Distributed Spacecraft Missions (DSM) Technology Development at NASA Goddard Space Flight Center

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IGARSS 2018
What is a Distributed Spacecraft Mission (DSM)?

A DSM is a mission that involves multiple spacecraft to achieve one or more common goals.

Drivers

- Enable new science measurements
- Improve existing science measurements
- Reduce the cost, risk and implementation schedule of all future NASA missions
- Investigate the minimum requirements and capabilities to cost effectively manage future multiple platform missions and to cost effectively develop and deploy such missions
**NASA Goddard DSM Activities**

**DSM Definitions, Taxonomy, Survey, Scientist Interviews, Identification of Main Technology Challenges**

**An Earth Science Use Case and DSM RFI**

**DSM Technology Roadmap based on DSM RFI Concepts**

**2 Design Reference Missions (DRM) Framework for 2 Types of DSM, Constellations (DRM-C) and Precision Formation Flying (DRM-PFF)**

**Intelligent and Collaborative Constellations (ICC): Software Architecture Design and eFS-Based Communications Protocols Development**

### Strategic IRAD Development

- **2013**
  - DSM Definitions, Taxonomy, Survey, Scientist Interviews, Identification of Main Technology Challenges

- **2014**
  - An Earth Science Use Case and DSM RFI

- **2015**
  - DSM Technology Roadmap based on DSM RFI Concepts

- **2016**
  - 2 Design Reference Missions (DRM) Framework for 2 Types of DSM, Constellations (DRM-C) and Precision Formation Flying (DRM-PFF)

- **2017**
  - Intelligent and Collaborative Constellations (ICC): Software Architecture Design and eFS-Based Communications Protocols Development

- **2018**
  - 2 Design Reference Missions (DRM) Framework for 2 Types of DSM, Constellations (DRM-C) and Precision Formation Flying (DRM-PFF)

### Transitional Development Projects

- **ESTO/AIST14**
  - "Trade-space Analysis Tool for Designing Distributed Missions (Constellations), TAT-C (Constellation Mission Design)"

- **CANYVAL-X**
  - CubeSat Astronomy by NASA and Yonsei Univ. using Virtual Telescope Alignment Experiment (GN&C Validation for PFF)

- **SST'16 with ESTO/AIST16**
  - "Generalizing Mission Design Using TAT-C and Machine Learning" (Constellation Mission Design)

- **EPSCoR with NMSU and UNM**
  - "Earth and Heliophysics Conceptual Missions Design (In Preparation)"

- **ESTO/IIP16**
  - "Miniaturization Imaging Spectrometer to Measure Vegetation Structure and Function - MiniSpec” (Reduced SWaP Constellation Design)
<table>
<thead>
<tr>
<th><strong>A Distributed Spacecraft Mission (DSM)</strong> is a mission that involves multiple spacecraft to achieve one or more <em>common</em> goals.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constellation</strong></td>
</tr>
<tr>
<td><strong>Formation Flying</strong></td>
</tr>
<tr>
<td><strong>Fractionated spacecraft</strong></td>
</tr>
</tbody>
</table>
DSM Survey*

- About 73% of missions use identical (or very similar) spacecraft
- 68% of missions launch all spacecraft on a single launch vehicle

72% of missions are real or likely to be implemented within a decade (or so)

Most missions are constellations where spacecraft don’t interact

Heliophysics has almost half of the science concepts

*Updated 12/2016
• Collected data on 65 missions
• Wide range of DSM:
  o Constellations
  o Clusters
  o Formation Flying
  o Virtual Telescopes
  o Fractionated Spacecraft
  o Temporal Constellations
• Wide range of applications:
  o Science (Earth, Planetary, Astrophysics, Heliophysics
  o Commercial Communications and Earth observation
  o Defense
  o Tech Demonstrations

• Past Missions (Dynamics Explorer 1981) to far future missions such as MAXIM
• Number of flight elements from 2 to 100
• Most common type is a Heliophysics constellation of 2-6 identical non interacting spacecraft making multipoint measurements from Earth orbit

