Autonomous Operations through Onboard Artificial Intelligence

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Outline

- ASE Demonstration Scenario
- Technology Overview
- Techsat-21 Mission Description
- Onboard Technology Components
  - Science
  - Planning
  - Execution
- Software Status
- Applications & Benefits
- Summary

ASE Mission Scenario

Next Repeat Track Orbit – Reimage Same Area in More Detail

New Science Images

Why fly autonomy software onboard?

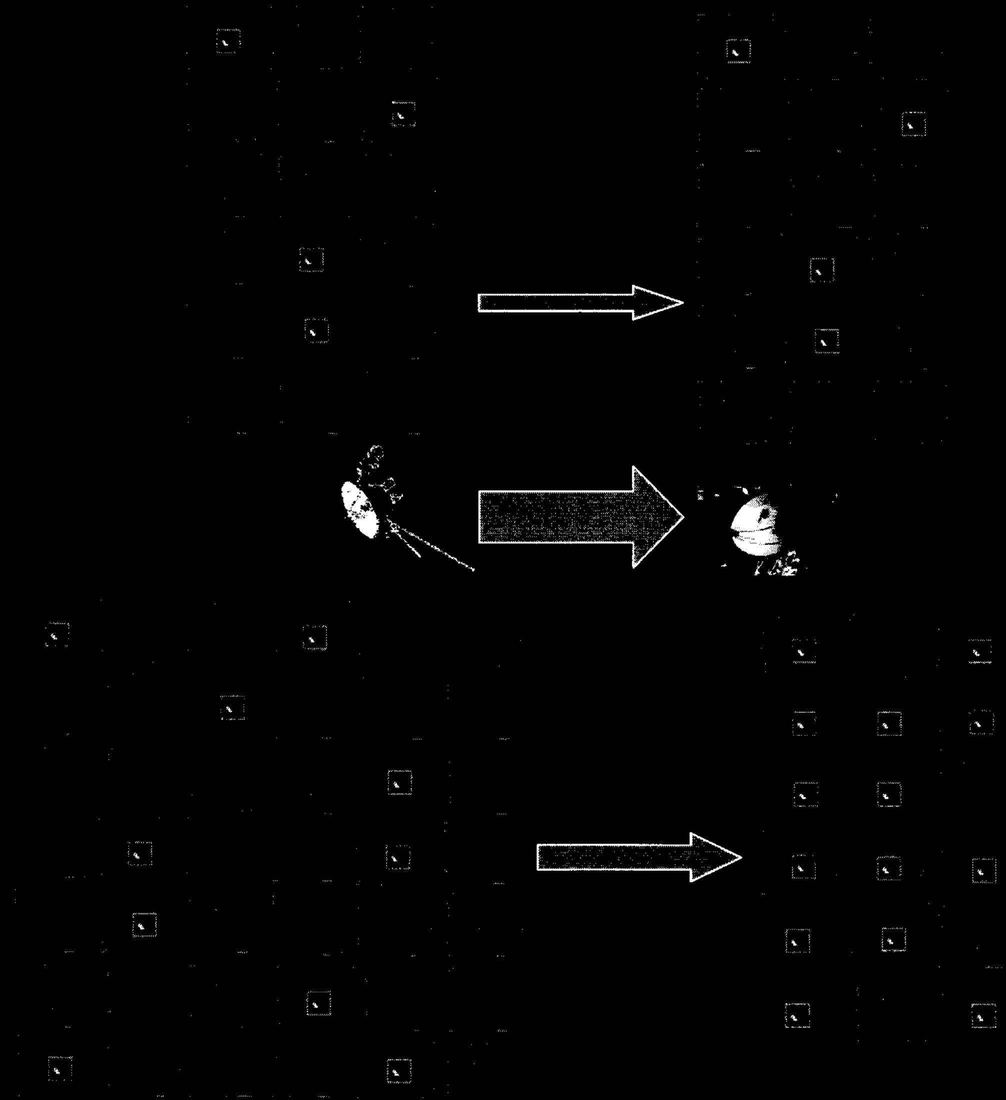
- Utilize limited downlink resource

Old Way:

- Take 200 Images
- Downlink 200 images

New Way:

