anned NAS

Presentation to

Advanced System Integration and Control for Life Support Workshop

August 26, 2003

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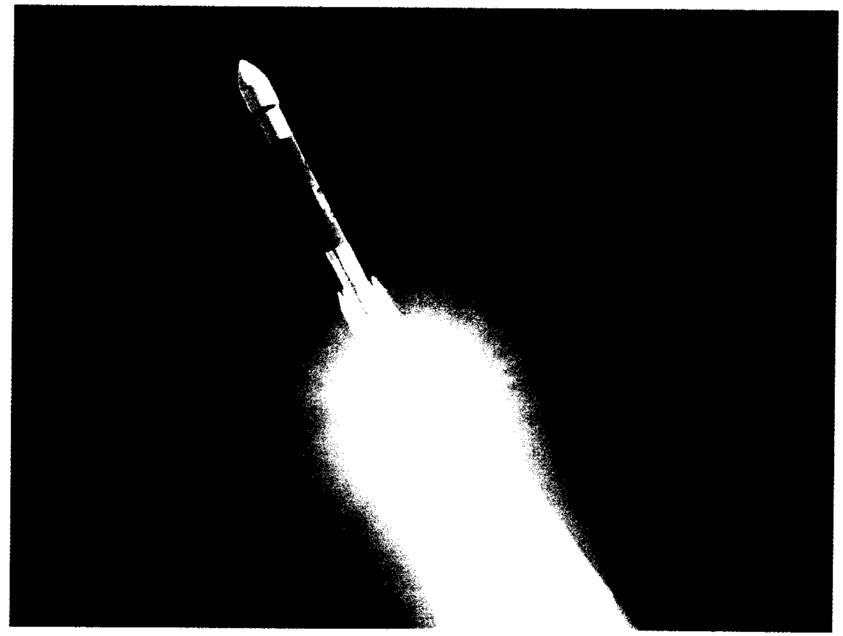
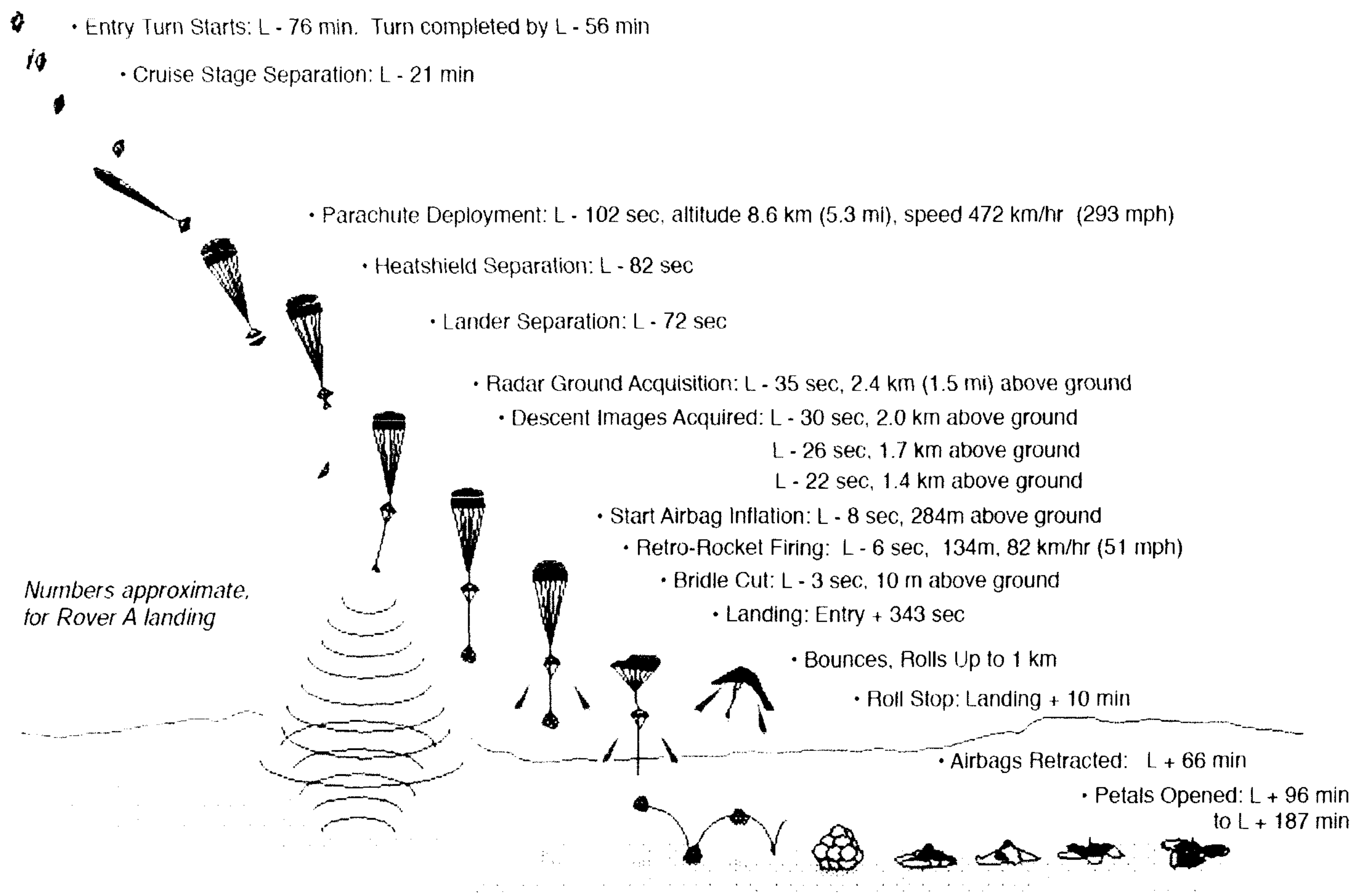
OUTLINE



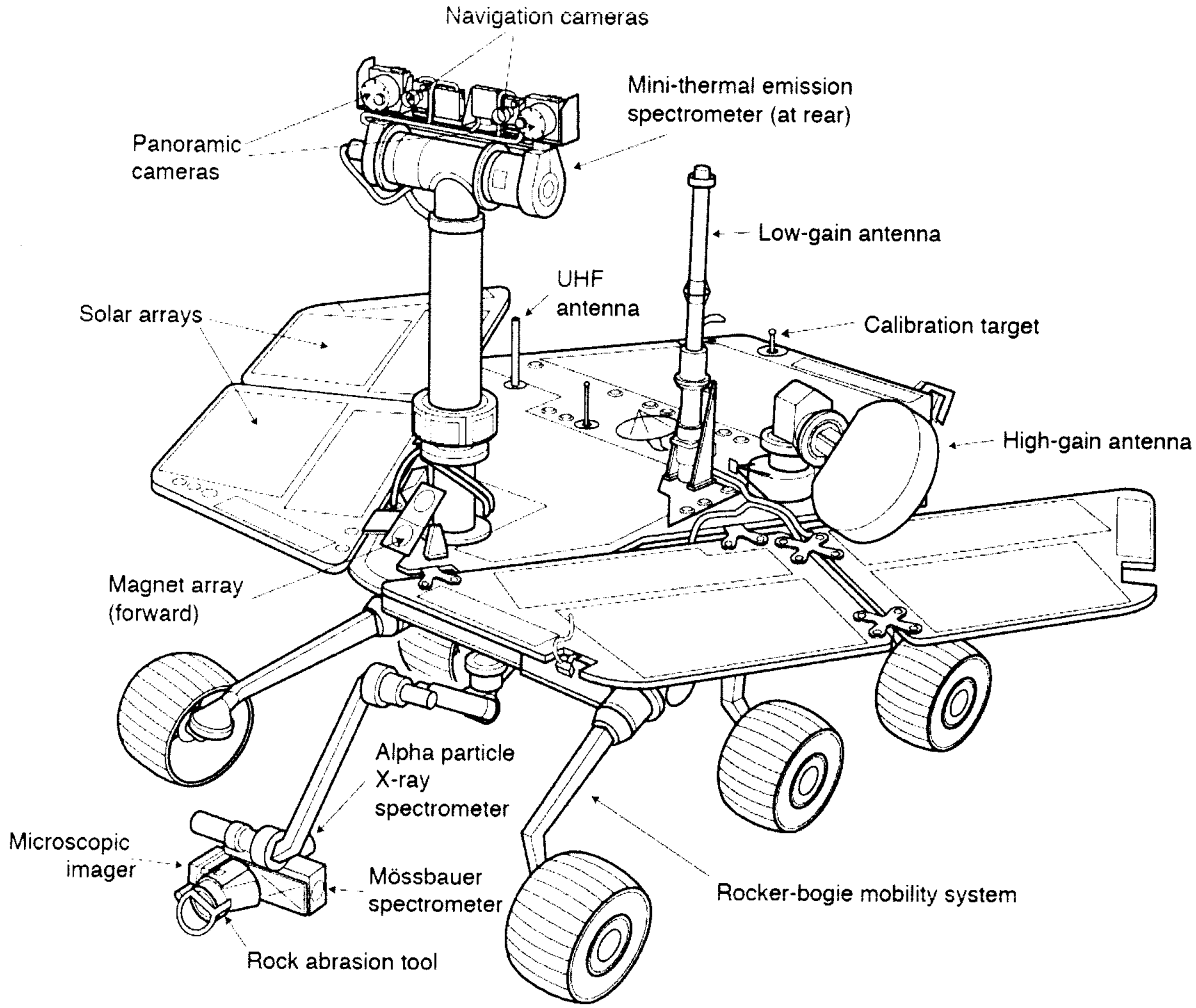
- MER Mission
  - Flight
  - Surface
- MSL Mission
  - EDL
  - Surface
- Long-Term
- Other Control Examples
  - Formation Flying
  - Adaptive Optics/Wavefront Control
  - Environmental Sensing
- Summary

EDL



Entry, descent and landing

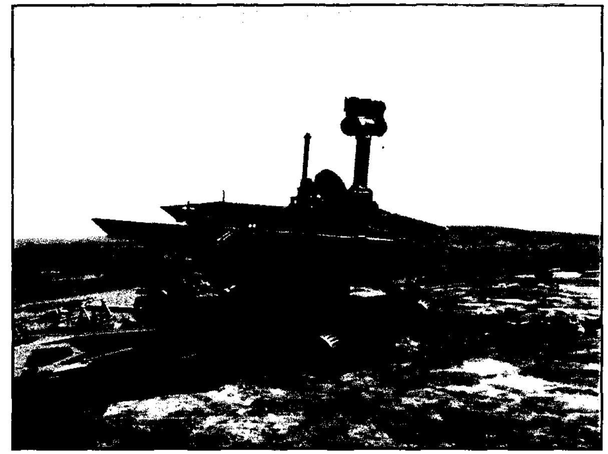
Rover



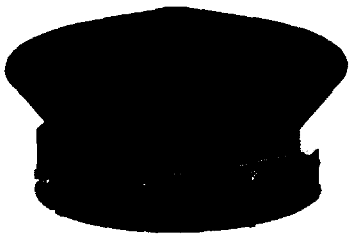
Mars Exploration Rover

Surface Operations

- Sojourner-based
- Cannot recognize targets
- Navigation by terrestrially-defined waypoints, computed wheel turns
  - Perhaps use visual odometry--more accurate
- Inverse Kinematics on board
- Basic motion is arc from initial location/pose to final location/pose
- Move about a foot: use hazcam stereo to calculate next increment
- No global onboard map, but high-quality IMU
- Long traverse mode (outside stereo)
- Instrument placement mode (within stereo bubble) 3 sols
  - Move to standoff position
  - Move to manipulation envelope (downlink stereo imagery)
  - Move to uplinked target position/contact

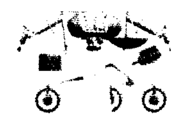


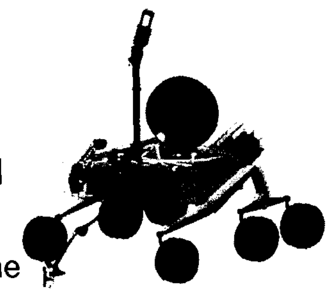
Mission Architecture



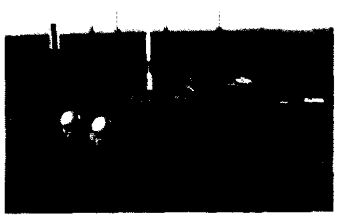
CRUISE/APPROACH
- Type-II transfer
- 10-12 month flight time
- 5-6 course corrections
- Optical nav for approach
- Separation @ entry – 10 min, no carrier deflection

