
Technologies:

- 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

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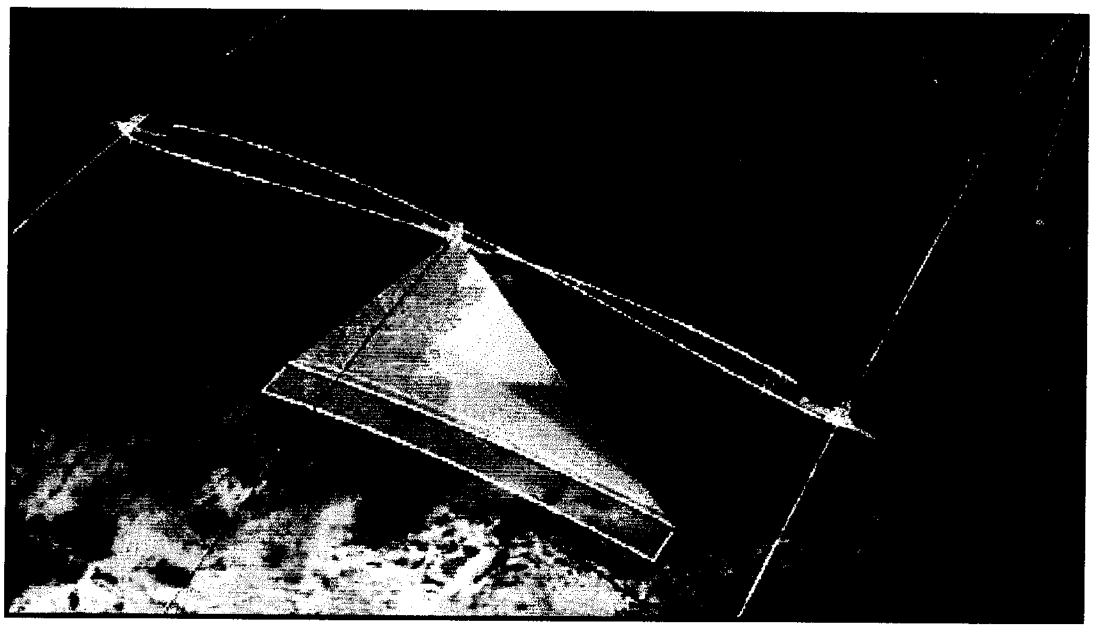
Distributed Autonomy

The Techsat-21 Autonomous Sciencecraft Constellation

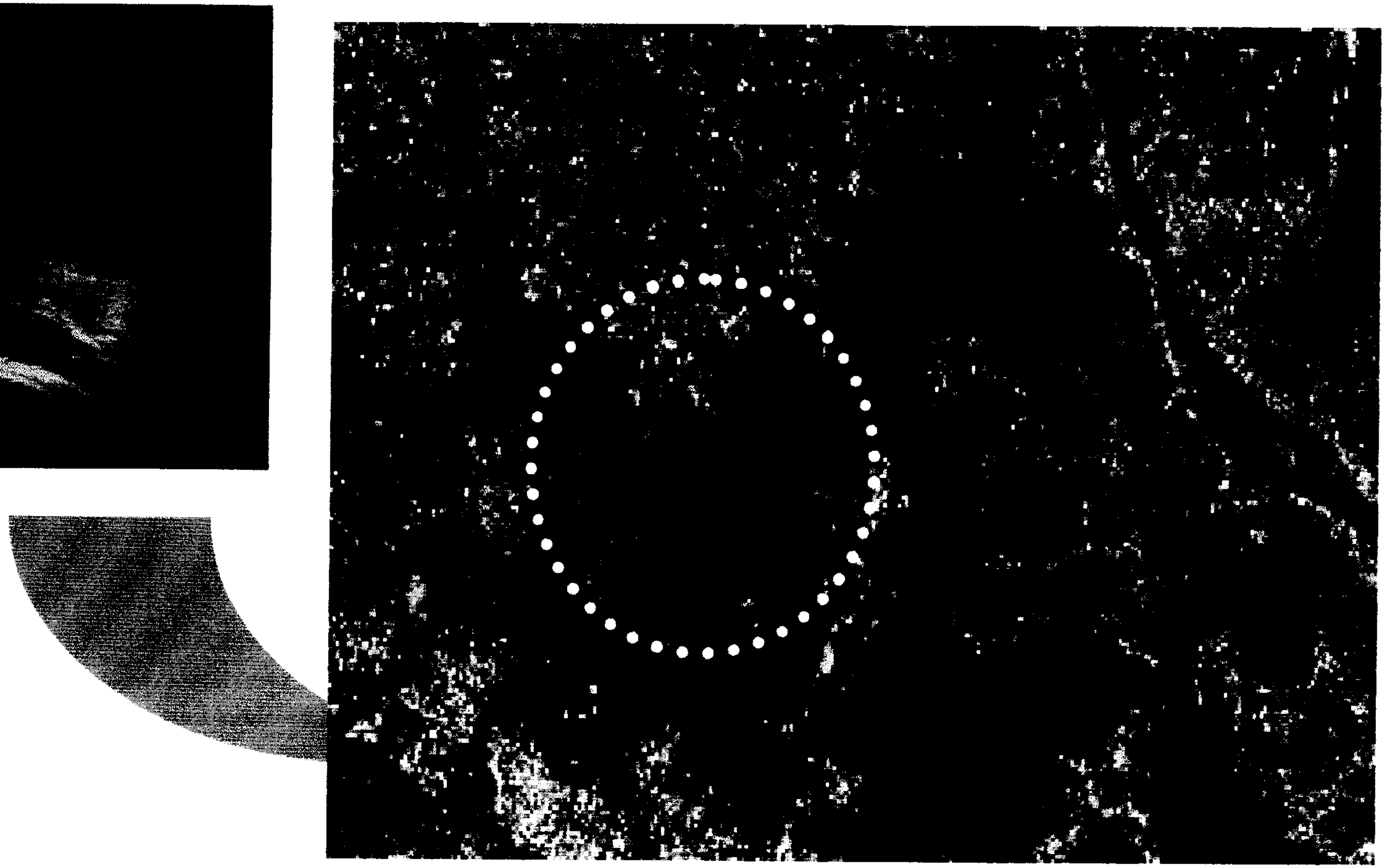
Steve Chien, Rob Sherwood
Jet Propulsion Laboratory