**Number of Spacecraft per Science Distributed mission**

- Mode: 2
- Median: 3
- Average: 5 (with QB50) or 3.6 (without QB50)
May impact the perceived cost of proposed missions

Need to derive better cost models appropriate to SmallSats and to DSM

Need to validate new cost models using recent DSM (e.g., CYGNSS)

Cost Correlations

- Did not have cost and mass information for all missions

- Little correlation observed between number of satellites and cost, when sorted by different categories

- Maximum correlation seen when sorted by size, then orbit type then distribution type
Science Questionnaire:
Imagine that you could do your science with constellations of satellites, from 2 or 3, up to 100, rather than with single satellites. Imagine that there would be a regular pipeline of satellites, continually being launched and replaced, and that the number of satellites could be expanded or contracted based on the science data being obtained. Imagine that a major push in shrinking instrument sizes makes much smaller satellites possible.

For some specific examples, we can assume that economies of scale have been implemented and efficient assembly lines put in place, such that, with much smaller satellites, cost is no greater than current missions (or at least no greater than the rapidly escalating cost estimates for current Decadal Survey missions).

Given these capabilities:
1. Which kind of science could you do that you cannot do now?
2. What measurement capabilities have a compelling scientific justification and are attainable only (or clearly advantageously) with a distributed spacecraft mission? Specifically, which science measurements or data would you like to collect with what temporal or spatial frequency that would be an augmentation from current capabilities and that would go above and beyond what might be recommended by a Decadal Survey?
3. Which benefits can you envision from distributed missions?
4. Generally in a mission, which capabilities would you like to have that you do not have in current missions? For example:
   a. Targeting (individual, global, collaborative) capabilities
   b. Autonomy, intelligence, onboard processing
   c. Precision/relative positioning and attitude control
   d. Distributed aperture measurements for observations
   e. Orbit, inclination, altitude
   f. Other?
5. In your mind, could constellations contribute to improved data continuity compared to single spacecraft missions?
6. Which size spacecraft would you consider? Why?
7. Which sort of missions would NOT benefit from a distributed approach? i.e., which missions must absolutely remain centralized?
8. Can you suggest a "reference mission" which would be an exemplar of the benefits of a constellation approach?

Interviewed 53 scientists (15% of all GSFC scientists)

- General Interests
- Specific Concepts

General Findings (from Interviews):

- Helio: most advanced and most interested in DSM
  - Multi-point measurements
  - Mostly constellations; PFF for occulters, High Energy Sc.
- Earth Science:
  - Many potential applications
  - Sampling in spatial, temporal, spectral, angular dims
  - Micro- or MiniSats rather than CubeSats
  - Data Continuity
  - Cross-Calibration
- Astrophysics: Rising interest
  - PFF more than general constellations
  - Occulters, Virtual Telescopes, Tethered missions
  - CubeSats for tech demos
- Planetary Science:
  - Currently, less plans on DSM
  - DSM for combined space & planetary assets
  - DSMs for minimizing communications costs
  - Multiple viewpoints for scheduling and targeting
DSM Technology Roadmap

We Start with Science …

... and End with Science

Analyze and Share Science Data Processing
- Scalable data management for large DSM
- High accuracy multi-platform calibration, registration & fusion

Operate Ground Data Processing
- Multi-spacecraft mission ops
- Centers and ground data systems
- Solutions for DSM “big data” operations challenge

Conceive and Design, Design and Development Tools
- Pre-Phase A/Phase A DSM mission design tools
- Prototyping & Validation testbeds
- Model-based engineering tools

Build and Test Manufacturing, I&T and Assembly
- Develop/extend standards
- Integration and Testing (I&T) frameworks

Launch and Deployment
- Low-thrust propulsion
- Low-cost deployment multi-spacecraft systems

Operate Communications
- High-speed S/C to S/C comms
- Low-cost & fast SmallSats uplink/downlink

