Earth Science Enterprise Technology Planning Workshop

Intelligent Distributed Spacecraft Infrastructure

Mark Schoeberl (Co-Chair) - GSFC
John Bristow (Co-Chair) - GSFC
Carol Raymond (Facilitator) - JPL

23-24 January 2001

Earth Science Enterprise Technology Planning Workshop

Intelligent Distributed-Spacecraft Infrastructure

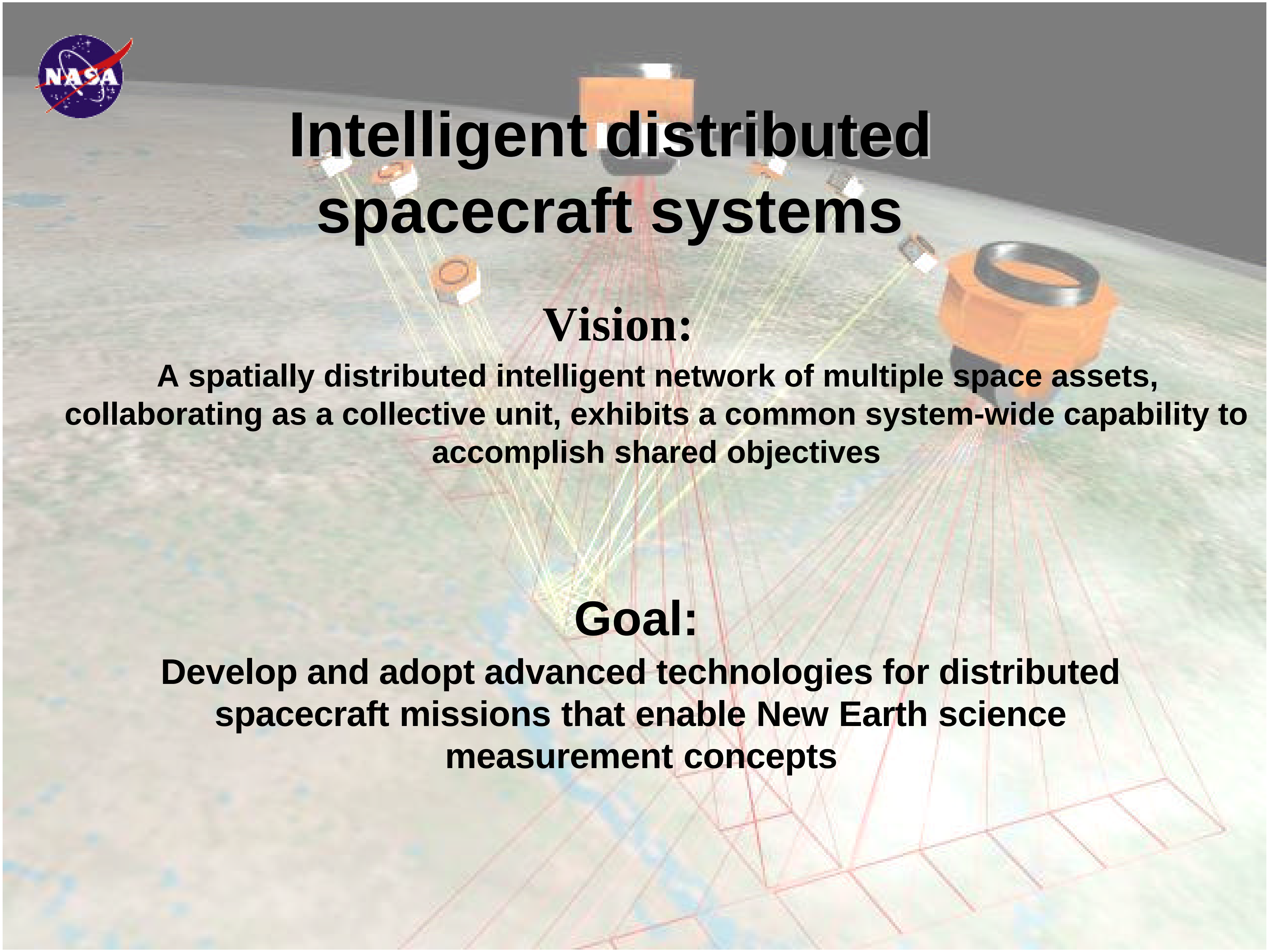
Agenda

Topic	Presenter
Small Satellite Challenges/Sensorweb	M. Schoeberl - GSFC
Miniature GPS-based multi-function Instrument for Autonomy of Spacecraft Constellations Sounding	T. Yunck - JPL
Leonardo	W. Wiscombe - GSFC
Global Precipitation Mission	D. Folta - GSFC
Tandem/multi Synthetic Aperture Radar	S. Madsen - JPL
Control Architechture	R. Carpenter - GSFC
Control of Distributed Spacecraft	J. How- MIT
Remote Agent	R. Washington-ARC
Model for Planning and Scheduling Observations for Many Satellites Simultaneously	R. Morris - ARC
Constellation Operations	A. Barrett - JPL
Formation Planning, Control, and Reconfiguration Algorithms	M. Campbell - U.Wash
Agent-based Autonomy	
GPS/Formation Flying	Srinivasan - JPL
Communications	P. Stadter - JHU/APL
Airborne testbed	T. Balch- CMU
TechSat 21 Fm. Control	J. Tierno- Honeywell

Participants

Chandra Mirchanani	LM/GSFC
John Bristow	GSFC
David Folta	GSFC
David Breskman	Lockheed
Jonathan How	MIT
Brian Williams	MIT
Chris Kucera	Booze Allen&Hamilton
James Paul	House SC
George Davis	Commerce One
Derek Surka	Princeton Satellite
Jorge Tierno	Honeywell
Ed Howard	NOAA
Tucker Balch	CMU
John Carl Adams	Lockheed
Michael Huhns	U of SC