ASC Mission Scenario

Cluster Management:
Constellation
Reconfiguration

Onboard Replanning



Safe & Precise Landing

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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

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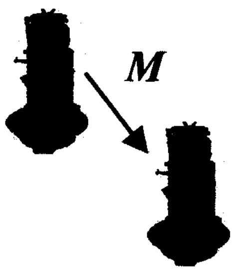
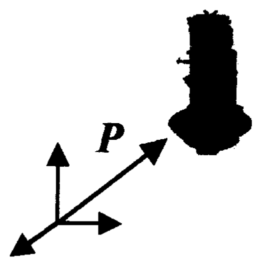
Motion Estimation Through Feature Tracking



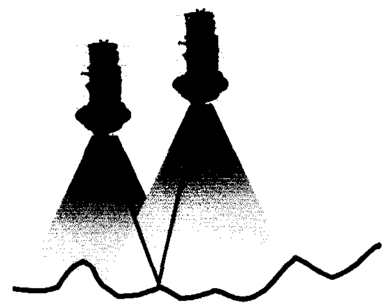
Features tracked during descent to comet analog. Motion estimation from imaging only is accurate to 1% of distance traveled.

Landmark-Based Absolute Position Estimation



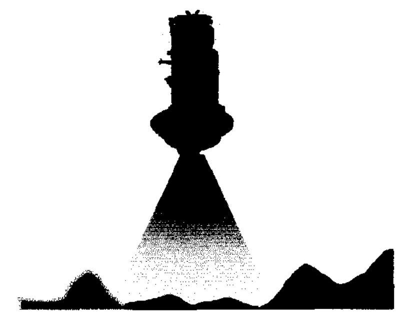
Crater landmarks automatically detected in NEAR Imagery. Crater center accurate to 10 m from 100 km orbit.

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

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Health Monitoring & Diagnosis: BEAM