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



Software Technologies

- Onboard Science (JPL)
  - Feature detection & change detection
  - Enables onboard decision-making based on science
- Onboard Planning (JPL developed CASPER)
  - Enables onboard development of new plans in response to science events
- Robust Execution (ICS developed SCL)
  - Enables robust plans to deal with run-time uncertainties

<u>Supporting Software</u>

- Onboard Orbit Determination and Prediction (JPL or ITT/GSFC)
  - Enables planning of future instrument data takes
- Onboard SAR image formation software (JPL)
  - Including image reduction code

TechSat-21 Mission

- US Air Force Technology Demonstration Mission - 3 satellite configurable constellation
- Launch: January 2006, 1 year mission, + possible 1 yr extended
- High relative and absolute positioning accuracy
- 35.4° inclination, 550 Km orbit
- ~90 minute orbit, ~13-day repeat track
- Each spacecraft has an X-band synthetic aperture radar (SAR)
- ~3 m ground processed radar resolution (range and x-range)
  - Onboard formation 10m resolution
- Backscatter of X-band wavelength can easily distinguish water vs. ice, lava vs. mud, forest, etc.

- AFRL is providing the 3 spacecraft, the control flight software, operations, and the ground systems
- JPL is providing the on-board autonomy software, ASE science

TechSat-21 Flight Environment

- General purpose flight processor PowerPC 750
  - 175 MIPS/133 MHz processor developed by BAE
  - 128 MB RAM
  - Access to non-volatile memory only every 8 hours
  - Basic flight software estimated to use 10% of CPU
  - Runs OSE Operating System (by Enea)
    - RTOS used by many cell phones

TechSat 21 Flight Experiment

Program Objectives

Fly in formation

Merge sensor data from 3 sats

Assess future mission utility

Experiment Objectives

Reconfigure formations: linear, circular, other

Know relative position to 10m, then to 1cm

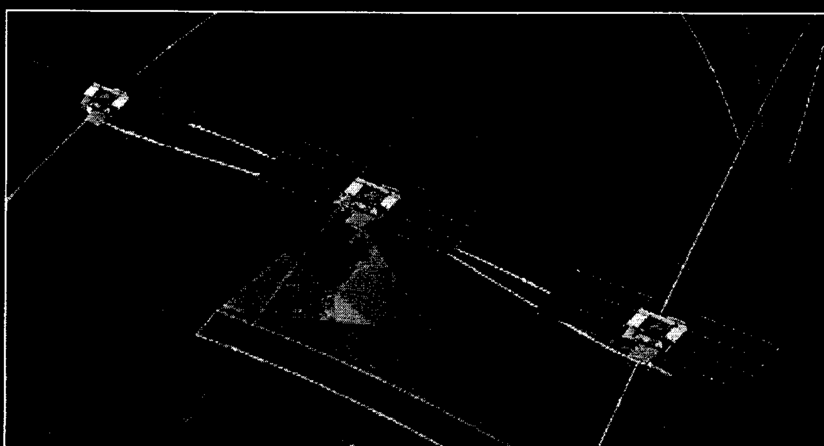
Monitor command scripts then full satellite autonomy

Evaluate new algorithms for different sensor modes

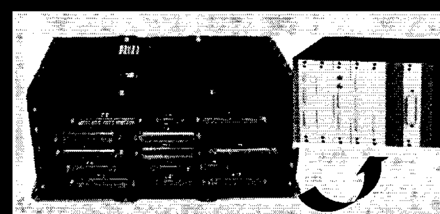
Involve Users to generate high value experiments

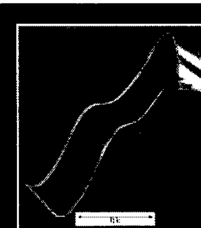
Experiment Configuration

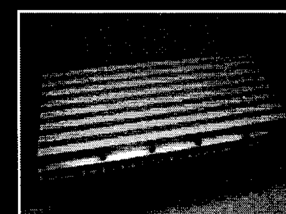
Three independent, LEO microsats with coherent X-band RF payloads (150 kg each, 2.0 m^2 ESA antenna)