ENTRY/DESCENT/LANDING
- Direct Entry on mid- to late-2010
- Comm provided by UHF link to orbiting asset and DTE X-band
- Sun and Earth constrained to 20deg min elevation at landing site
- Arrival prohibited within +/- 60 days of solar conjunction



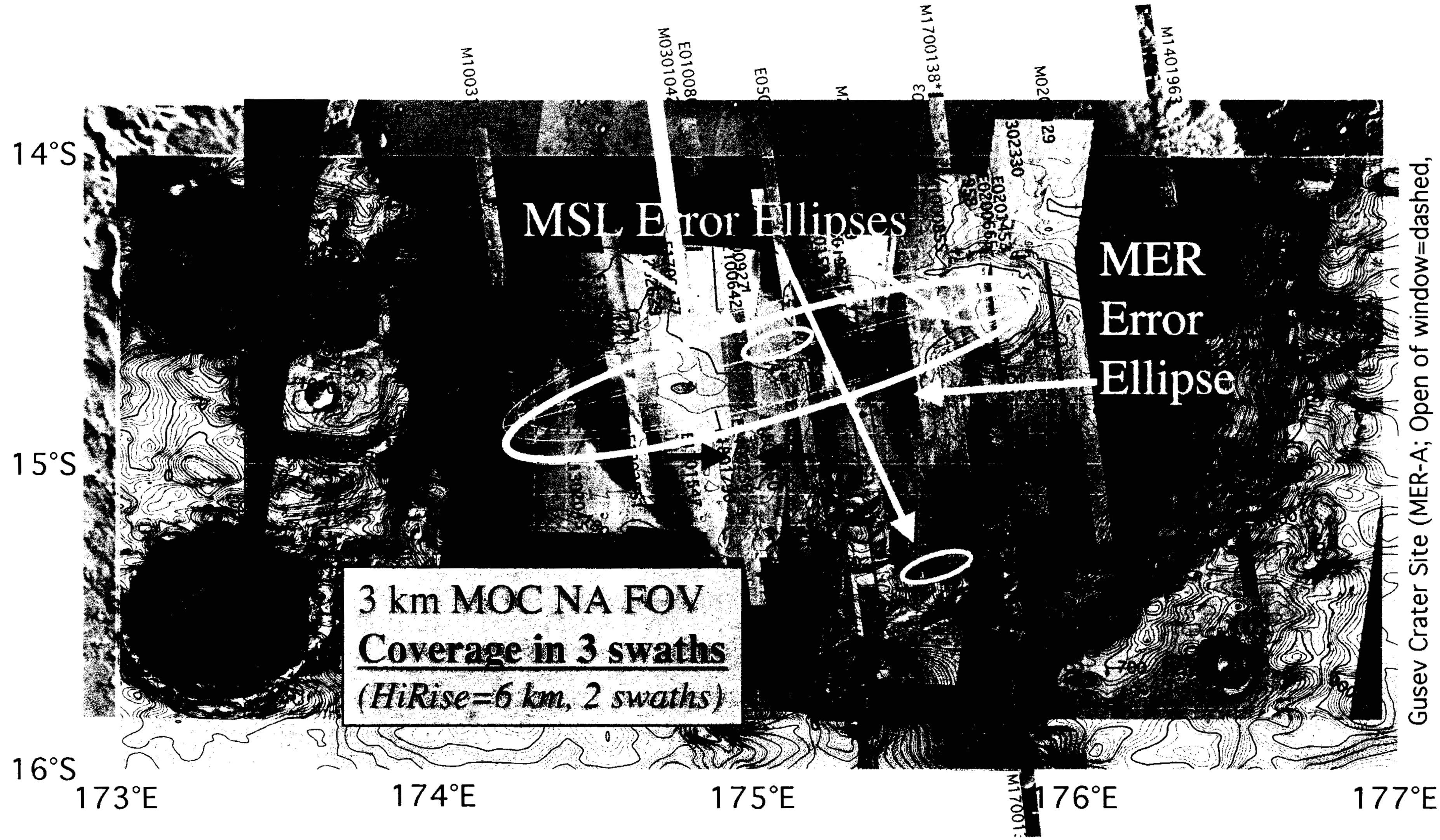


SURFACE MISSION
- 900 kg rover baseline
- 687 Sol lifetime baseline
- 6+ km mobility
- 112 kg payload of instruments and support
- Radioisotope Power Source assumed, pending final decisions
- Surface Avionics used for all 3 mission phases

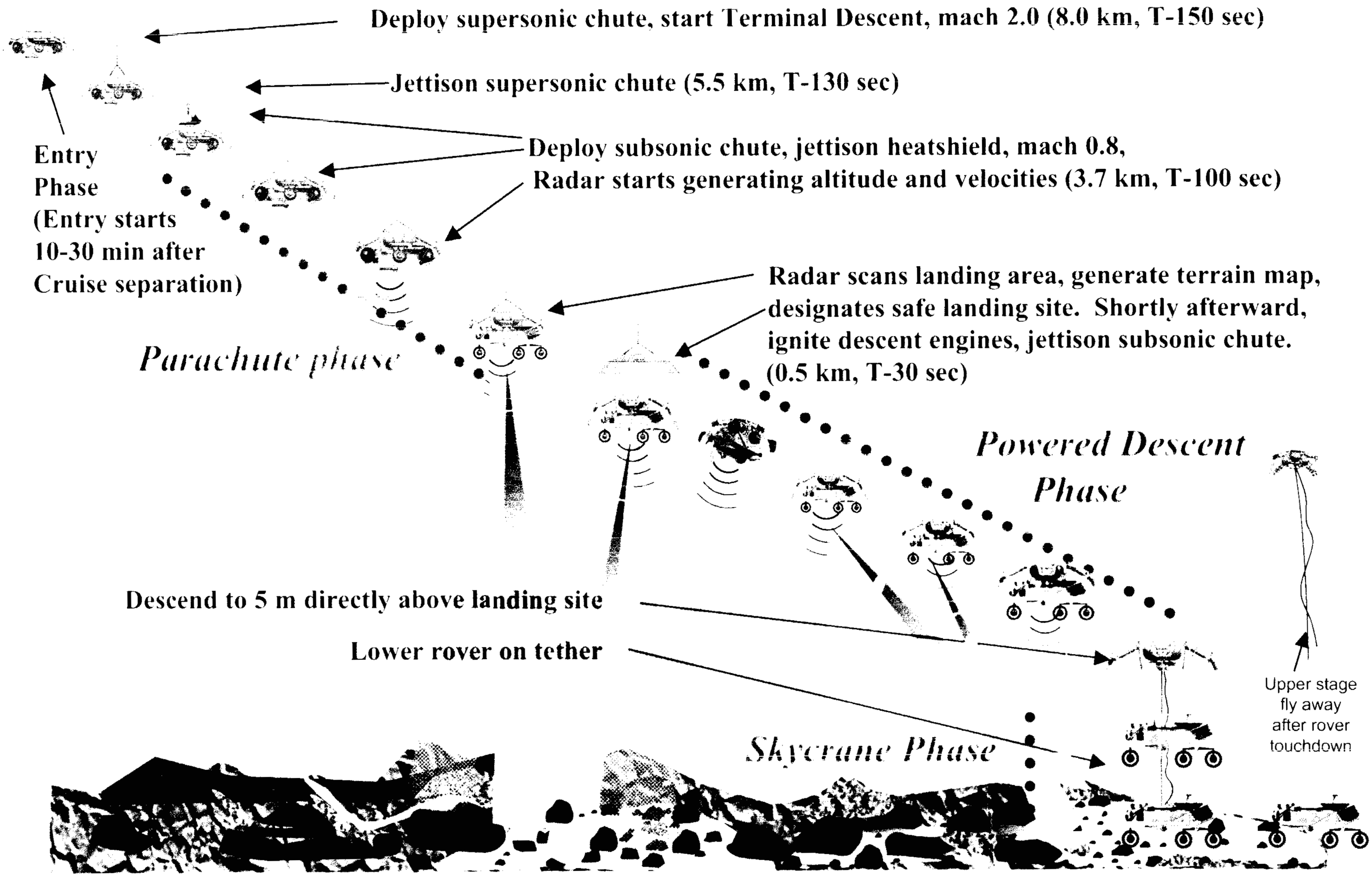


LAUNCH
- Oct. 27, 2009
- Delta IV/ATLAS V w/ 5-m fairing
- **IVa planetary protection**

