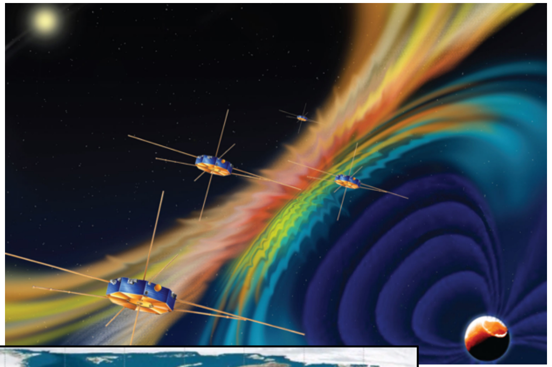
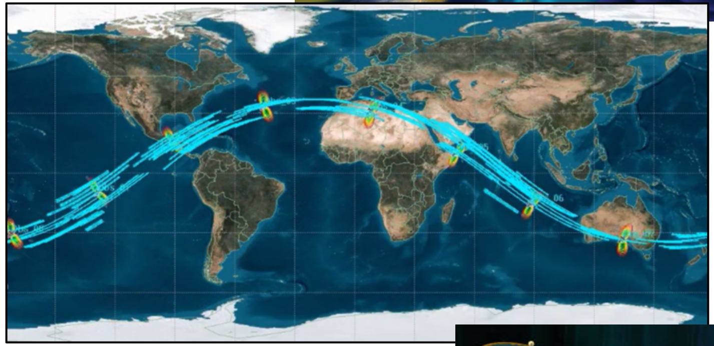
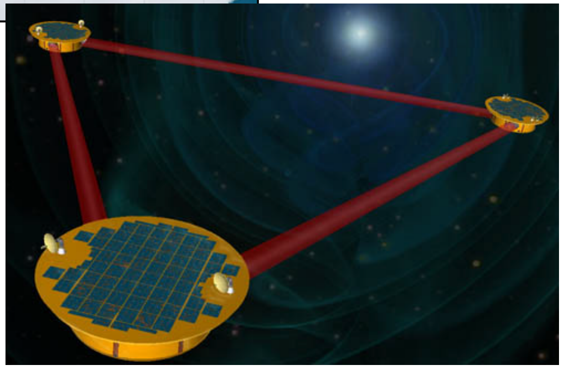






Distributed Spacecraft Missions (DSM)

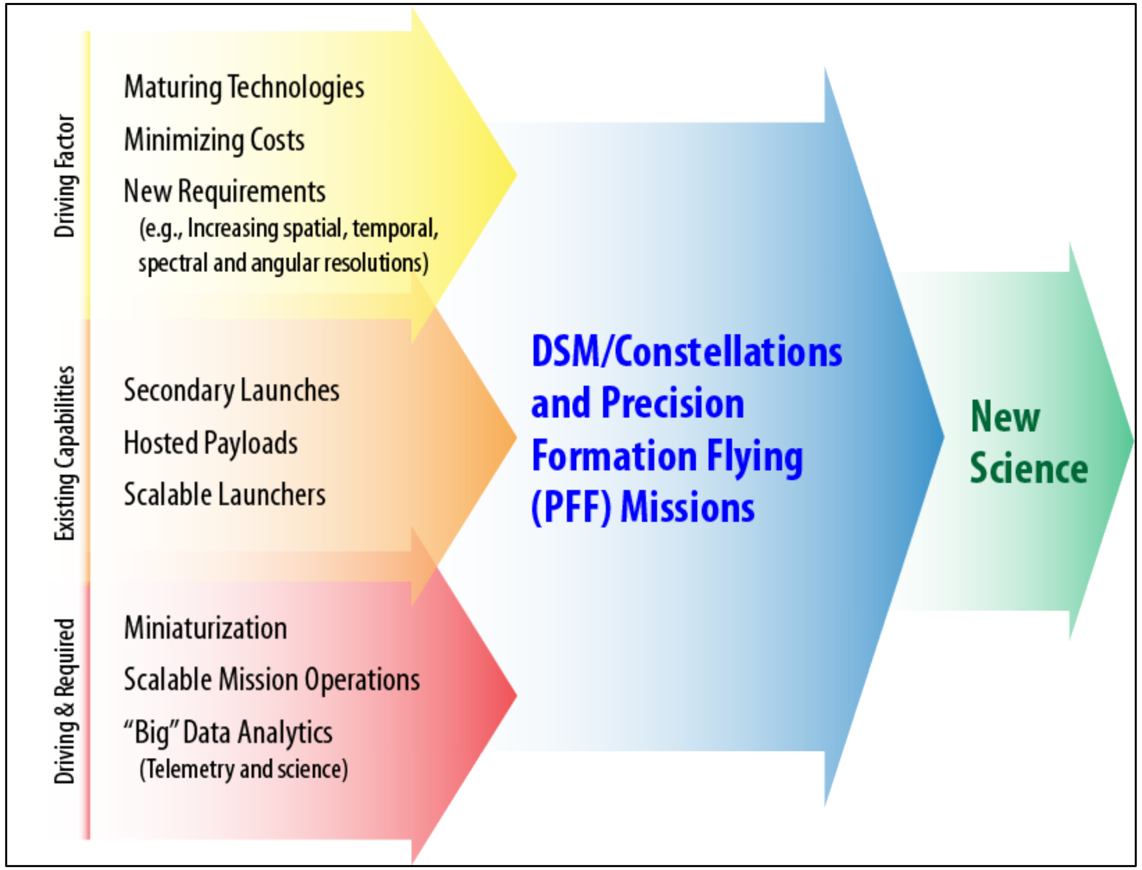
Jacqueline Le Moigne
Earth Science Technology Office
Advanced Information Systems Technology Program