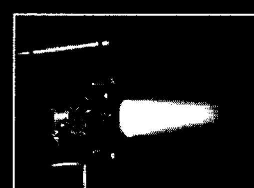


Advanced Spacecraft Subsystems


3U Compact PCI Avionics

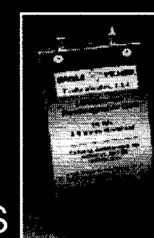

Thin Film Solar Array


Phased Array Antennas


Hall Effect Microthruster


160 GByte Mass Memory


Carrier Phase Differential GPS


Li-Polymer Battery

ASE Mission Plan

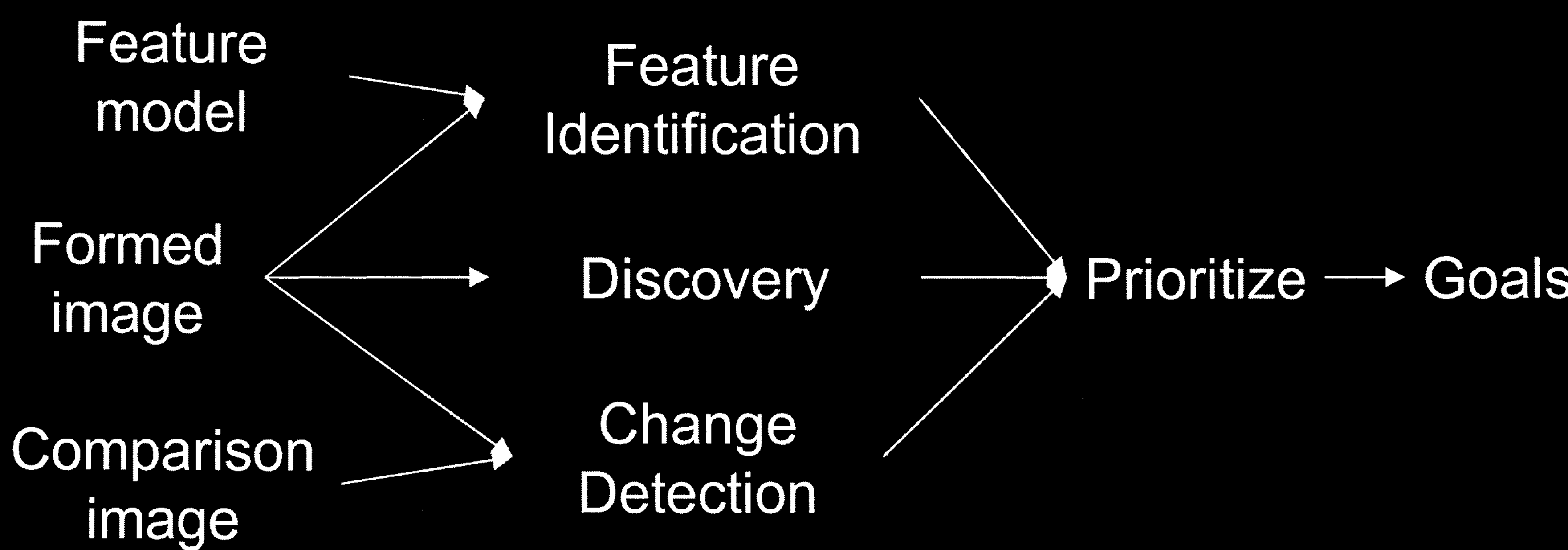
January 2006	TS-21 Launch
L+ 5 weeks	SCL active
L + 7 weeks	CM & Formation flying demonstrated
Months 2-3	ASC operates in passive mode; commands logged but not issued to SV
Month 3	Data scored by ASE; all data downlinked
Month 4	Onboard Data prioritization using ASE
Months 5-6	Demonstrate retargeting using electronically steerable instrument; demonstrate autonomous downlink;
Months 7+	Demonstrate retargeting including slews (full ASE)

* - all onboard replanning may be ground validated but not ground modified

Technology Components: Onboard Science

- Onboard Image Formation software
- Onboard Science Components
  - Change recognition software
  - Feature recognition software (looking for specific patterns)
  - Discovery software (generalized recognition algorithm)
- Feature Identification, Change Detection, and Discovery capabilities are valid for multiple features and processes: we are not limited to specific types of science targets
- The science analysis algorithms can be used for any image dataset (not just radar)