Operate GN&C
- HW & SW for:
  - Autonomous sensing & control
  - Absolute & relative navigation
  - Coordinated pointing

Analyze Onboard Intelligence
- Onboard recognition of events of interest
- Onboard goal-oriented planning & scheduling
- Autonomous re-targeting and reconfigurability
DSM Design Reference Missions Framework

• Considering 2 DSM types:
  o DRM-C: Loose Constellation Framework
  o DRM-PFF: Precision Formation Flying Framework

• Defining DRMs Framework Requirements in terms of:
  o The 8 Technology areas defined in the roadmap, and
  o 8 DSM Science Mission Concepts
    ▪ 4 Constellations and 4 Precision Formation Flying

• IRAD projects in 6 Tech Areas responding to at least 1 or 2 of the 8 DSM Mission Concepts
## Goddard DSM Activities:
### Some Critical DSM Technologies

<table>
<thead>
<tr>
<th>Capability</th>
<th>Technology</th>
<th>Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coordinate the simultaneous acquisition of multiple observations</strong></td>
<td>Autonomous onboard recognition of science event of interest</td>
<td>Enable opportunistic science Mitigate orbit-to-ground latency</td>
</tr>
<tr>
<td></td>
<td>Autonomous onboard data analysis for optimal science return</td>
<td>Enable opportunistic science Mitigate orbit-to-ground latency Reduce date volume</td>
</tr>
<tr>
<td></td>
<td>Autonomous DSM S/ C reconfiguration and/ or instrument pointing</td>
<td>Enable low latency opportunistic science</td>
</tr>
<tr>
<td></td>
<td>High-speed S/ C to S/ C SmallSat communications</td>
<td>Enable autonomous, low latency distributed science</td>
</tr>
<tr>
<td></td>
<td>Autonomous on-board navigation</td>
<td>Reduce operations cost by minimizing ground tracking</td>
</tr>
<tr>
<td><strong>Precision Formation Flying (PFF) Capabilities</strong></td>
<td>Autonomous precision relative spacecraft positioning to a state-of-the-art SmallSat level of accuracy</td>
<td>Enable distributed telescope architectures</td>
</tr>
<tr>
<td></td>
<td>Autonomous precision pointing to a state-of-the-art SmallSat level of accuracy</td>
<td>Enable virtual telescopes Enable collaborating spacecraft / sensors</td>
</tr>
<tr>
<td></td>
<td>High-speed S/ C to S/ C smallsat communications</td>
<td>Enable collaborating/ cooperating spacecraft / sensors</td>
</tr>
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</table>
Recent DSM R&D Activities

• **Design and Modeling Testbed**
  - Autonomous Rotorcraft as a 6DoF Spacecraft Emulator
  - Model-Based System Engineering Applied to Distributed Spacecraft Missions
  - Trade-Space Analysis Tool for Constellations (TAT-C)

• **Spacecraft to Spacecraft Crosslinks**
  - Software Bus Network (SBN) Message Routing Protocol
  - SmallSat Constellation Inter-Satellite Link System Simulator

• **Communications & Navigation**
  - Rapid Formulation of a low SWAP Integrated Communications & Navigation Terminal
  - Prototype Low SWaP-C Multi-Regime Integrated Communications & Navigation Terminal

• **Coordination of Simultaneous Acquisition of Multiple Observations**
  - Deep Learning for Constellations of SmallSats

• **GN&C Control and Sensing**
  - Active 2-Axis Positioning Mechanism for Detectors and Occulters
  - Precision Alignment Determination and Control System for a Precision Formation Flying Distributed Spacecraft Mission (DSM)
  - High precision relative position sensing system for formation flying spacecraft
  - Long Range (1 AU) Ranging & Data Comms with Small Satellite Laser Links for Deep-space Science

• **“Big Data” Challenge for Large Constellations**
  - Real-Time Analytics Test System for Distributed Spacecraft Missions
### DSM Architecture Characteristics