October 08, 2019

Current NASA Observing Strategy

DSM and Future Missions Environment

***Technology advances** have created an opportunity to make new measurements and to continue others less costly, e.g., **SmallSats** equipped with science-quality instruments and **Machine Learning** techniques permit handling large volumes of data.*



New Mission Designs to:

- **Utilize Distributed Spacecraft Missions (DSM),** i.e., missions that involve multiple spacecraft to achieve one or more common goals.
- **Coordinate Space Measurements with Other Measurements (e.g., in-situ).**

New Observation and Exploration Goals:

- Enable new science measurements
- Improve existing science measurements
- Reduce cost of future NASA missions

New Observing & Exploration Strategies

New Technology Environment:

- Novel Instrument Design
- Smaller Spacecraft and Components for reduced Size, Weight and Power (SWAP)
- Constellations vs. Monolithic Missions

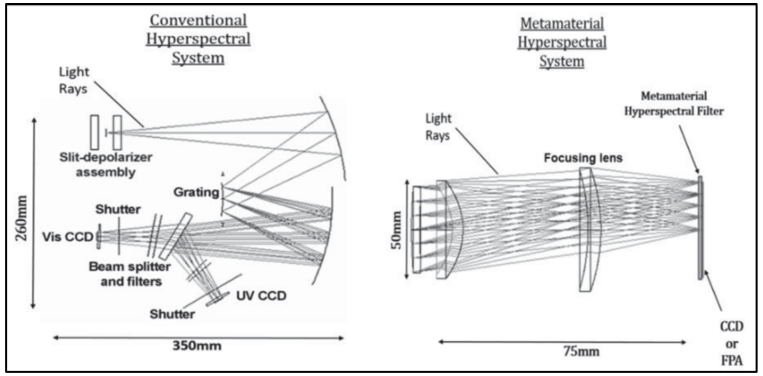
New Programmatic Environment:

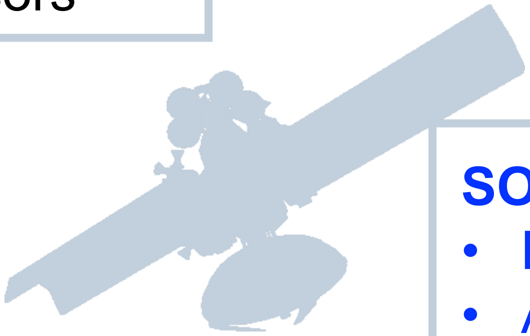
- Smaller Budgets
- Various Partners: OGAs, Industry, Academia, International
- New and Unique Science Measurements vs. Dedicated Missions
- Varied Launch and Deployment Opportunities