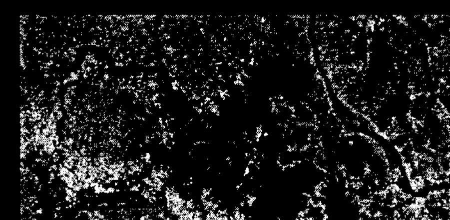
Science Processing Algorithms



Change Detection

- Purpose:
  - Determine areas of change in image
- Products
  - Downlink whole image on change (300 KB)
  - Downlink changed portion only
  - Downlink summary of changes (new boundary line segments)
  - Downlink rate of change of area only
- Resulting goals
  - Additional data take of same target area
  - New data take at related location (e.g. downstream for a flood)
- Targets – lakes freezing, flooding, aeolian processes, lava flows

Lava flows
Kilauea, HI



Flooding

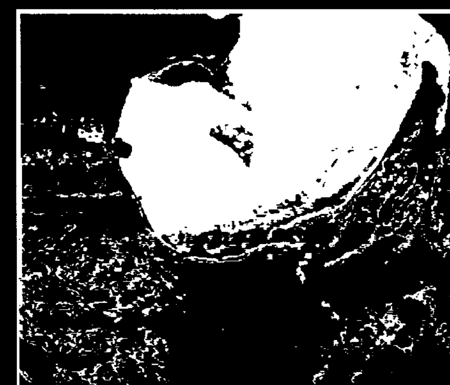
Change Detection Example:

Ice melt

Aksai Chin Lake
Kashmir
X-SAR images

Apr. 94 Lake iced over

Oct. 94 Ice melted



Changed Area is White

Change Detection: Compression Rate

- Example 1:“open water” calculation

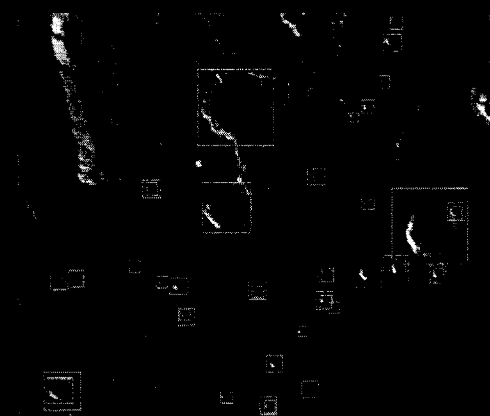
		File size	compression
– total image area	2.4×10^8 m^2	1.9 GB	
– area of interest (lake area)	1×10^8 m^2	800 MB	2.3
– flow segmented boundary file		20 KB	95K
– dA/dt		5 KB	380K

- Example 2: “lahar” (mud) emplacement calculation

		File size	compression
– total image area	9×10^7 m^2	240 MB	
– area of interest (lahar area)	6×10^5 m^2	1.6 MB	150
– area of change boundary file		60 KB	4K
– dA/dt		10 KB	24K

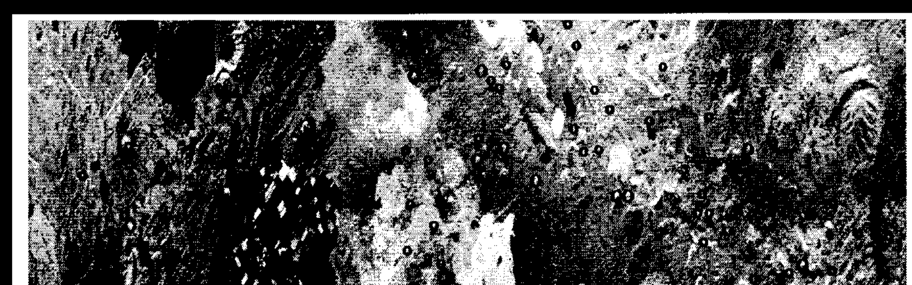
Feature Identification

- Purpose:
  - Identify occurrences of predefined interesting features
- Products
  - Downlink whole image on detect
  - Downlink portion around selected features
    Downlink summary of features detected
- Targets
  - Cinder cones
  - Impact craters
  - Volcanic craters
  - Sand dunes