Landing Error Ellipse Comparisons

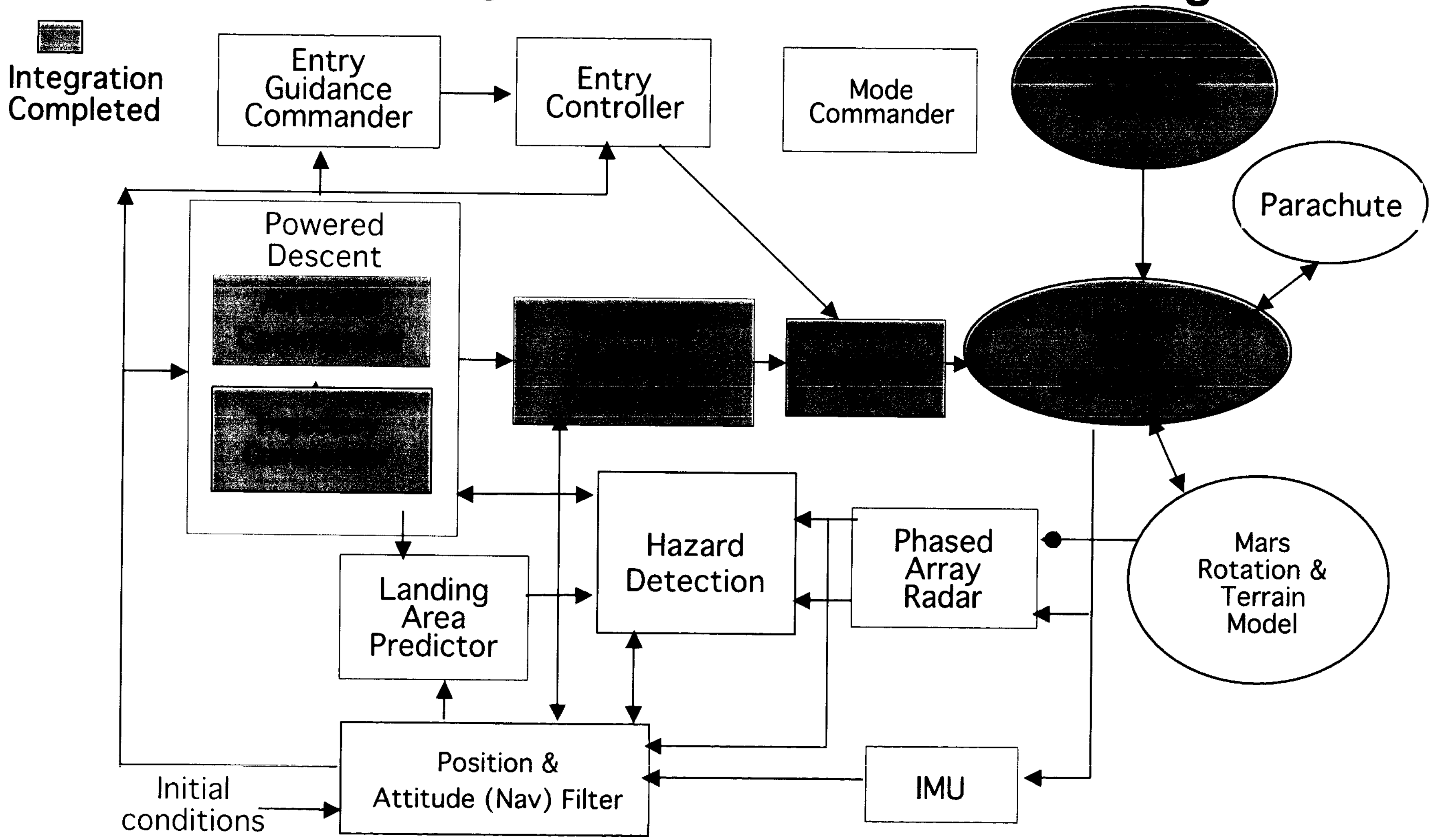


MSL Entry, Descent, and Landing Timeline



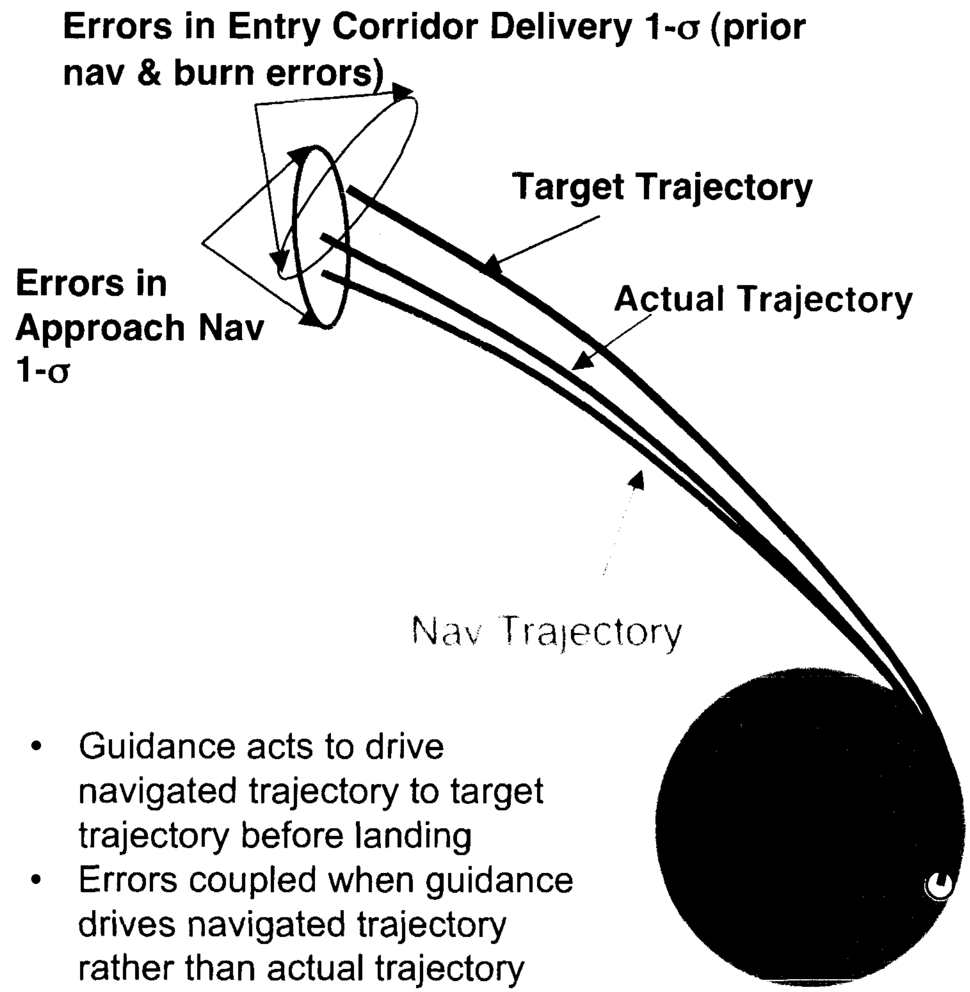
MSL

Guidance, Navigation, and Control Block Diagram



Entry Guidance and Navigation

- Initial position and velocity values with correlated uncertainties from cruise navigation used to initialize the EDL navigation filter
  - Attitude initialization with correlated uncertainties supplied by the onboard cruise attitude determination filter
  - Other nav state and covariance ICs provided by parameter input
- Approach navigation errors are main contributor to overall EDL navigation error
  - If approach navigation delivery errors are within the limits of the error capabilities of the guidance system, delivery error and other errors can be removed by the closed-loop EDL GN&C system
  - Limited by initial knowledge error, assuming no external data after entry and before supersonic chute deploy

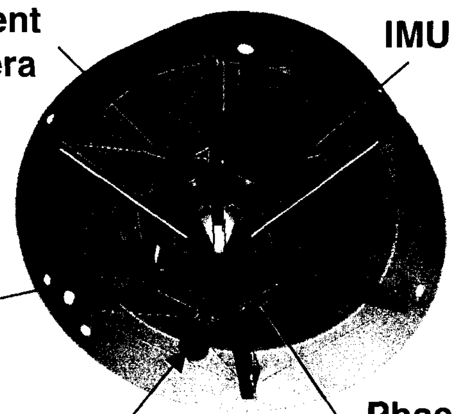


- Guidance acts to drive navigated trajectory to target trajectory before landing
- Errors coupled when guidance drives navigated trajectory rather than actual trajectory
- "Shape" of the error ellipses dependent on approach geometry and mission profile

Overview

Objective

To increase safe landing probability through terrain sensing and onboard computing for hazard avoidance.



Onboard Algorithms
- Hazard Detection
- Safe Site Selection
- Sensor Fusion for Hazard Avoidance
- Velocity Estimation
- Target Tracking
- Terrain Relative Navigation
- Terminal Guidance and Control

State of the Art

- Hazard Tolerance: (0 m divert) Airbags are flight tested, pallet 3/8 scale mode built and tested.
- Local Hazard Avoidance: (100m divert) Concepts exist and prototypes are being tested.
- Regional Hazard Avoidance: (1000m divert) Viable component concepts, no prototypes exist.

Mission Relevance

- Mars Smart Lander
- Mars Scouts
- Titan Aerobot
- Europa Lander
- Comet Nucleus Sample Return
- Human Exploration of Mars

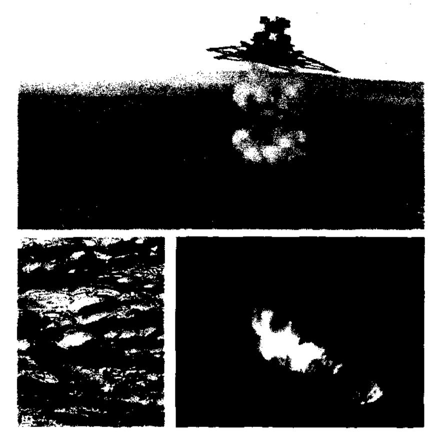
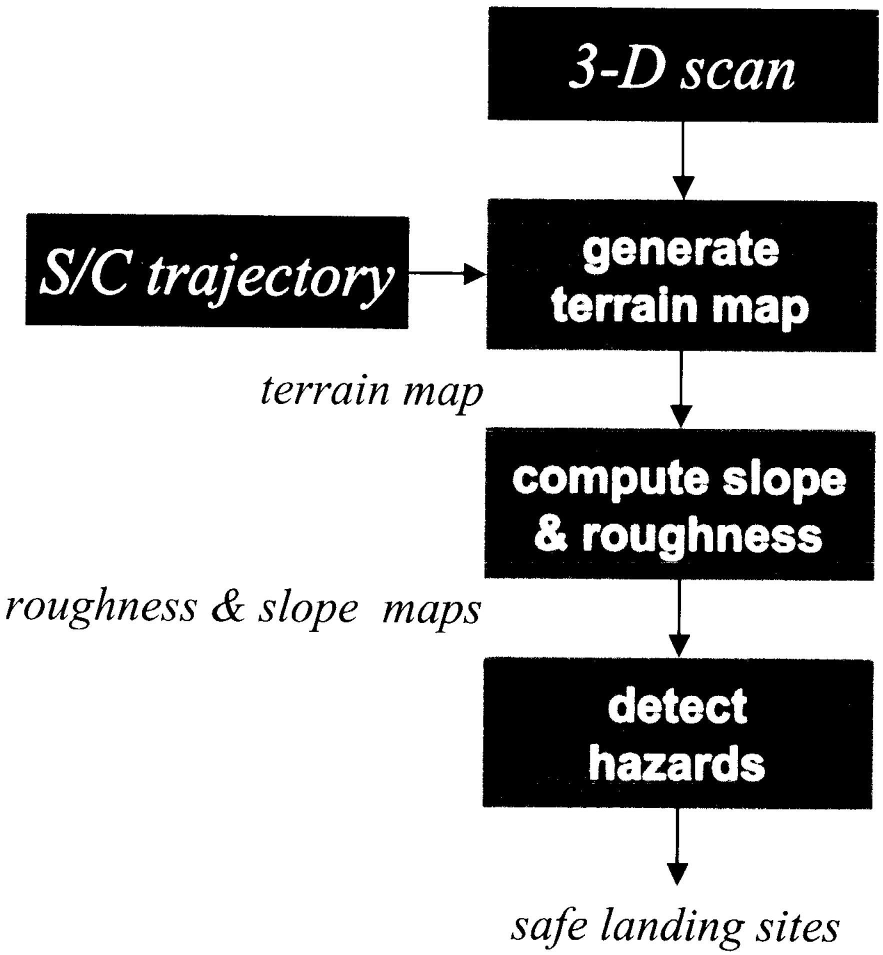
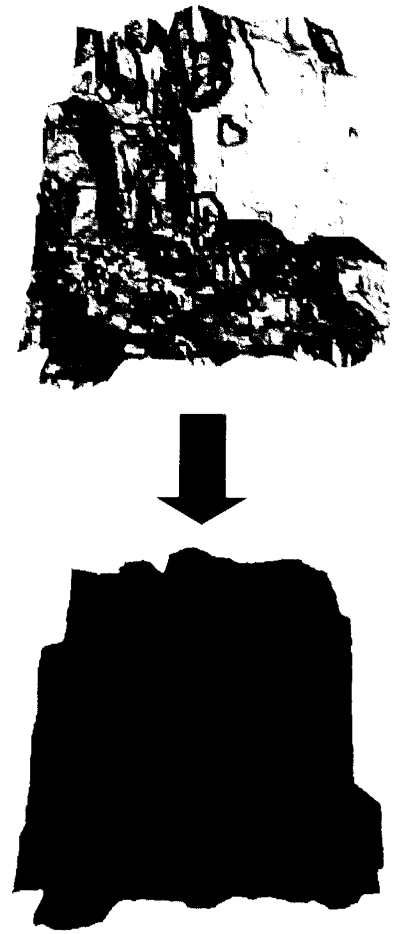
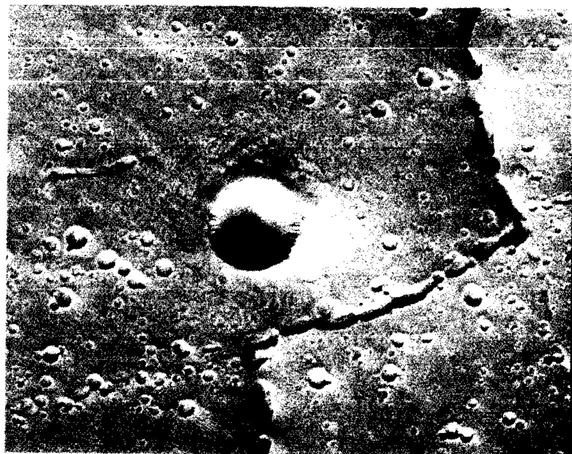


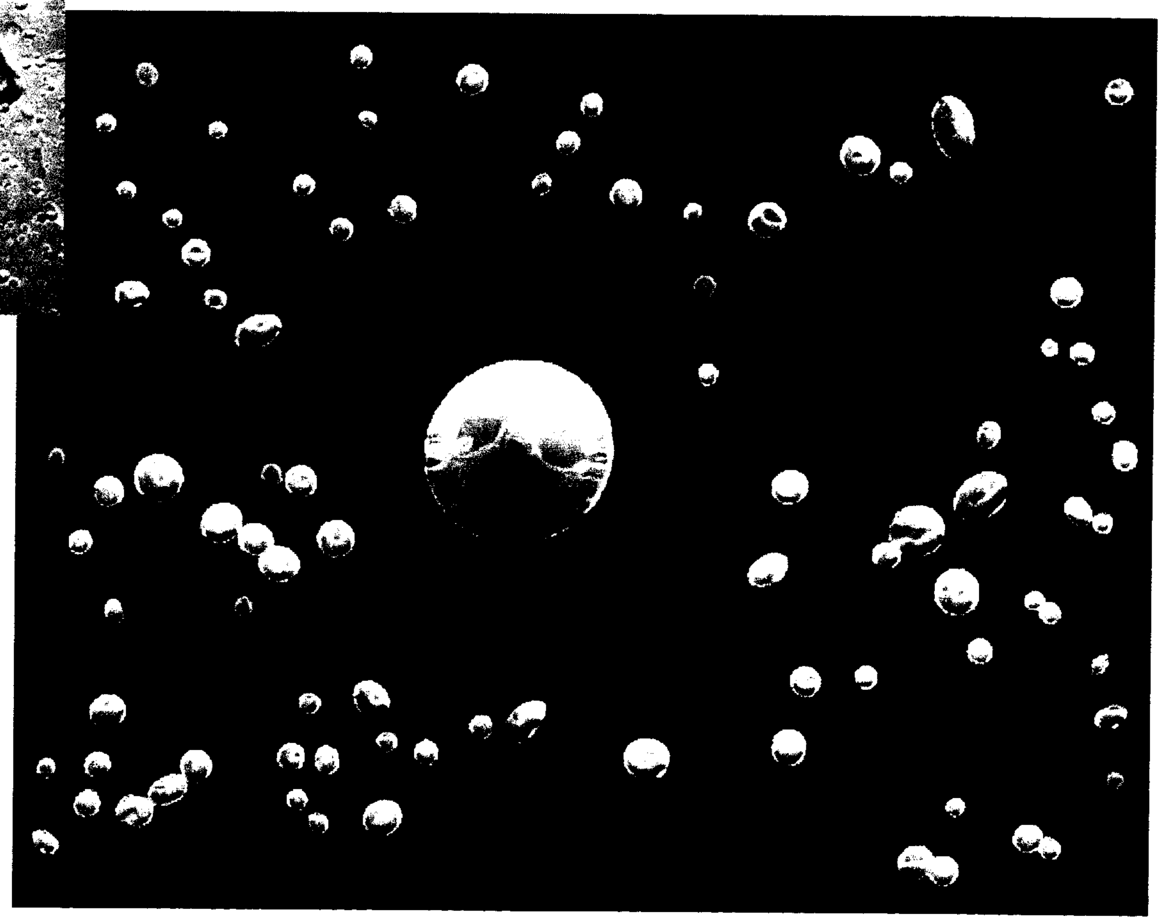
Illustration of Lidar-based Hazard Detection