Costas Tsatsoulis	U of KS
Jon Agre	JPL
Soren Madsen	JPL

Victor Lesser	U of MA
Les Gasser	U of IL
Mark Campbell	U of WA
Pete Klupor	AFRLVS
Tony Barrett	JPL
Reid Simmons	CMU
Rich Washington	AMES
Andrew Howard	USC
Daniel S. Katz	JPL
Stephen J. Talabac	Commerce One
Patrick A. Stadter	JHU/APL
Wayne Devereux	Veridian Eng.
Kurt R. Smith	GSFC/ESTO
Sam Hollander	NRL
Joan Dunham	CSC/GSFC
Robert Morris	NASA/Ames
Tom Yunck	JPL
Robert B. Lee III	LaRC



Intelligent distributed spacecraft systems

Vision:

A spatially distributed intelligent network of multiple space assets, collaborating as a collective unit, exhibits a common system-wide capability to accomplish shared objectives

Goal:

Develop and adopt advanced technologies for distributed spacecraft missions that enable New Earth science measurement concepts

Intelligent Distributed Spacecraft Infrastructure

Component Technologies

Communications

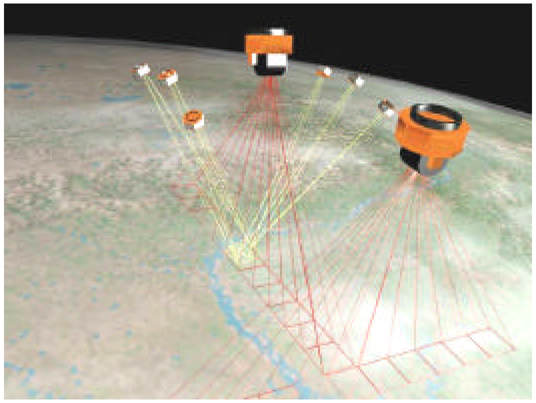
- Acquisition, tracking and pointing algorithms
- Protocols, networking
- Ranging
- Command & control
- Data handling & processing

Micro/Nano Spacecraft

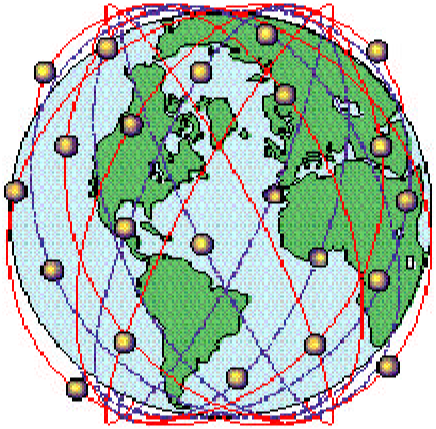
- Advanced solar arrays/batteries
- Micro star trackers
- Micropropulsion
- Mission design/testing tools

Autonomy

- High level planning & scheduling
- Fault Diagnosis and Recovery
- Command & control
- Low level navigation & pointing
- Instrument control
- Science data processing
- Distributed control
  - Relative navigation
  - Collision avoidance
  - Collective pointing
  - Collective Planning