#### DISTRIBUTED SPACECRAFT MISSIONS CHARACTERISTICS (07/26/2013)

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>MONOLITHIC</th>
<th>DISTRIBUTED</th>
<th>DISTRIBUTED</th>
<th>DISTRIBUTED</th>
<th>DISTRIBUTED</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Constellation</td>
<td>Formation Flying</td>
<td>Fractionated</td>
<td>AD-HOC/VIRTUAL MISSION</td>
</tr>
<tr>
<td>Appearance and Functionality</td>
<td>Homogeneous</td>
<td>Heterogeneous</td>
<td>Homogeneous</td>
<td>Heterogeneous</td>
<td>Heterogeneous</td>
</tr>
<tr>
<td>Spatial Relationship</td>
<td>NA</td>
<td>General/Any (e.g., multiple orbits)</td>
<td>Swarm</td>
<td>General/Any (e.g., multiple orbits)</td>
<td>Cluster</td>
</tr>
<tr>
<td>Inter-Spacecraft Relationship and Functional Configuration</td>
<td>NA</td>
<td>None</td>
<td>Peer-to-Peer</td>
<td>Hierarchical</td>
<td>Peer-to-Peer</td>
</tr>
<tr>
<td>Spatial Control</td>
<td>Ground and On-Orbit</td>
<td>Ground</td>
<td>Ground and On-Orbit</td>
<td>Ground</td>
<td>Ground</td>
</tr>
<tr>
<td>Temporal Deployment</td>
<td>All at once</td>
<td>Incremental</td>
<td>All at once</td>
<td>All at once</td>
<td>Accretionary</td>
</tr>
<tr>
<td>Temporal Control</td>
<td>NA</td>
<td>“Flash Mob”</td>
<td>Precise Correlated Measurements</td>
<td>Precise Correlated Measurements and Control</td>
<td>Loose/Ad-Hoc Correlated Measurements</td>
</tr>
<tr>
<td>Autonomy</td>
<td>None</td>
<td>Semi-Autonomy</td>
<td>Fully Autonomy</td>
<td>Semi-Autonomy</td>
<td>Semi-Autonomy</td>
</tr>
<tr>
<td>Number of Spacecraft</td>
<td>1</td>
<td>[2-10]</td>
<td>[10-50]</td>
<td>&gt; 50</td>
<td>[2-10]</td>
</tr>
<tr>
<td>Launch Approach</td>
<td>Single</td>
<td>All at Once</td>
<td>Multiple Launches</td>
<td>All at Once</td>
<td>Multiple Launches</td>
</tr>
<tr>
<td>Launcher Approach</td>
<td>Dedicated</td>
<td>Dispenser</td>
<td>Multiple Launches</td>
<td>Dispenser</td>
<td>Multiple Launches</td>
</tr>
<tr>
<td>Payloads</td>
<td>Dedicated</td>
<td>Heted, Payloads</td>
<td>Combination</td>
<td>Dedicated</td>
<td>Heted, Payloads</td>
</tr>
</tbody>
</table>
## DSM Architecture Characteristics

**Examples**

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>MONOLITHIC (Ex: Landsat)</th>
<th>DISTRIBUTED</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CONSTELLATION - Example: ST-5</strong></td>
<td>Homogeneous</td>
<td>Homogeneous</td>
</tr>
<tr>
<td>Appearance and Functionality</td>
<td>Homogeneous</td>
<td>Homogeneous</td>
</tr>
<tr>
<td>Spatial Relationship</td>
<td>N/A</td>
<td>General/Variable (e.g., multiple)</td>
</tr>
<tr>
<td>Inter-Spacecraft Relationship and Functional Configuration</td>
<td>N/A</td>
<td>None</td>
</tr>
<tr>
<td>Spatial Control</td>
<td>Ground and On-Orbit</td>
<td>Ground</td>
</tr>
<tr>
<td>Temporal Deployment</td>
<td>All at Once</td>
<td>Incremental</td>
</tr>
<tr>
<td>Temporal Control</td>
<td>N/A</td>
<td>&quot;Flash Mob&quot;</td>
</tr>
<tr>
<td>Autonomy</td>
<td>None</td>
<td>Semi-Autonomy</td>
</tr>
<tr>
<td>Number of Spacecraft</td>
<td>1</td>
<td>[2-10] (3)</td>
</tr>
<tr>
<td>Spacecraft Mass (kg)</td>
<td>Variable Size and Mass</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Launch Approach</td>
<td>Single</td>
<td>All at Once</td>
</tr>
<tr>
<td>Launcher Approach</td>
<td>Dedicated</td>
<td>Disperser</td>
</tr>
<tr>
<td>AD-HOC/VIRTUAL MISSION - Example: A-Train</td>
<td>Heterogeneous</td>
<td></td>
</tr>
</tbody>
</table>