Crater and Discontinuity Hazard





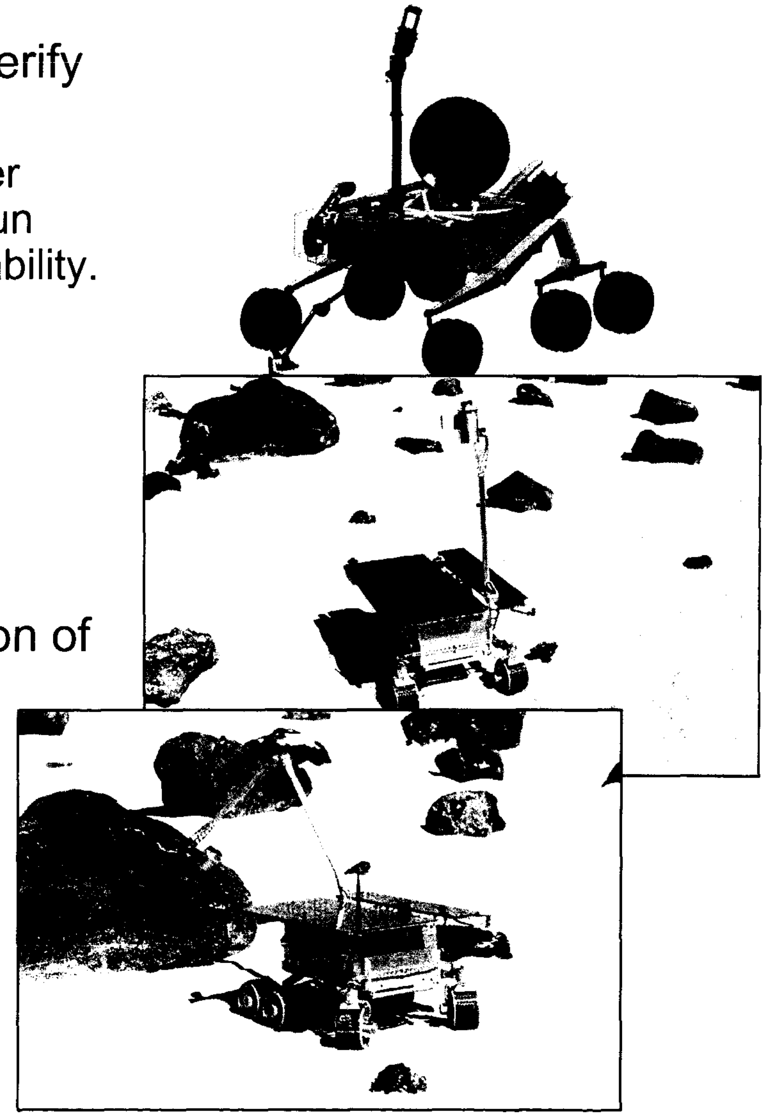
Safe Area

Cratered Area

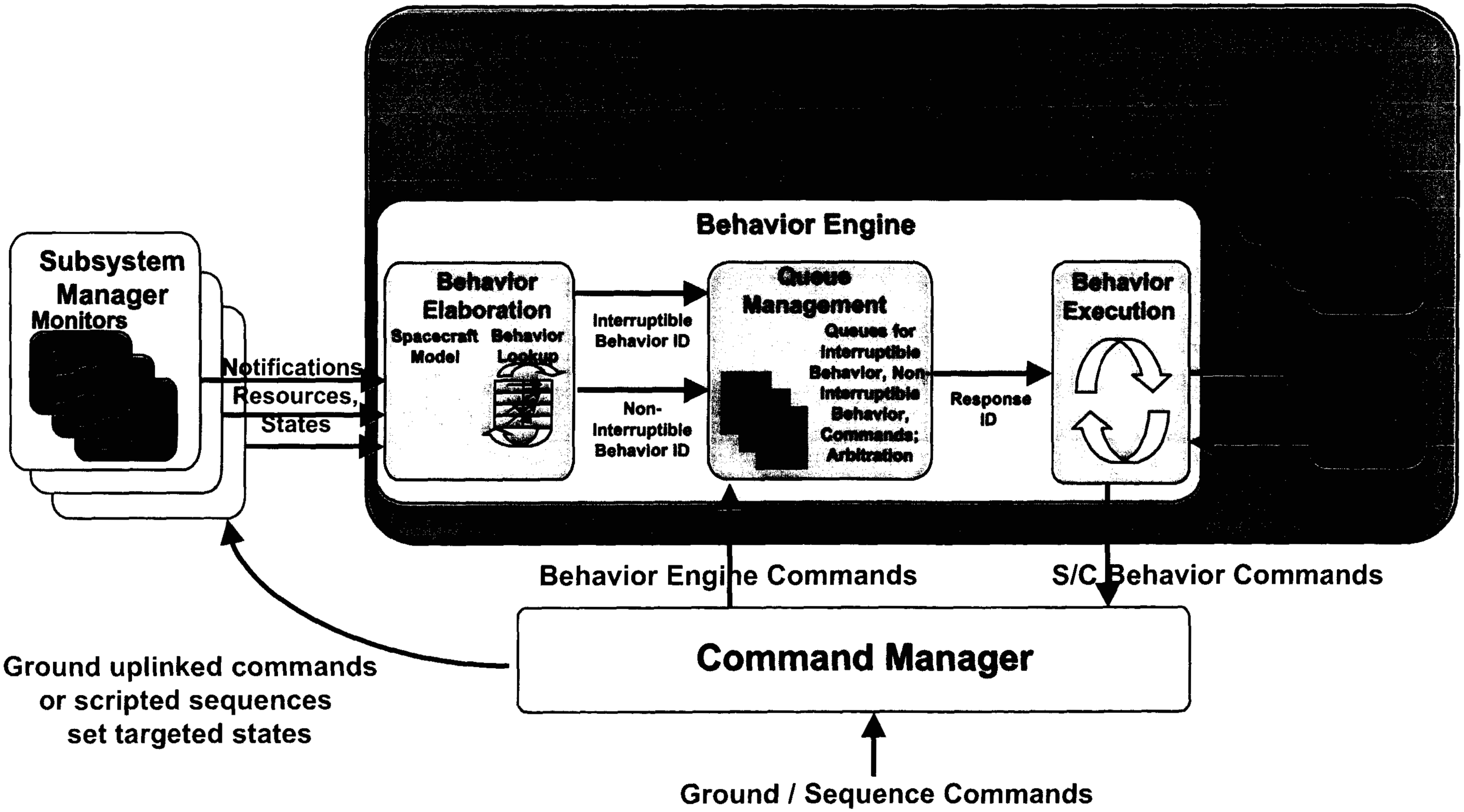
Discontinuity Area

Planned Capabilities

- On Board planning, scheduling, executive (verify that planned segments can be executed)
  - Path Planning will include elevation map, other constraints such as illumination view angle, sun angle and, perhaps, soil modeling for traversability.
  - May be cautious on long traverses
- Wide baseline stereo
- Visual sinkage estimation
- Possibly 2D and 3D visual tracking
- Full articulation kinematics on board
- Improved position estimation via sensor fusion of kinematic and visual sensory information
- Single Sol instrument placement
  - May have visual servoing
- Manipulation:
  - On-board arm collision detector
  - Improved force control

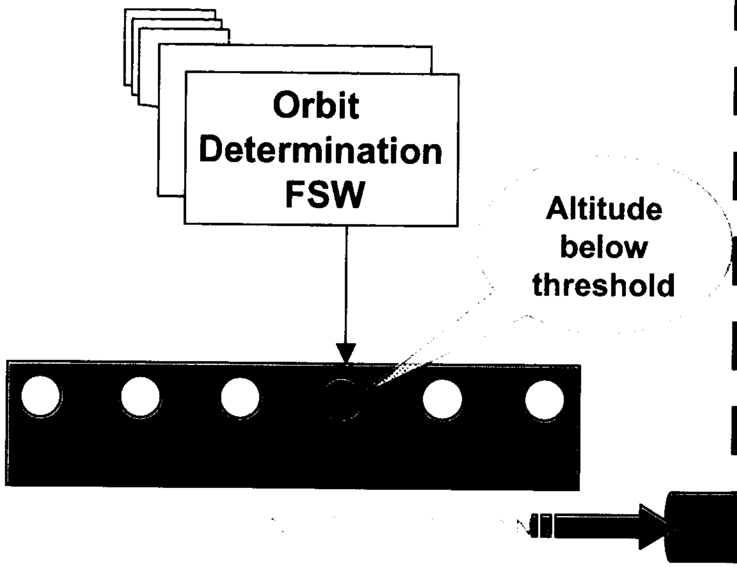


Autonomy System Architecture



Control in Unmanned NASA Missions
Autonomy

Subsystem Manager | Behavior Engine



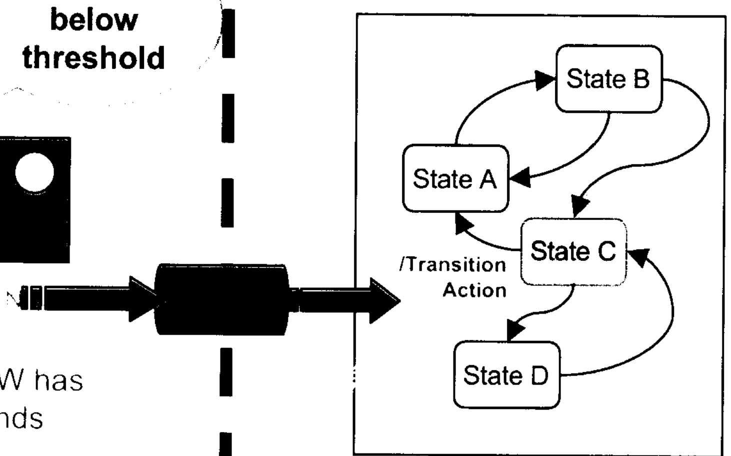
1 Monitor Determines that Host FSW has an out-of-bounds condition, and sends indication to the Behavior Manager.

2 This indication drives a **transition** from one state to another state (e.g. State C to State A).

Bring altitude back to within tolerance.

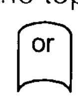
3 Transition Actions as a result of the requested state change are acted on.

4 Actions checked in the Flight Constraints, Behavior look-up table AND the S/C Dependency Model

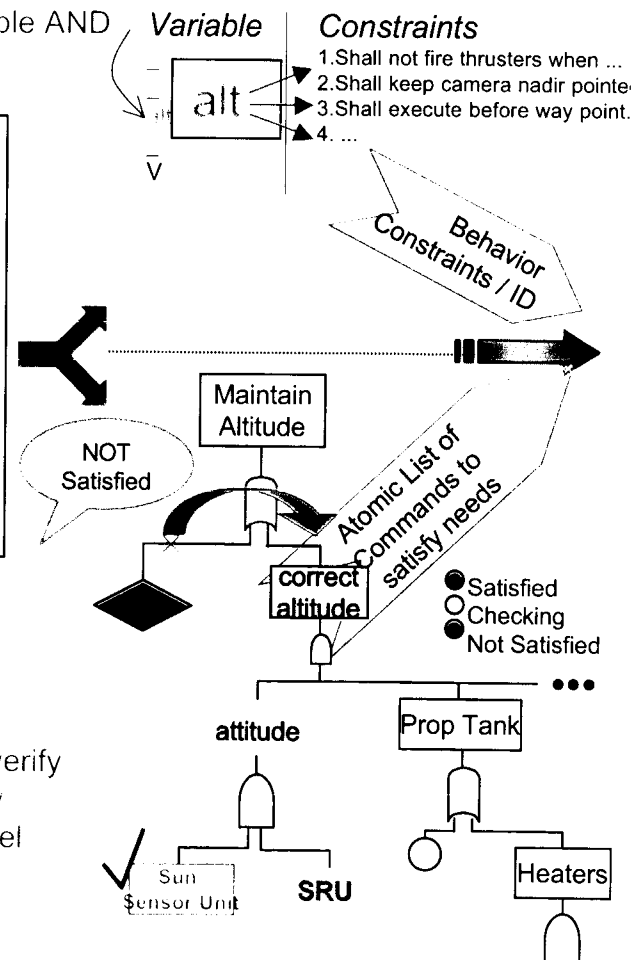


State Chart

5 The S/C dependency model determines necessary assets to satisfy "**Maintain Altitude**" (ie, verify attitude, ready prop tanks, ready thrusters ..) to satisfy the top level event "or" condition.