Leonardo, an advanced concept using a virtual platform approach to measure the bi-directional reflectance distribution function



ATOMS, a constellation to measure atmospheric temperature and tropospheric water vaopr using GPS sounding and microwave crosslinks

Measurement Approach

- Synthetic Aperture Radar
- Multi-angle radiometry
- GPS Sounding
- Hyperspectral Imaging
- Solar Occultation
- Microwave crosslinks

Science Needs

High Spatial Resolution:

- Land Imaging
- Multiple-Angle Viewing
- Surface Hydrology & Precipitation
- Ocean Salinity
- Vegetation Recovery
- Atmospheric Chemistry
- Surface Deformation
- Tropospheric water vapor
- Event-driven data collection

Summary of Capability Needs

Identified two major classes of distributed spacecraft science missions:

- “Accretionary” formations
  - Opportunistic, passive trains (at present)
  - Require modular, open architecture to allow flexibility in adding and replacing formation components
- Deliberate multi-spacecraft architecture
  - Exhibit many formation control needs
    - Loose (GPM)
    - Virtual platform (Leonardo)
    - Precision formation flying (SAR/GRACE)
  - Swarms
    - Radio Occultation
    - Magnetic fields

Identified some future science goals:

- Multi- or tandem-spacecraft Synthetic Aperture Radar
- Virtual Platform for radiative flux (Leonardo)
- Loose clusters for coverage (GPM)
- Radio Occultation GPS constellation for atmospheric temperature and moisture (ATOMS)
- Dedicated swarms for high temporal resolution measurements

Summary- Notional Missions

Tandem SAR:	2-5 spacecraft (homogeneous) 100 kg class baseline tolerance to 10-50m relative pointing 0.02° (X-band) 0.2° (L-band) position 0.1-1m
Radio Occultation GPS:	6-100 spacecraft (homogeneous) 30 kg class
Leonardo:	6-12 spacecraft (heterogeneous) 30-100 kg class pointing control/knowledge to 0.5°/0.1°
Global Precipitation:	3-9 spacecraft (formation) 1 spacecraft (core) 50 kg/150 kg

Requirements for Intelligent Distributed Spacecraft Infrastructure

Science and measurement requirements:

- **High Spatial/Temporal Resolution:**
  - Hyperspectral Land Imaging
  - Severe Storm Prediction
  - Surface Hydrology & Precipitation
  - Tectonic Hazard Prediction
  - Ozone Monitoring
  - Atmospheric water vapor
- **Multiple Angle Viewing**
  - Bidirectional Reflectance Distribution Function (BRDF)
  - Vector surface deformation (hazard prediction)

Relevance to Future ESE Mission

- Global Precipitation Mission
- Leonardo (BRDF measurement concept)
- Soil Moisture and Ocean Salinity
- Time-Dependent Gravity Field Mapping
- Vegetation Recovery
- Topography and Surface Deformation
- GPS Atmospheric Sounding Constellation
- Sensorweb Vision

Description of Technology

Autonomy

- Planning & Scheduling
- Navigation & Pointing
- Intelligent Execution
- Reconfiguration and control