### Notes:
- **DSM** refers to a Distributed Space Mission architecture.
- The table compares different architectural characteristics between monolithic and distributed space missions.
- Examples include ST-5, GRACE, DARPA SYSTEM F6, and A-Train.
Example DSM Activities

**Trade-space Analysis Tool for Constellations (TAT-C)**

**Generalizing Distributed Missions Design Using the Trade-Space Analysis Tool for Constellations (TAT-C) and Machine Learning (ML)**

**PI:** Jacqueline Le Moigne, NASA Goddard Space Flight Center

**Objective**
- Extend TAT-C Capabilities, *i.e.*, increase the dimension of the trade-space with:
  - Various trajectories, orbital planes, mission replanning, orbit and Maneuver Modeling, etc.
  - New trade modules (instrument, launch, onboard computing, etc.)
  - Optimize the Trade-Space Exploration by Utilizing Machine Learning and a Fully Functional Knowledge Base (KB) to Efficiently Traverse a Large Trade-Space

**Approach:**
- Include Mission Ops in Cost Module; Develop TAT-C ML / GMAT Interface; Develop Figures of Merit (FOM) for Mission Replanning
- Include Occultors, Lidars and Bi-Static Radars; Develop New Launch Module; Leverage AIST14/French results for Onboard Proc. Trades
- Develop KB via semantic web technologies, formal knowledge representations and related taxonomies
- Machine Learning using Adaptive Operator Selection strategies (AOS) and Knowledge-Driven Optimization (KDO)
- Improve GUI and interfaces to OSSEs and MBSE

**Co-l’s:** P. Dabney, M. Holland, S. Hughes/GSFC; S. Nag/BAERI; A. Siddiqi, V. Foreman/MIT; P. Grogan/Stevens; D. Selva, N. Hitomi/Cornell

**Key Milestones**
- Define SLI and TROPICS Full Requirements
- TAT-C Machine Learning Ontology Defined
- Mission Ops in Cost & Risk Module
- Instrument Models Development
- Knowledge Base and Maneuver Modeling Complete
- TAT-C ML/GMAT Interface
- TAT-C ML Validation Using SLI and TROPICS

**TRL in = 2**

**TRL current = 2 or 3**

**Funded through ESTO/AIST14&AIST6**
TAT-C Now Available through AMCE Cloud Interface

### Tradespace Analysis Tool for Constellations (TAT-C)

<table>
<thead>
<tr>
<th>INPUT</th>
<th>RUN</th>
<th>RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIMPLE</td>
<td>START</td>
<td>OVERVIEW</td>
</tr>
<tr>
<td>ADVANCED</td>
<td>STATUS</td>
<td>CHARTS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STORAGE</td>
</tr>
</tbody>
</table>