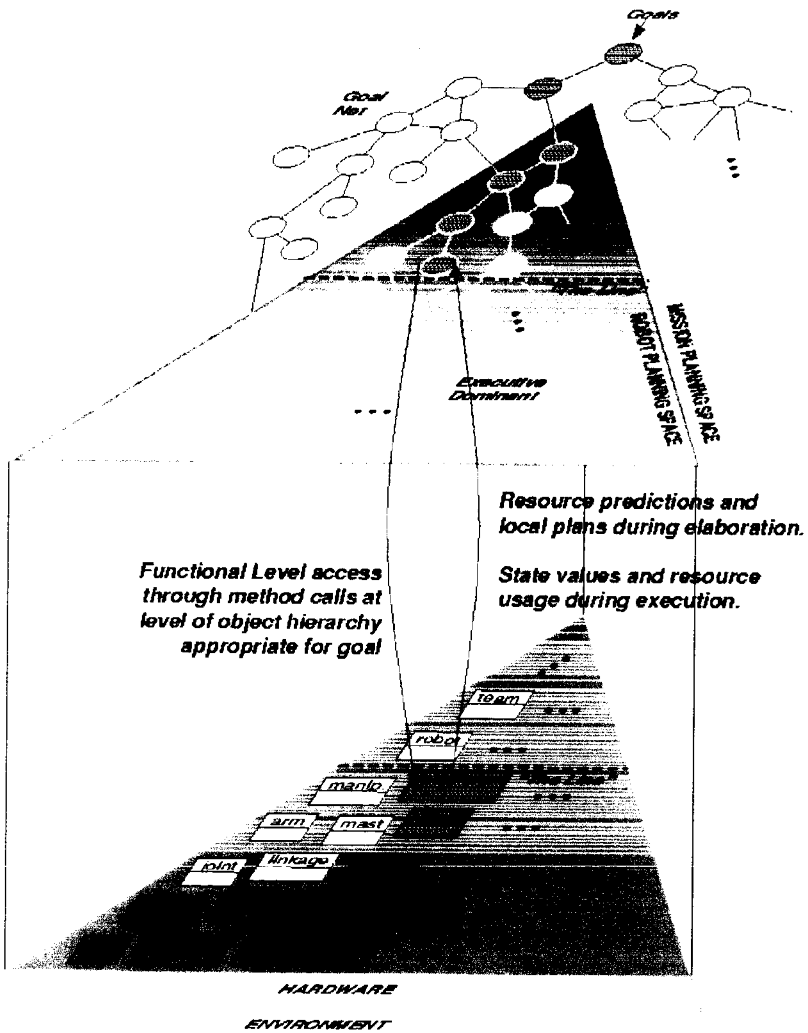
Flight Constraints (behavior look-up table)



S/C Dependency Model

Control in Unmanned NASA Missions
Autonomy

CLARAty = Coupled Layer Architecture for Robotic Autonomy



THE DECISION LAYER:

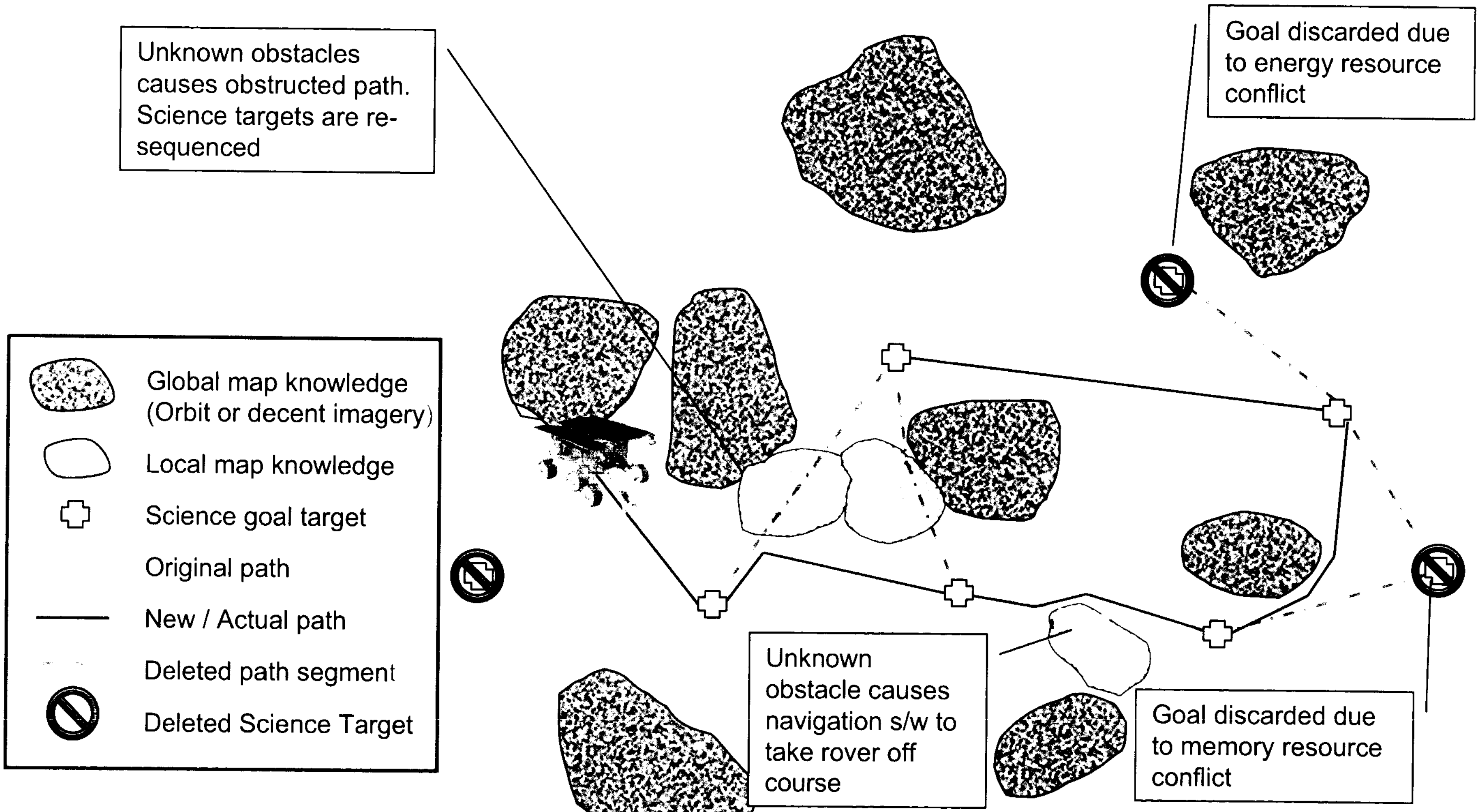
Declarative model-based representation of system capabilities and constraints. Various high-level autonomy technologies can provide planning, scheduling, and execution capabilities – (e.g. CASPER, CLEaR, TDL, MDS GEL, CRL)

[redacted]

THE FUNCTIONAL LAYER:

Generic and reusable robotic software components. Object-oriented design that can be adapted to various robotic, rover, and simulation platforms. Provide basic functionality and low-level autonomy capabilities. Packages include: I/O, Motion Control, Manipulation, Locomotion, Navigation, Perception, Resource Management, and System Control.

CLARAty Decision Layer - Full Navigation Scenario

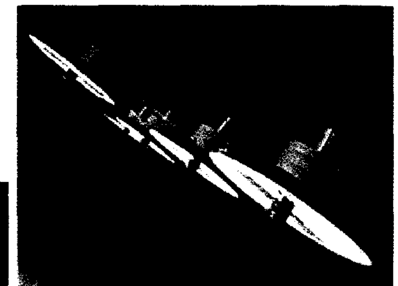


Courtesy of Fisher, Estlin et al.

Overview

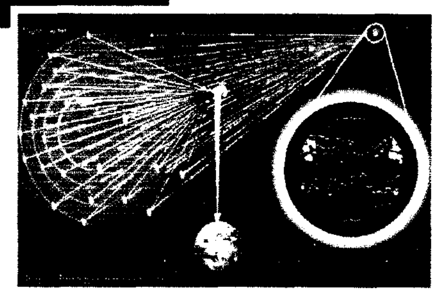
A new class of Code S space missions enabled by Formation Flying (FF) architecture:

- TPF – Terrestrial Planet Finder
- MAXIM – Micro-Arcsecond X-ray Imaging Mission
- SPECS – Sub-millimeter Probe of the Evolution of Cosmic Structure
- SI – Stellar Imager



Mission Needs:

- Precise geometrical formation and alignment,
- Precise synchronized motions, and
- Autonomous reconfigurations of multiple spacecraft to operate collaboratively as an instrument

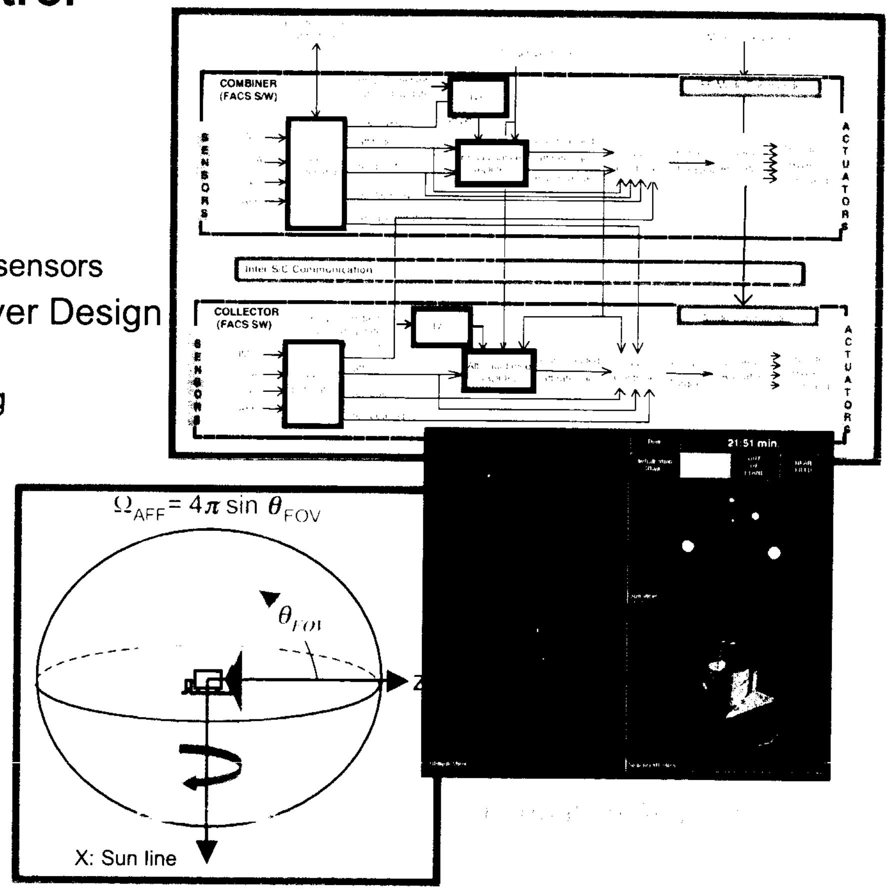


Enabling Technologies:

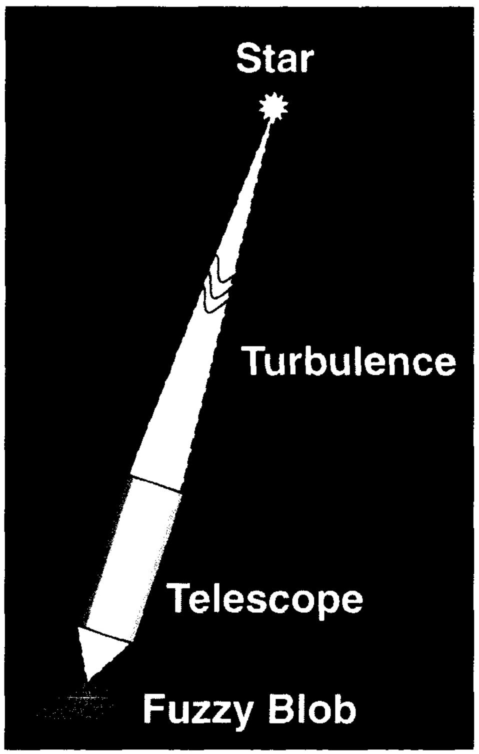
- Precision formation flying control algorithms and software
- On-board direct formation sensing for acquisition, precise alignment & control
- On-board inter-spacecraft communications

Formation Flying Guidance and Control Algorithms

- **Formation Flying Guidance and Control**
  - Precision formation control
    - Relative positions controlled to 10 cm
    - Attitudes controlled to 1 mrad
  - Guaranteed Formation Initialization
    - From "Lost-in-Space" to formation
    - Using limited field-of-view, distributed formation sensors
  - Optimal Formation Path Planning and Maneuver Design
    - Optimal reconfiguration guidance
    - Minimum fuel/energy consumption and balancing
  - Collision Avoidance
    - Basic collision avoidance for N s/c
  - Formation Synchronized Motions
    - Interferometric Observation-on-the-Fly
    - Thruster synchronization
    - Attitudes and relative positions synchronized



What is the problem?