Mars MOC: crater identification

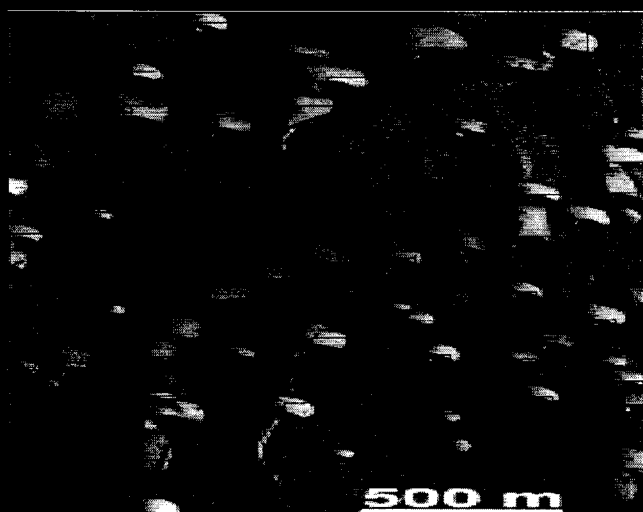
Lava Beds Nat'l Monument

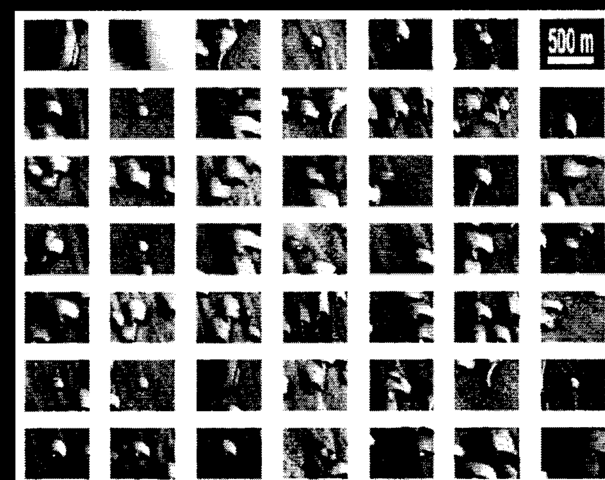


Circles indicate identified lava cones
Blue circles indicate highest confidence matches

Discovery Algorithm

- Purpose
  - Identify regions of an image that differ significantly from the local background
- Products
  - Downlink whole image on significant outlier
  - Downlink portion around marked points
  - Downlink count of marked points





Mars Global Surveyor Image

Note: visible data

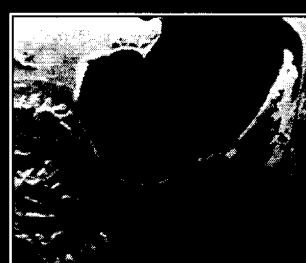
ASE Science

- Utilize onboard science analysis to summarize, retarget, or rapidly respond to science events to increase science return
- Select targets/phenomena that:
    - Have extraterrestrial analogues
    - Are suitable for TS-21 instrument and mission parameters
    - Are suitable for existing science analysis algorithms
        - Change Detection
        - Feature Identification
        - Discovery

ASE Science Targets

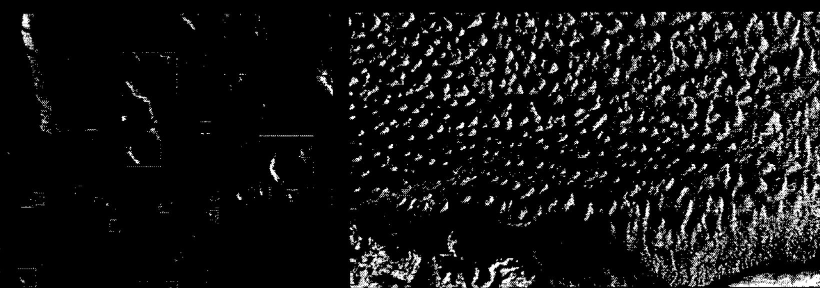
Autonomous Change Detection

- Primary targets
  - Ice formation/retreat
- Secondary targets
  - Flooding
  - Volcanic processes
    - Lahar emplacement
    - Lava flow emplacement
    - Topographic change



Autonomous Feature Identification

- Primary targets
  - Volcanic cinder cones and craters
  - Impact craters
- Secondary targets
  - Sand dunes