Sensor Webs

- Science event alert
- Collective Pointing

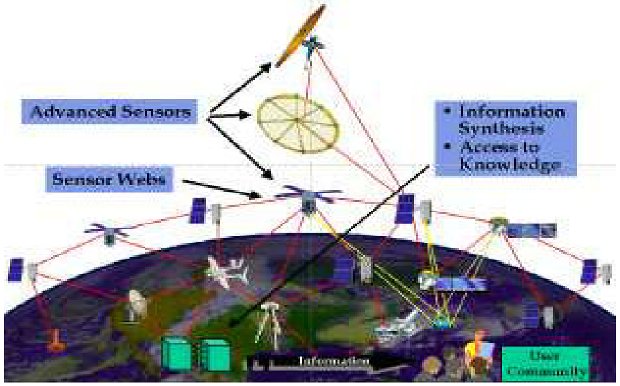
Communications

- Ad hoc networking
- Protocols
- Commanding & data handling

•Micro/Nano Spacecraft

- Micro star trackers
- Advanced power systems
- Multi-frequency crosslinks

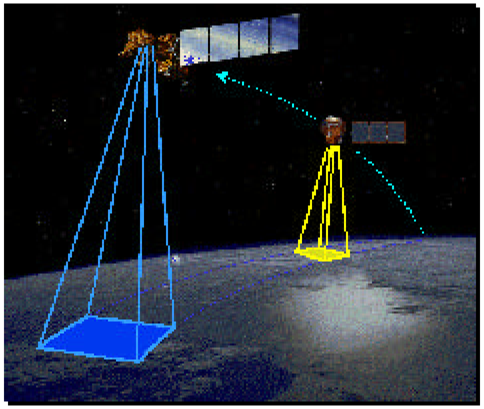
Illustration of Technology

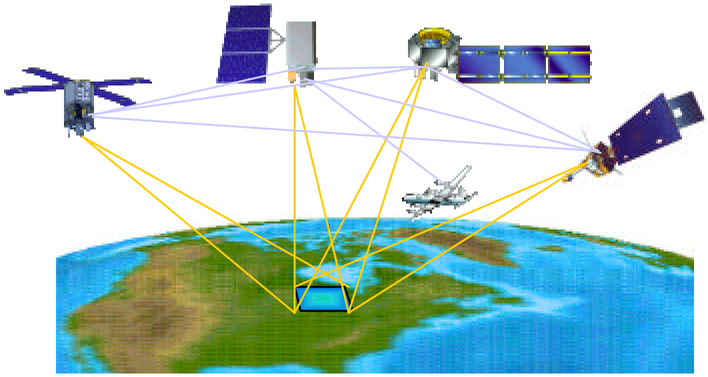


Distributed Spacecraft & Sensor Webs

State of the Art for Intelligent Distributed Spacecraft Infrastructure (Autonomy)

State of the art for the Technology





Major Technology Elements and Current TRL

- Component Autonomy
  - Deployment
  - Maneuver Planning & Execution (5)
  - Planing and Scheduling (5)
  - Fault Detection and Isolation (5)
  - Spacecraft Pointing
  - Safehold

Technology Development

- Capability Needs
  - Develop high level autonomy that enables multiple spacecraft missions in cost and capability
  - Collective planning and scheduling
  - Ad hoc networking of satellites
  - Collective pointing
  - Relative navigation with collision avoidance
  - Collective fault detection isolation and recovery

State of the Art for Intelligent Distributed Spacecraft Infrastructure (Microspacecraft)

Nanosats <25 kg
25 kg< Microsats <100 kg (50 watts)

Major Technology Elements and Current TRL

- Autonomous Formation Flying for constellation autonomy -TRL 5
- Multifunctional Structures
- Miniature low-power X-band transponder
- Autonomous ground operations
- MEMS attitude adjustment
- Li-Ion batteries
- Low impulse bit thrusters

Technology Development

- Passive or cell phone communication
- Strongly integrated technology
- Master/Slave control
- Micro star trackers
- Micro reaction wheels
- Micro propulsion
- Advanced solar arrays
- High density energy storage

Validation Plans for Intelligent Distributed Spacecraft Infrastructure

Flight Validation Rationale

- Major Implementation Shift
  - New spacecraft commanding paradigm
  - Build confidence and provide path to spacecraft fleets
- Validation of the most critical subsystem is possible only from space:
  - Behavior
  - Collective operation of independent spacecraft
  - Effects of orbital dynamics on formation control and collective operation
  - Virtual platform demonstration

Top-Level Development and Flight Schedule

- Automated subsystems
  - Flight validation in 2004/05
- Fully integrated autonomy in flight software
  - Flight validation in 2006
- Ready for science mission launch in 2009

Expected benefits

- Enables new science
  - Supports simultaneous multiple-angle viewing
  - Enables co-observing
  - Detect and characterize events that occur on Earth and its surrounding atmosphere
  - Manage ground contacts of multiple close spacecraft
- Benefits Operations
  - Reduces Mission Costs
  - Supports lights out autonomy
  - Enables “fire and forget” scenarios
  - Uniform and consistent commanding interface
  - Easier verification of command sequences
  - Eliminates most upload errors
  - Enables executing complex multiple spacecraft mission sequences with less skilled ground-based operators

Accommodation Requirements

- Processing power
- Memory

Validation Plans for Intelligent Distributed Spacecraft Infrastructure (Micro/Nanospacecraft)

Description/Justification of Flight Validation

- 2 spacecraft cooperating (or 1 s/c in preplanned and duplexed operations with existing spacecraft)
  - Active and passive communications
  - Cooperative pointing
  - Adaptive reconfiguration
  - Crosslinks

- Major Implementation Shift
  - New manufacturing paradigm

- Validation of the system-level interactions is possible only from space:
  - Pointing
  - Slave operation of dependent spacecraft
  - Effects of orbital dynamics on formation control and collective operation
  - Virtual platform demonstration