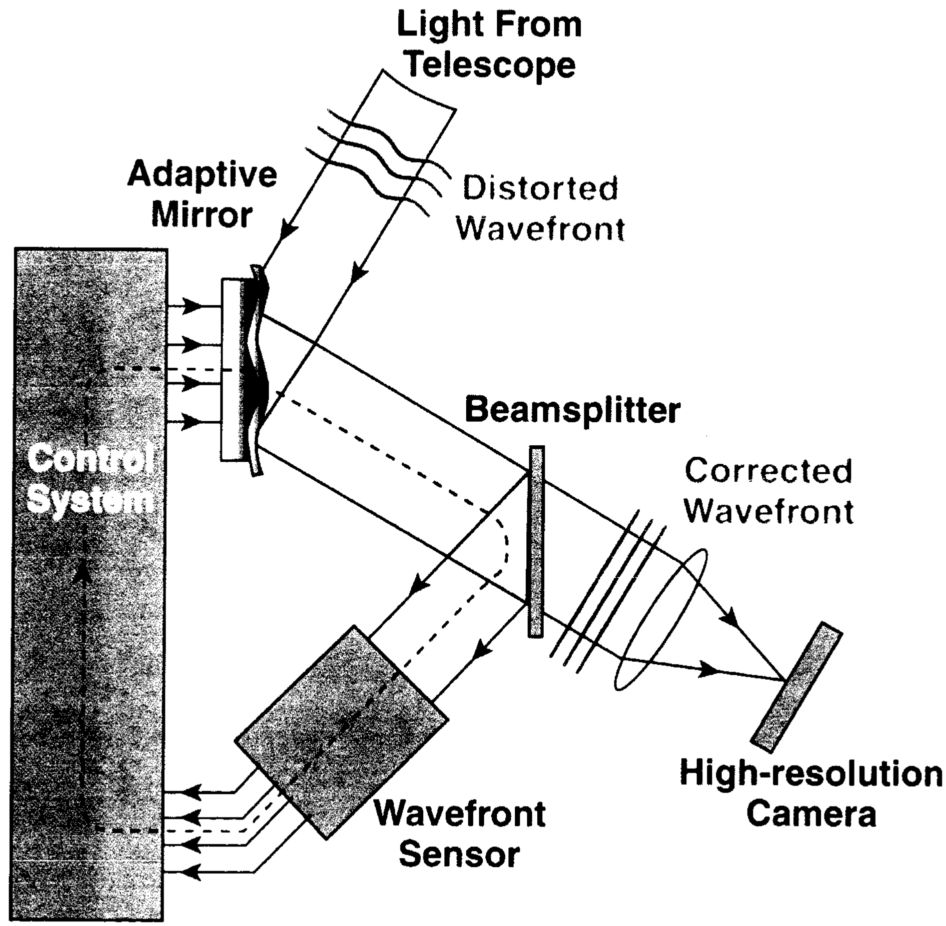
Turbulence in earth's atmosphere makes stars twinkle (creates wavefront distortions)

More importantly, wavefront errors spread out light, blurring detail. Point sources appear as blobs

(slide courtesy of Claire Max)/CfAO

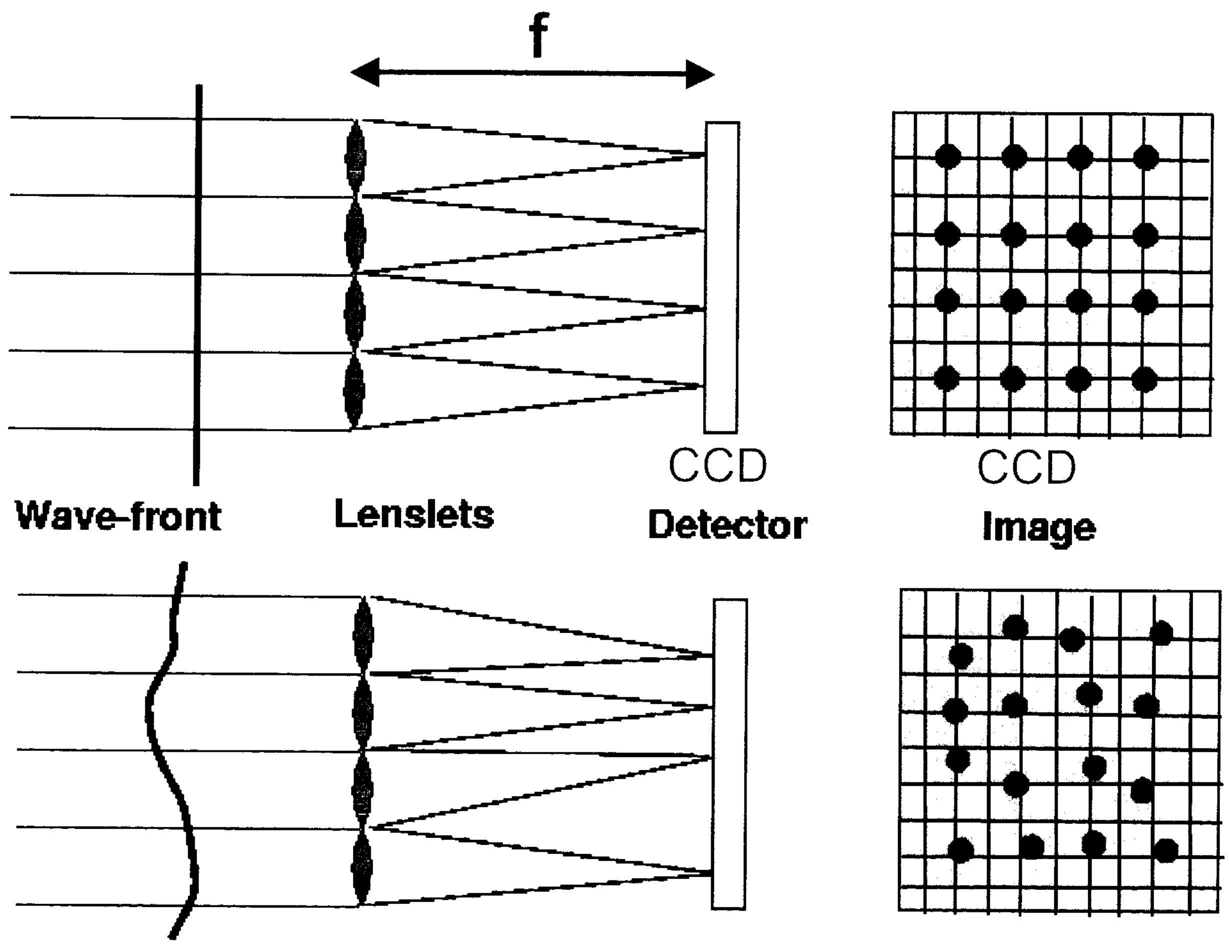
Schematic of Adaptive Optics System

Feedback loop: next cycle corrects the (small) errors of the last cycle



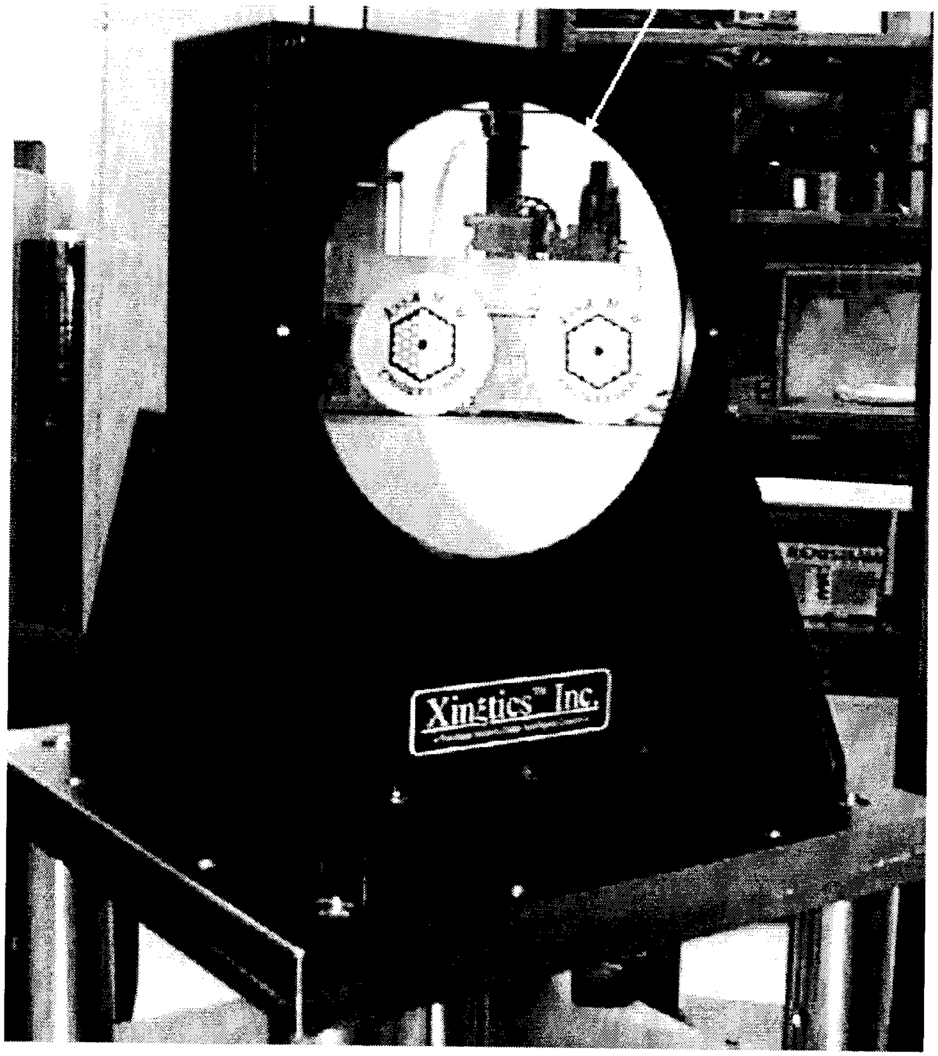
(slide courtesy of Claire Max)/CfAO

Shack-Hartmann wavefront sensor concept - measure subaperture tilts



(slide courtesy of Claire Max)/CfAO

Front View of Xinetics DM



- 349 active actuators
- 21 actuators across
- Actuator spacing 7mm
- Actuator Stroke~5 μm
- Actuator bandwidth >2KHz
- Mirror diameter 14cm

Image Without AO

"Just an uninteresting Binary system"