Discovery

- Primary targets
  - Will run on all observations

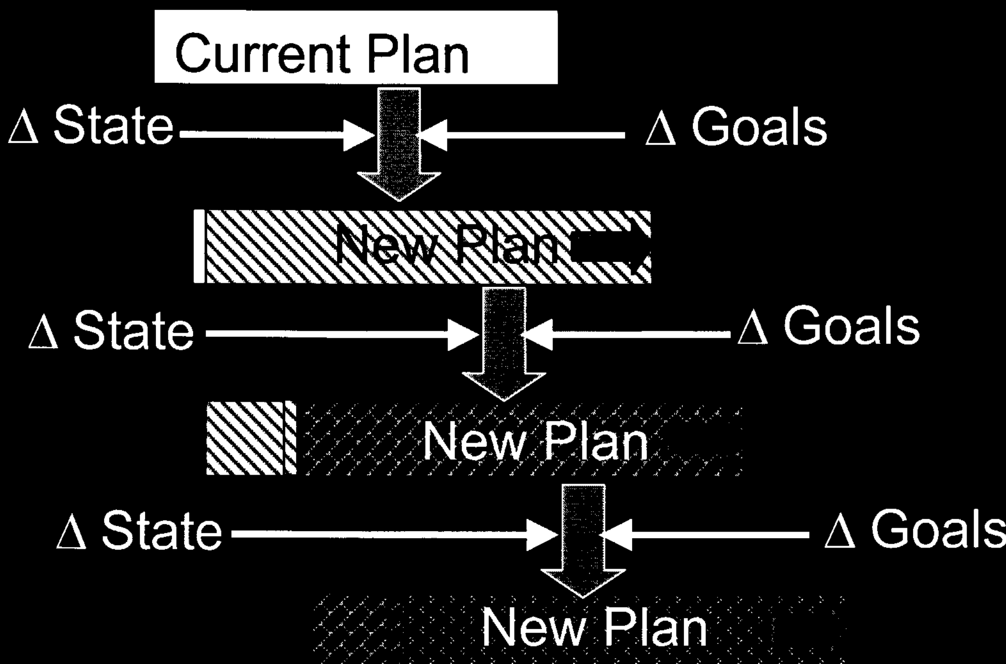
Technology Component: Onboard Replanning

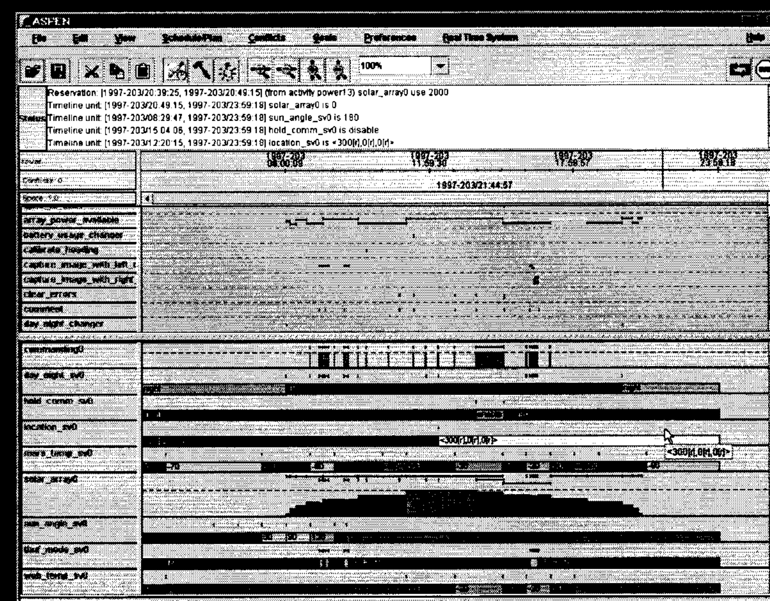
- CASPER use a model of spacecraft activities to construct a mission plan to achieve mission goals while respecting spacecraft operations constraints
  - Example goals: science requests, downlink requests, maneuver requests
  - Example constraints: memory, power, propellant, etc.

- TS-21 will utilize the CASPER continuous planning system onboard to replan to achieve newly derived science goals

Onboard Replanning

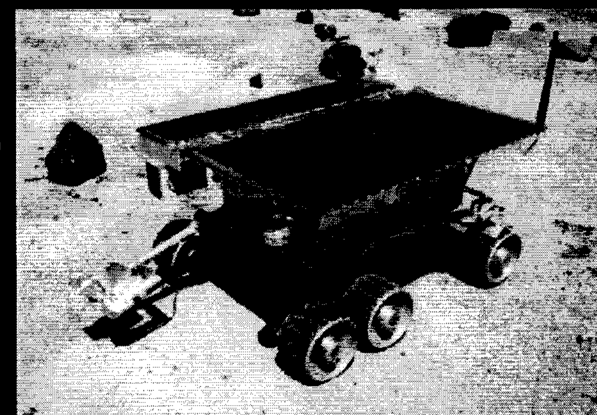
- CASPER uses continuous planning techniques to achieve a quick response time