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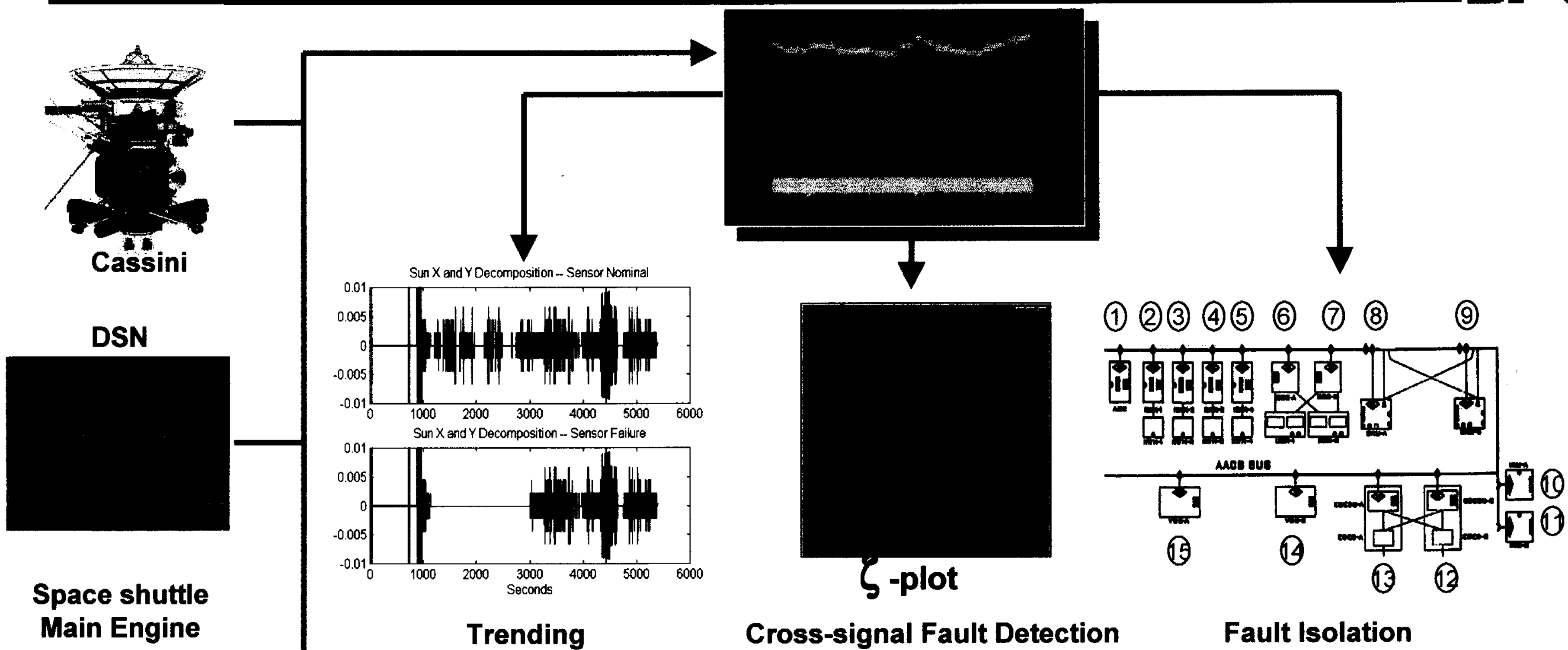
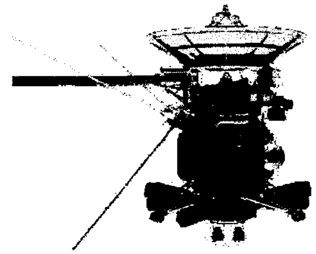


ADVANCES

- 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)**

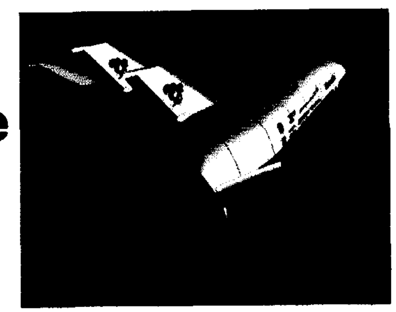
Space Shuttle Main Engine

- **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**

Software Engineering

- Best software engineering practices are the key to fielding autonomy flight software
- Need software architectures which enable ground-to-flight migration of capabilities
- Need to show that complexity emerges only from the problem domain, and that autonomy capability *manages* that complexity in the operational context
- Most compelling need for onboard autonomy appears to be on in situ planetary exploration missions

Autonomy Software Validation

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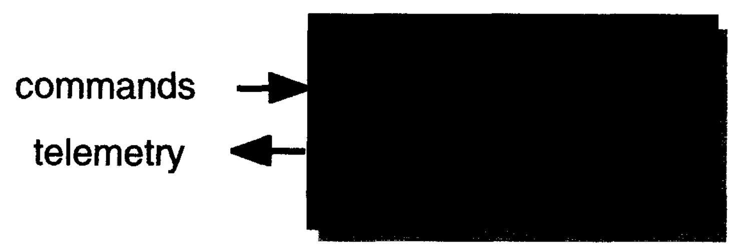
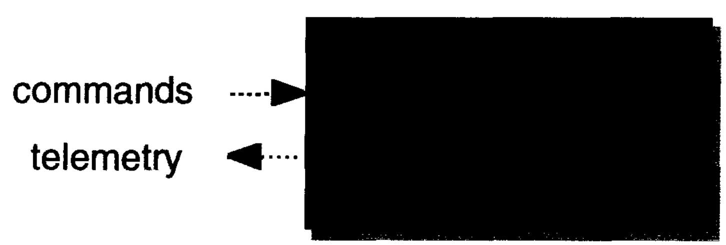
- JPL is teaming with Ames' world-class effort in formal methods for software verification (M. Lowry et al)
- But validation is different: How to build confidence that an autonomous space system will "do the right thing?"
- <u>Promising idea</u>: (borrowed from model-based fault diagnosis)
  - Cannot enumerate all possible software failures
  - Can appropriate bounds be placed on overall software-based system behavior?
  - Validation occurs at design, test and run time



Send command sequence.

Does the resulting telemetry match predictions?



Observe behavior in the loop.

Is the system accomplishing its goals and respecting boundary conditions in spite of anomalies?

Summary

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- 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
  - Mining of science data sets
  - Position estimation for NEAR

NASA