#### SIMULATED MISSION
- **Start Date:** 07/05/2017
- **Duration:** 54 days (2017-08-28)

#### ORBIT ALTITUDES
- **Min:**
- **Max:** 489 to 676 km

#### ORBIT LATITUDES
- **Range:**
- **Offset:** 90.0S : 20.0S

#### ORBIT INCLINATION
- **Min:**
- **Max:** 77.0 degrees

#### CONSTELLATION SIZE
- **Min:**
- **Max:** 1 satellite

#### INSTRUMENT FoV
- **Min:**
- **Max:** 5 degrees
**Mission Description**

- CANYVAL-X: engineering demonstration using CubeSats (1U+2U)
- Validate GN&C for precise dual-spacecraft formation flight along an inertial line-of-sight.
- Solar Alignment Goals
  - Control < 1.2 deg (20 cm at 10 m)
  - Stability < 1 arc-min over 5 sec (0.3 cm at 10 m)

**Status**

- NASA & Yonsei Univ. under international agreement
- GSFC delivered: Sun Sensor (May 2015), Micro thrusters (mCAT) (Sep 2015)
- Yonsei Univ. built 2U and 1U spacecraft
- KARI performed environmental testing
- Launched January 2018 on the PSLV-40 Mission from India.
- Reached stable orbit and heard radio beacon, but current ground station issues and have not been able to command the spacecraft yet.

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**Example DSM Activities**

**Virtual Telescope Alignment Experiment**

- CANYVAL-X: The CubeSat Astronomy by NASA and Yonsei using Virtual Telescope Alignment experiment (Shah/ GSFC)

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- **mCAT (GSFC+GWU)**
- **Fine Sun Sensor (GSFC)**
- Yonsei Univ. funded by Korean Aerospace Research Institute (KARI); GSFC IRAD contributions
Software Bus Network (SBN)  
**Multi-Step Routing**

- Extends the Core Flight System (cFS) Software Bus Network (SBN) application to work across processors/spacecraft that are not directly connected.
- SBN allows cFS to be used seamlessly on multiple processors/spacecraft.
- Previous versions of SBN required direct connection in order to communicate.
  - Example below, Spacecraft 1 and Spacecraft 3 could not communicate
- New version will allow routing through intermediate nodes.
  - Example below: Spacecraft 1 and Spacecraft 3 can communicate through Spacecraft 2
- Will enable cFS to be used in a wider variety of distributed architectures.
  - Architectures with constraints on which nodes can be directly connected (due to distance, line of sight, etc.)

```
Spacecraft #1  Spacecraft #2  Spacecraft #3
```

```
cFS       cFS       cFS
```

```
Spacecraft #1
```

```
Spacecraft #2
```

```
Spacecraft #3
```
Deep Learning on CubeSats

SoC/FPGAs allow for near GPU performance (high power/poor radiation tolerance) at a fraction of the power, and better radiation performance

- Deep learning now possible on CubeSats
  - Advances in low-power FPGAs give the compute power necessary to run large Neural Networks
    - GPUs still useful on ground to train the networks
  - Many software frameworks make designing neural networks easy and fast
    - Software such as Google’s TensorFlow or Keras
- Combine powerful existing tools to train Neural Networks on the ground, with optimized code to deploy the trained network onto a CubeSat-like platform

APPLICATION TO WILDFIRE DETECTION

Large amount of MODIS data

Example Deep Learning Architecture

Intelligent Reduction of Data

Resulting classification of data as Fire/Not Fire

99.59 % Correct Classification Rate
Intelligent & Collaborative Constellations (ICC)

ICC Movie Simulation
Summary – Next Steps

We Start with Science …

... and End with Science

Analyze and Share Science Data Processing
- Scalable data management for large DSM
- High accuracy multi-platform calibration, registration & fusion

Analyze Onboard Intelligence
- Onboard recognition of events of interest
- Onboard goal-oriented planning & scheduling
- Autonomous re-targeting and reconfigurability

Build and Test Manufacturing, I&T and Assembly
- Develop/extend standards
- Integration and Testing (I&T) frameworks

Launch and Deployment
- Low-thrust propulsion
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Operate Communications
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Operate GN&C
HW & SW for:
- Autonomous sensing & control
- Absolute & relative navigation
- Coordinated pointing

Operate Ground Data Processing
- Multi-spacecraft mission ops Centers and ground data systems
- Solutions for DSM “big data” operations challenge

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