Other CASPER Deployments

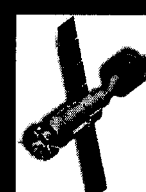
- Also being applied to
  - Autonomous rover control (Rocky7, Rocky8)
  - Ground communications station control (CLEaR)
- Also being used as single agent in Teamwork/Coordination (rover & spacecraft)
- Three Corner Sat Mission
  - August 2003 Launch



Technology Component: Robust Execution

- Uses Spacecraft Command Language (SCL) developed by Interface and Control Systems
- SCL integrates procedural programming with a forward-chaining, rule-based system for event-driven real-time processing
- In the ASC concept, SCL scripts will also be planned and scheduled by the CASPER onboard planner
- SCL is a mature software product used on many mission including several flights: Clementine I, ROMPS, DATA-CHASER, ICM for ISS, FUSE,…
- SCL to also be used in ground control of TS-21






SCL Usage on ASE

- SCL performs the executive functions of the ASE
  - Stored command sequences (time-based and event-driven)
  - Telemetry monitoring
  - Fault management & Command verification

- All ASE commands to the TechSat 21 Flight Software are issued through SCL Scripts and Rules
  - ASE requests the execution of specific scripts to provide commanding services, along with command sequencing and verification.
  - ASE can inject data into the SCL database which can cause SCL Rules to fire which in turn can execute scripts that provide commanding services.

- SCL Rules will be used on TechSat 21 to provide fault monitoring functions for the ASE.
  - For example, rules will be in place to monitor the temperature of the Mass Storage Module to ensure that operating limits are not exceeded.

Software Status

- Build 1 (August 2001)
  - Complete Integrated CASPER, Science on Workstation (Solaris) with SCL on PPC
- Build 2 (June 2002)
  - Integrate CASPER, Science, SCL on PPC
  - Missing Image Formation (August 2002)
  - Missing TechSat-21 FSW (October 2002)
  - Single Spacecraft
- Build 3 (Dec. 2003)
  - Include TS-21 FSW, image formation, higher fidelity sims, multi-spacecraft
  - Update models
- Build 4 (Dec. 2004)
  - Bug fixes
  - Used for ground element of technology validation

Applications: Io Volcano Observer

Benefits to NASA

NASA has called for autonomous capabilities

- Increase science return per returned bit
  - Makes best use of restricted downlink to maximize science return of the mission
  - Identifies at low resolution areas of interest for high-resolution investigation
- Allows discarding of redundant data
  - "no change - no gain"
- Faster reaction times
  - Overcomes communication delays as decision making process is onboard, so…
  - … there is rapid reaction to transient events, possibly of great scientific value due to their rarity or brevity

Future Missions Requiring Autonomy

	Mission	Time frame
EO	Europa Orbiter	Near term?
PE	Pluto Express	Near term?
NO	Neptune Orbiter	Mid-term
SRO	Saturn Ring Observer	Mid-term
GEC	Geospace Electrodynamic Connections	Near-term
IS	Interstellar Probe	Mid-term
MC	Magnetospheric Constellation	Mid-term
MMS	Magnetospheric Multiscale	Mid-term
RAMP	Reconnection and Multiscale Probe	Mid-term
RBM	Radiation Belt Mappers	Far-term
PASO	Particle Acceleration Solar Orbiter	Far-term
SN	Sentinels	Far-term
ARISE	Advanced Radio Interferometry, Space-Earth	Mid-term
CON-X	Constellation-X	Mid-term
OWL	Orbiting Array of Wide-angle Light Collectors	Mid-term

Summary

- Using on-board software for planning, science data analysis, execution, fault detection, and cluster management will increase mission value by:
  - Returning only the most important science data
  - Returning 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

Upcoming missions will benefit from TS-21's demonstration of integrated onboard autonomy

Information/Acknowledgements

- Web Site:

- Funding:
  - New Millennium Program ST-6 Project
  - TMOD Technology Program
  - Cross-Enterprise Technology Development Program