New Observing & Exploration Strategies

Technology Drivers

HARDWARE:
- Instrument Miniaturization (Freeform Optics, Photonic Integrated Circuits, etc.)
- Novel Components (Metamaterials, etc.)
- Smaller Spacecraft (CubeSats and Nanosats)
- High Performance Space Processors





SOFTWARE:
- Big Data Analytics
- Artificial Intelligence
- Autonomous Decision Making
- Onboard Computing
- Intelligent & Collaborative Constellations and Sensor Webs

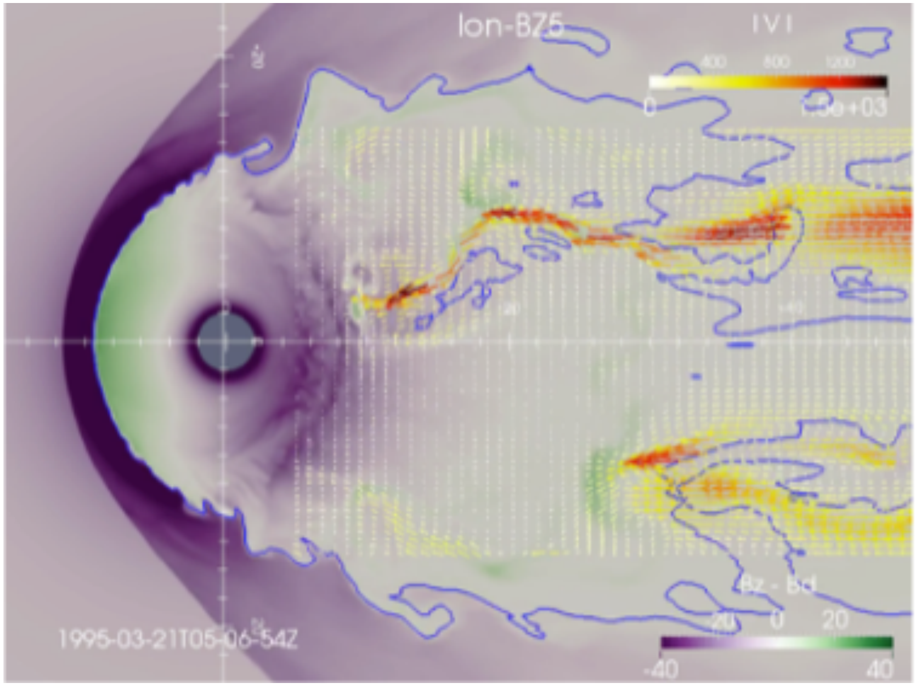
Distributed Spacecraft Missions (DSM)
Science Importance

What is a Distributed Spacecraft Mission (DSM)?

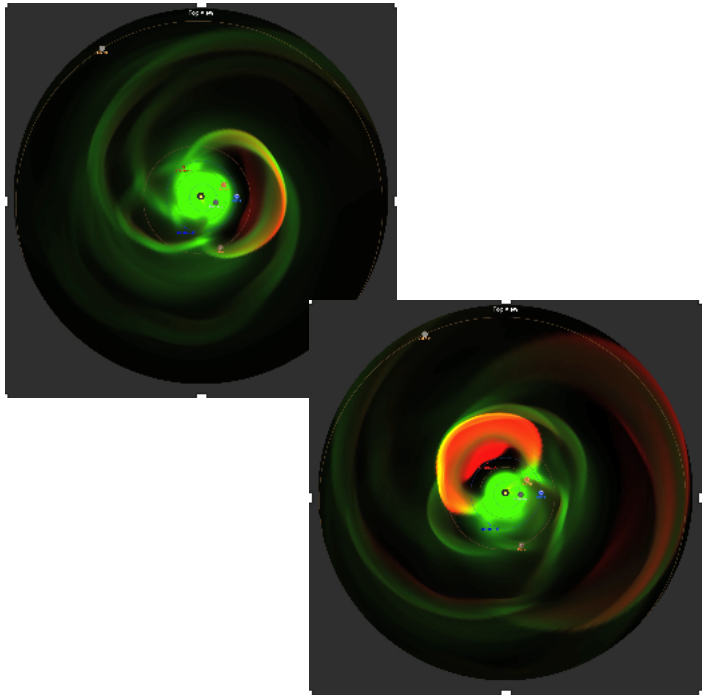
A Distributed Spacecraft Mission (DSM) is a mission that involves multiple spacecraft to achieve one or more common goals.