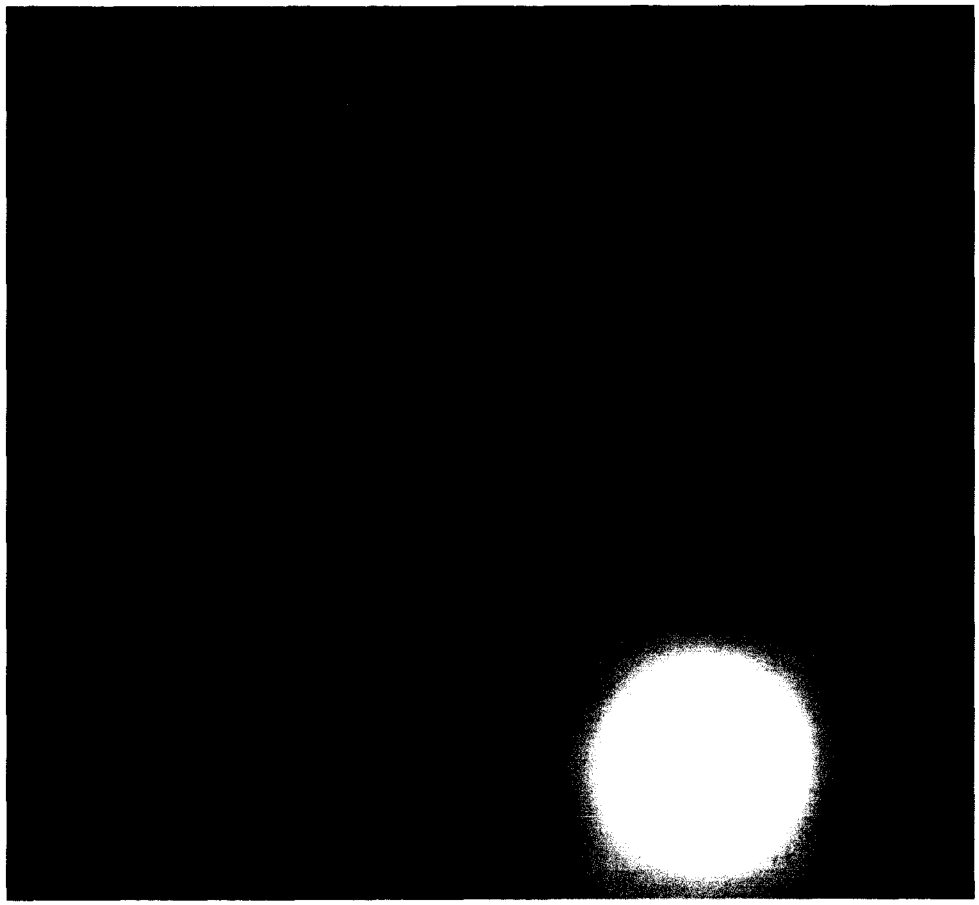
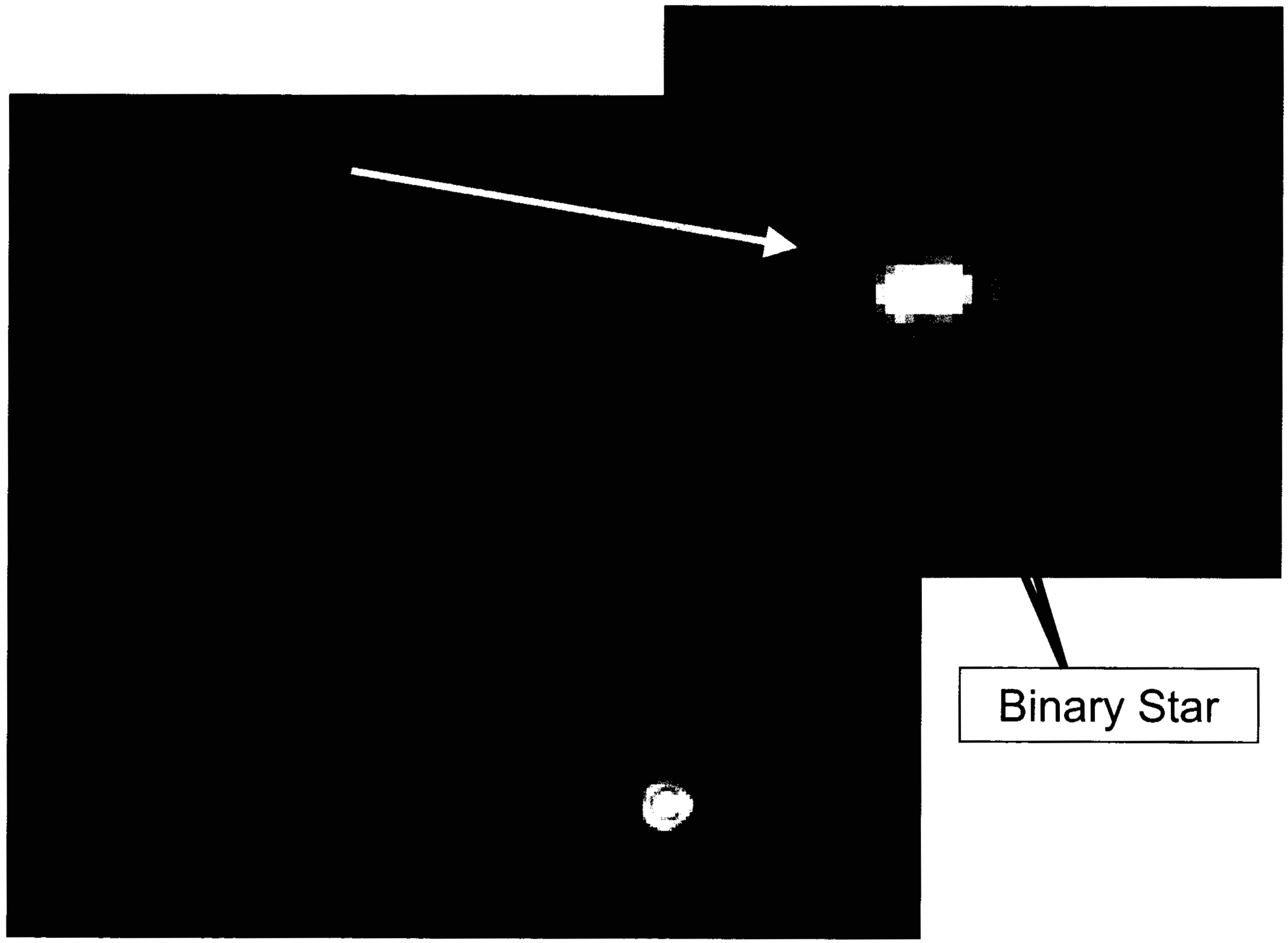


Image With AO

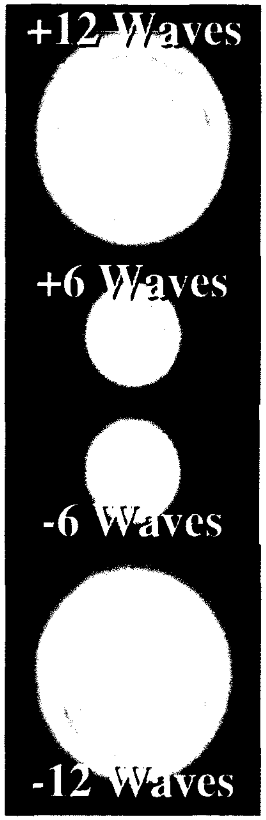
- Triple System
- Separation of B-C ~0.1 arcseconds
- Two or three Brown Dwarfs?

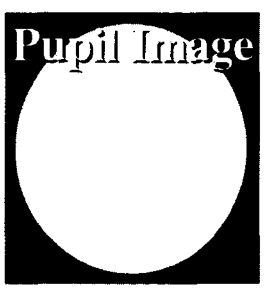


GL569, UT 28Jul02 by Burruss, Pelzer, Troy, Wallace

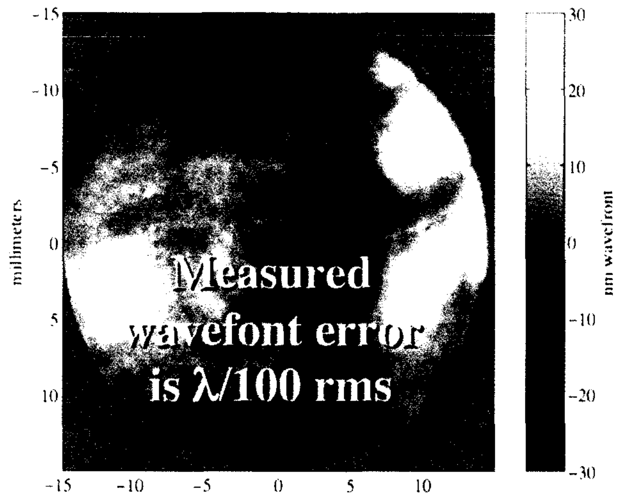
Control in Unmanned NASA Missions
Adaptive Optics and Precision Wavefront Control

Example of WFS data set

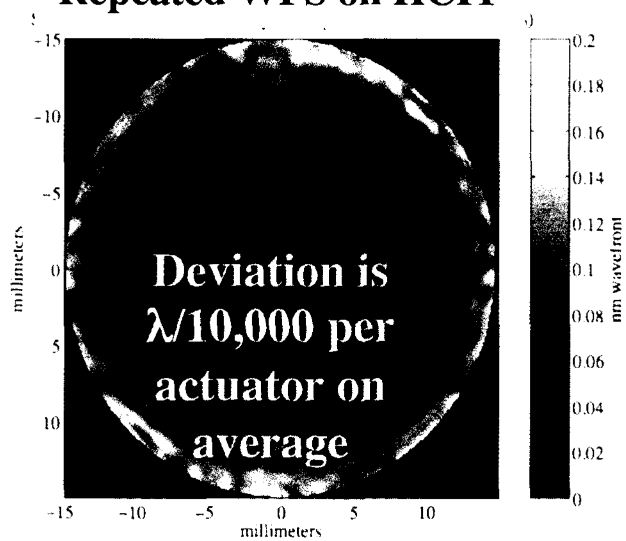




Example of Estimate Wavefront

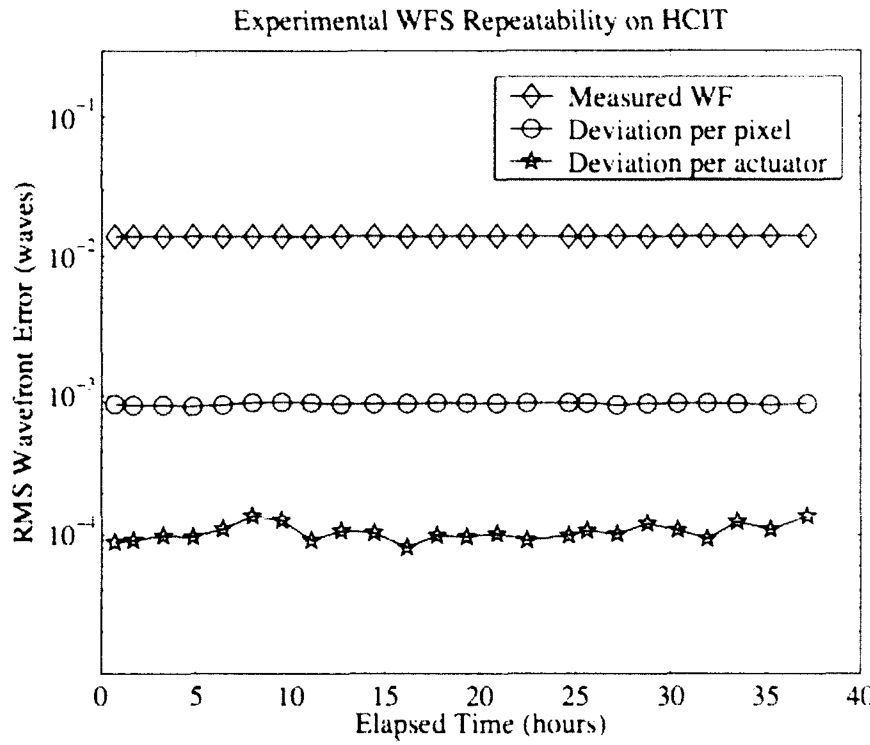


Standard Deviation of Repeated WFS on HCIT



Repeatability Wavefront Sensing on HCIT

- Collected WFS datasets repeatedly for almost 40 hours over a couple of weekdays
  - –26 runs total (24 complete datasets)
  - –Vacuum tank pumped down to 10 mTorr
  - –Pump was on during the experiment
  - –Temperature remained stable to < 25 mC
- Measured wavefront was about **λ/100 rms**
- WFS Repeatability was **λ/10,000 rms** per actuator (where the DM can affect control)

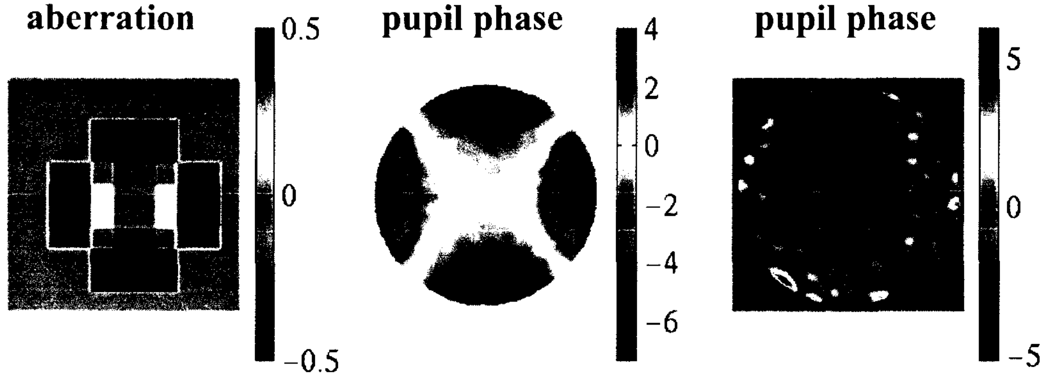


High Dynamic-Range Wavefront Sensing and Control for JWST

Our focus-diverse wavefront sensing includes phase unwrapping to ensure that unexpectedly large figure errors will not prevent accurate WFS. These 2 examples examine the response to low and mid spatial frequency errors injected into the JWST Wavefront Control Testbed system using the 80-actuator *aberrator* DM. In both examples, we corrected the sensed errors using the 349 actuator *corrector* DM.