Accommodation Requirements

- Means to measure pointing accuracy and orbit control
- Possible cooperating non-NMP spacecraft

Expected Benefits

- Low-cost reliable platforms for multi-spacecraft architectures
- Validation of manufacturing and testing paradigms
- Performance model of position, attitude and pointing knowledge and control of cooperating, and/or hierarchical constellation

Top-Level Development and Flight Schedule

- Refine needs of flight validation 2002-2003
  - Choose validation flight experiment

- Identify partners to leverage existing spacecraft as cooperating members

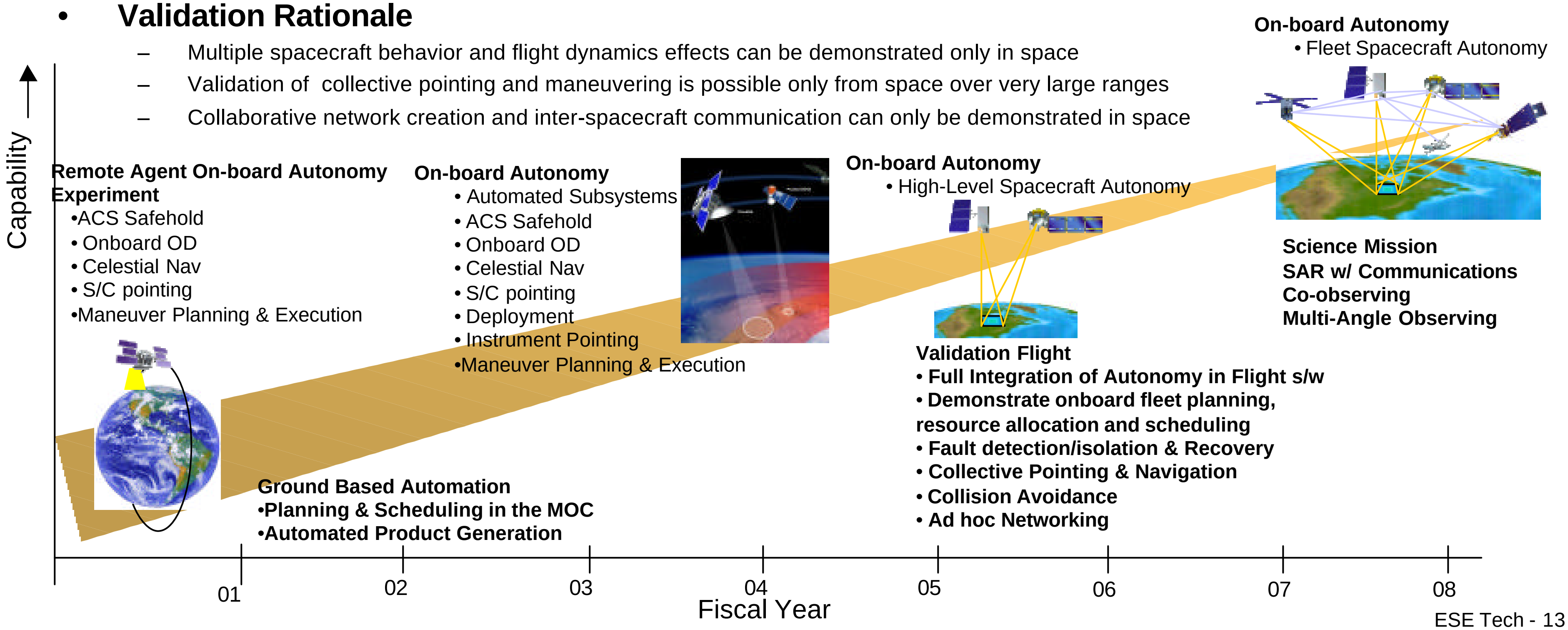
- NMP flight validation in 2006

- Support science mission in 2009

Autonomy Roadmap for Intelligent Distributed Spacecraft Infrastructure

Concept: Distributed Network of Intelligent Satellites Operating Collectively

- **Science Driver: Enables High Spatial-Temporal Resolution Data Collection**
  - Characterizing and Understanding Complex Dynamic Processes
  - Event Driven Science Data Collection
- **Technology Drivers**
  - Fleet Autonomy
  - Ad Hoc On-Orbit Networking
  - Reduced Weight, Volume and Cost
  - Increased Reliability
  - Upgrading Instruments by Replacing Elements of Fleet
  - Event Alert Capability
- **Validation Rationale**
  - Multiple spacecraft behavior and flight dynamics effects can be demonstrated only in space
  - Validation of collective pointing and maneuvering is possible only from space over very large ranges
  - Collaborative network creation and inter-spacecraft communication can only be demonstrated in space



