Earth Science Enterprise Technology Planning Workshop

Intelligent Distributed Spacecraft Infrastructure

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Carol Raymond (Facilitator) - JPL

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## Agenda

<table>
<thead>
<tr>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Satellite Challenges/Sensorweb</td>
<td>M. Schoeberl - GSFC</td>
</tr>
<tr>
<td>Miniature GPS-based multi-function</td>
<td>T. Yunck - JPL</td>
</tr>
<tr>
<td>Instrument for Autonomy of Spacecraft</td>
<td>W. Wiscombe - GSFC</td>
</tr>
<tr>
<td>Constellations Sounding</td>
<td>D. Folta - GSFC</td>
</tr>
<tr>
<td>Leonardo</td>
<td>S. Madsen - JPL</td>
</tr>
<tr>
<td>Control Architecture</td>
<td>R. Carpenter - GSFC</td>
</tr>
<tr>
<td>Control of Distributed Spacecraft</td>
<td>J. How - MIT</td>
</tr>
<tr>
<td>Remote Agent</td>
<td>R. Washington - ARC</td>
</tr>
<tr>
<td>Model for Planning and Scheduling</td>
<td>R. Morris - ARC</td>
</tr>
<tr>
<td>Observations for Many Satellites Simultaneously</td>
<td>A. Barrett - JPL</td>
</tr>
<tr>
<td>Constellation Operations</td>
<td>M. Campbell - U.Wash</td>
</tr>
<tr>
<td>Formation Planning, Control, and Reconfiguration Algorithms</td>
<td>Srinivasan - JPL</td>
</tr>
<tr>
<td>Agent-based Autonomy</td>
<td>P. Stadter - JHU/APL</td>
</tr>
<tr>
<td>GPS/Formation Flying</td>
<td>T. Balch - CMU</td>
</tr>
<tr>
<td>Communications</td>
<td>T. Tierno - Honeywell</td>
</tr>
<tr>
<td>Airborne testbed</td>
<td>J. Harris - Honeywell</td>
</tr>
</tbody>
</table>
### 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. Stadtter  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
### 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

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

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### 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

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**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 vapor using GPS sounding and microwave crosslinks.
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 $0.02^\circ$ (X-band) $0.2^\circ$ (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 $0.5^\circ/0.1^\circ$

Global Precipitation:  3-9 spacecraft (formation)
1 spacecraft (core)
50 kg/150 kg
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
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)
  - Planning 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

**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

**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

**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

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

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

**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

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

**Fiscal Year**
- 01
- 02
- 03
- 04
- 05
- 06
- 07
- 08
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
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)

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