Injected aberration	Retrieved pupil phase	Post-control pupil phase

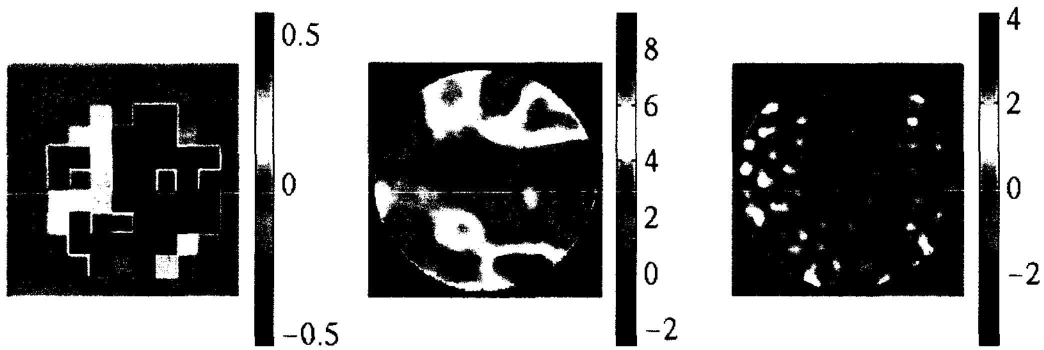
Low-order Zernike



0.97 rms, 3.16 p-v — 0.78 rms, 3.62 p-v — 0.099 rms, 1.78 p-v

- 3.6 l peak-to-valley of astigmatism was introduced using the "aberrator" DM
- 4 defocussed images were taken and processed
- Retrieved WF estimate was used to control the "corrector" DM
- Result was 8x lower RMS WFE

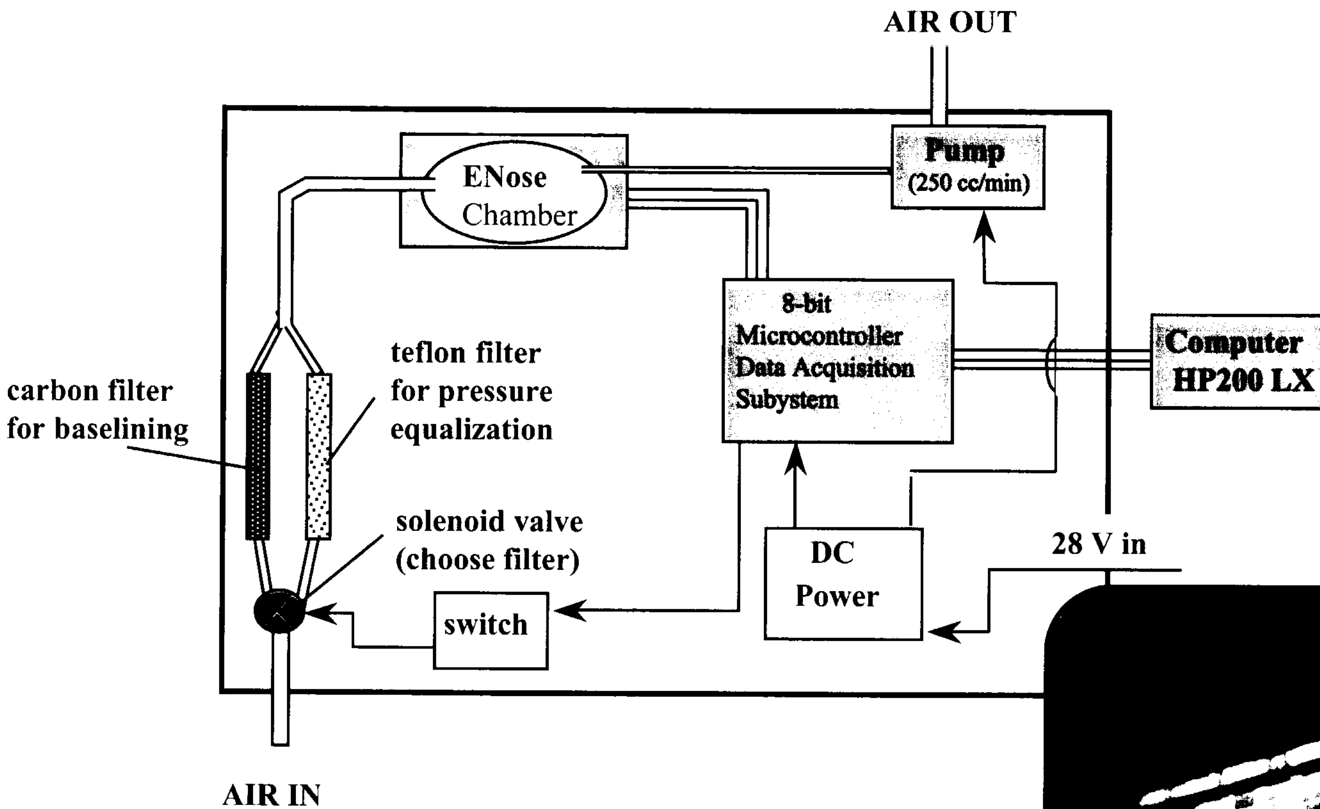
Random poke distribution

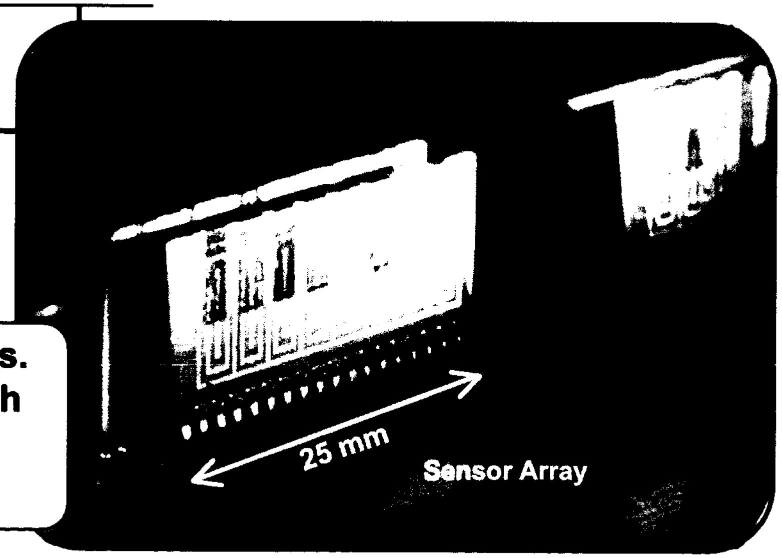


1.53 ms, 3.48 p-v — 0.62 rms, 3.78 p-v — 0.079 rms, 1.25 p-v

- 3.8 l p-v random poke pattern was applied using the "aberrator" DM
- 4 defocussed images were taken and processed
- Retrieved WF estimate was used to control the "corrector" DM
- Result was 8x lower RMS WFE

Experimental Flight Unit



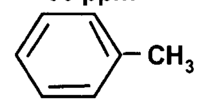


The ENose chamber contains four sensor substrates. Each sensor substrates contains 8 sensors on which polymer/carbon composite films are deposited and heaters to maintain constant sensing temperature

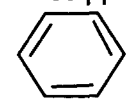
Control in Unmanned NASA Missions
Sensors for Environmental Control-ENose

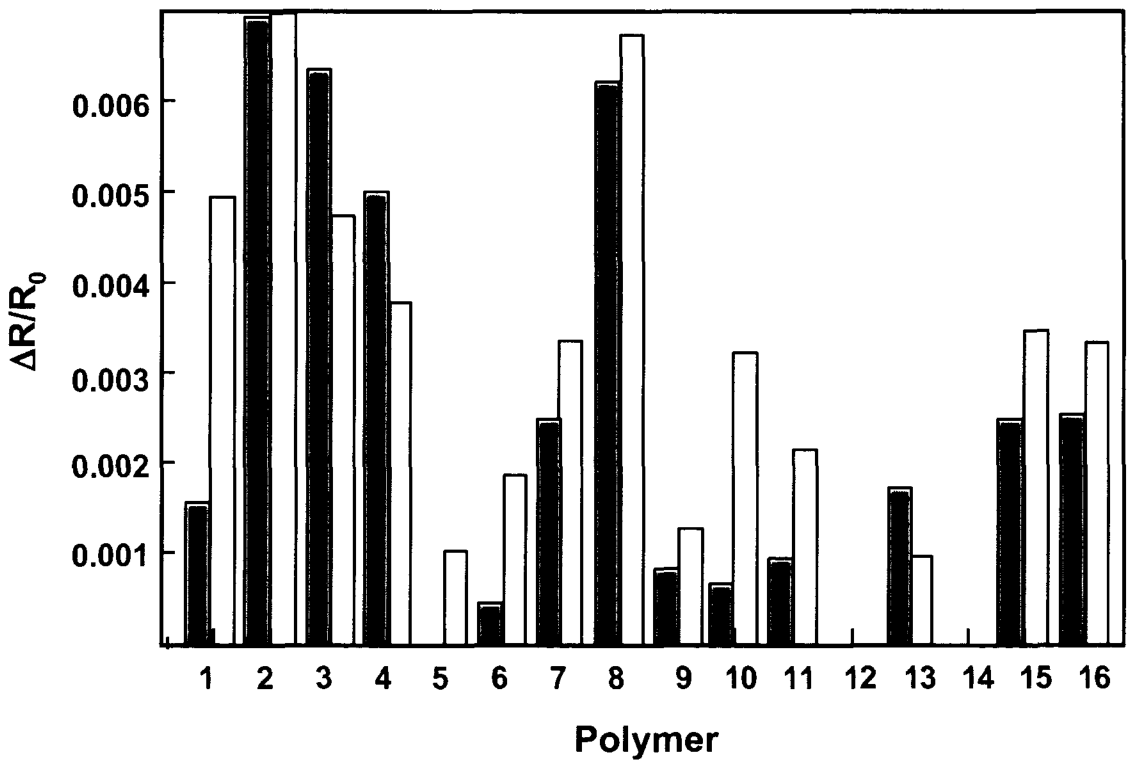
RESPONSE PATTERN OF SENSING ARRAY

toluene
50 ppm



benzene
50 ppm





1 Poly(2, 4, 6-tribromostyrene)
2 Poly(4-vinylphenol)
3 Poly(ethylene oxide)
4 Polyamide resin
5 Cellulose triacetate
6 Poly(2-hydroxyethyl methacrylate)
7 Vinyl alcohol/vinyl butyral, 20/80
8 Poly(caprolactone)
9 Poly(vinylchloride-co-vinyl acetate)
10 Poly(vinyl chloride/acetate) 90/10
11 Poly(vinyl acetate)
12 Poly(N -vinylpyrrolidone)
13 Styrene/isoprene, 14/86 ABA
14 Poly(vinyl stearate)
15 Methyl vinyl ether/ maleic acid 50/50
16 Hydroxypropyl methyl cellulose, 10/30

Similar compounds can be distinguished by their fingerprints. Benzene and toluene are both aromatic, and have similar but distinguishable response patterns.

Summary

- Significant control activity in NASA
  - Flight control R&D
  - Rover Control R&D
  - Sophisticated control for Astronomical and Astrophysical missions
- Increase in Autonomy/Automation is essential for deep space manned missions
  - Flight/Site Preparation/Maintenance
  - Life support
- Robustness is a concern
- Need to address life support system control issues