Remote Agent On-board Autonomy Experiment
- ACS Safehold
- Onboard OD
- Celestial Nav
- S/C pointing
- Maneuver Planning & Execution

Ground Based Automation
- **Planning & Scheduling in the MOC**
- **Automated Product Generation**

On-board Autonomy
- Automated Subsystems
- ACS Safehold
- Onboard OD
- Celestial Nav
- S/C pointing
- Deployment
- Instrument Pointing
- Maneuver Planning & Execution

On-board Autonomy
- High-Level Spacecraft Autonomy

Validation Flight
- **Full Integration of Autonomy in Flight s/w**
- **Demonstrate onboard fleet planning, resource allocation and scheduling**
- **Fault detection/isolation & Recovery**
- **Collective Pointing & Navigation**
- **Collision Avoidance**
- **Ad hoc Networking**

On-board Autonomy
- Fleet Spacecraft Autonomy

Science Mission
SAR w/ Communications
Co-observing
Multi-Angle Observing

Validation Plans for Intelligent Distributed Spacecraft Infrastructure - On-orbit Autonomy Testbed (Part 1 of 2)

Problem Statement:

Multiple approaches to autonomy exist and multiple elements of spacecraft autonomy require flight validation to address paradigm shifts, verify behavior, develop confidence and ensure safety

Examples include:

- Autonomy required for single and distributed spacecraft :
  - Fully integrated autonomy in flight software
    - Providing a reusable core for future missions
  - Fault detection and recovery
  - Event detection and notification
  - Planning and scheduling with resource allocation
  - Adaptive planning/scheduling

- Autonomy required for distributed spacecraft only:
  - Formation control
  - Collective pointing of separate spacecraft
  - Communications, Ad-hoc networking of space assets
  - Collision avoidance
  - Fault Detection and correction across the fleet
  - Cooperative planning and schedule

Validation Plans for Intelligent Distributed Spacecraft Infrastructure - On-orbit Autonomy Testbed (Part 2 of 2)

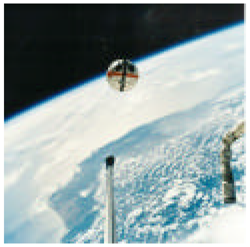
Proposed Path for Development:

- On-orbit testbed environment which provides hardware-in-the-loop 6-DOF Interactions in Microgravity
  - Enables direct comparisons of multiple approaches to autonomy for example:
    - Fuzzy Logic Control (GSFC)
    - Remote Agent (Ames/JPL)
  - Supports Development and Validation of Autonomous Subsystems
    - S/C Pointing, Instrument Pointing, Formation Navigation, OD, etc.
  - Provides Environment for Multiple S/C Development/Validation
- Potential Environments
  - Single S/C
    - Advantages - True Space Environment, 6 DOF
    - Drawbacks - Expensive, No Fleet Validation, Cannot Refurbish, Difficult to do Multiple Experiments
  - Multiple S/C
    - Advantages - True “Fleet” Test Environment, 6 DOF
    - Drawbacks - Very Expensive, Cannot Refurbish, Timeline Could Be Short for Multiple Experiments
  - MIT Spheres Program offers a testbed on ISS that provides for refurbishment and customization
    - Advantages - Affordable, Multiple Vehicle, Can Reconfigure, Refuel, Refurbish, Specialized Equipment Could be Tested, Unlimited Timeline
    - Drawbacks - Still Pressurized Environment, Not True Spacecraft

Example:
MIT Spheres Program Benefits

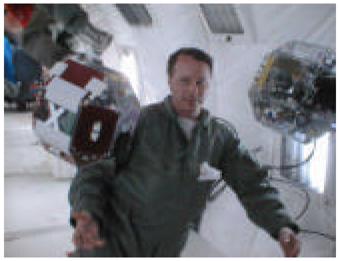
Leverage ISS-based free-flyers already under development:

- Personal Satellite Assistant (ARC; in development)
- AERcam (JSC; Shuttle flight heritage)
- SPHERES (MIT; already manifested on ISS 10/02 launch)



AERCam

PSA



SPHERES

Offers Flexibility:

Autonomy and control researchers could propose experiments and flyoffs

Uploadable algorithms

ISS Crew act as proxy researchers

- Refurbish and upgrade resources
- Virtual presence for researchers