In Heliophysics

Multiperspective imaging of these structures is needed to determine the true 3-D Topology of Solar Corona and Eruptive Events, for fundamental physical understanding and improved space weather forecasting. (NASA GSFC)



Geospace Dynamics Constellation (GDC), Decadal Survey mission since 1990s. Multi-scale processes over a vast region of space can only be studied by a dense constellation.

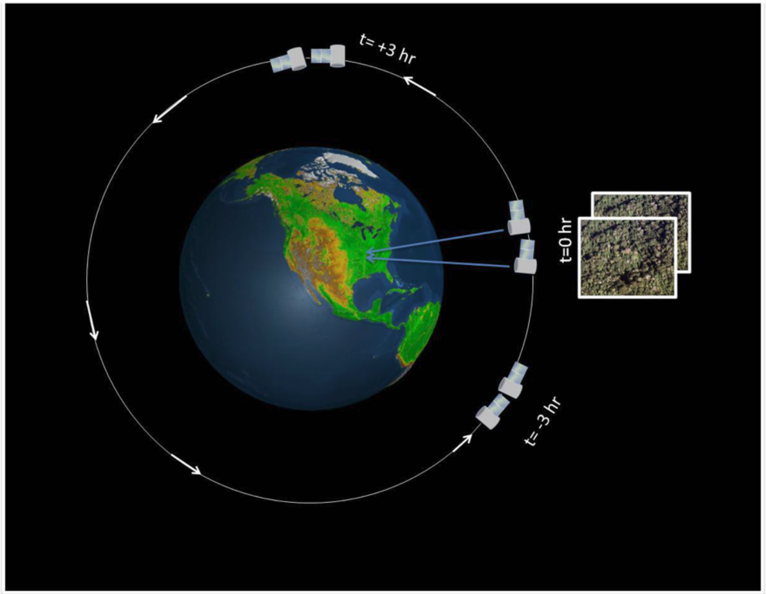


Multi-point measurements needed to view Sun and solar wind structures from multiple vantage points. Provides better understanding of solar wind and CME evolution to support science and exploration efforts (e.g. Gateway to Mars).

Distributed Spacecraft Missions (DSM)
New Observing Strategies (NOS) for Earth Science

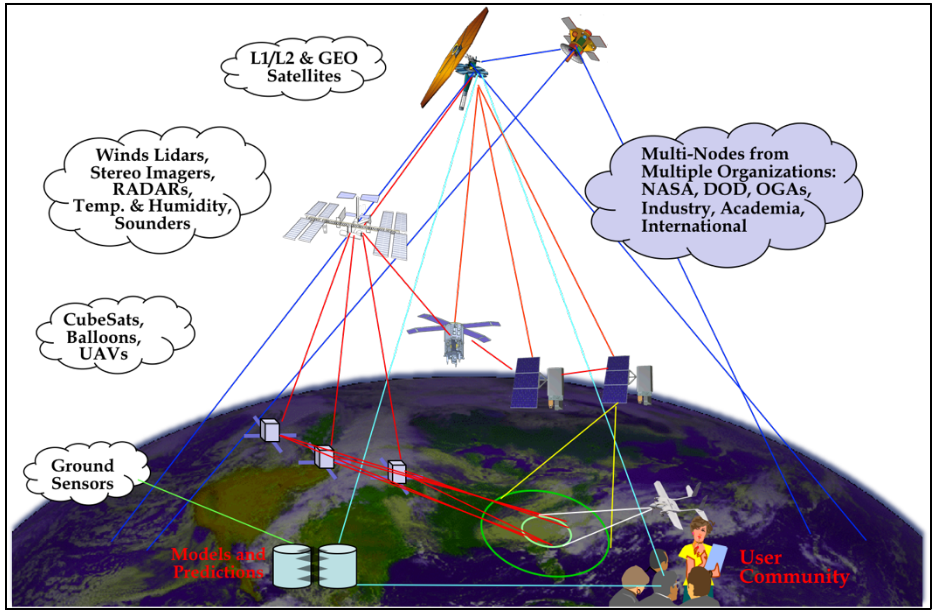
In Earth Science

- Provide a dynamic and more complete picture of physical processes or natural phenomena
- Multiple collaborative sensor nodes (SensorWeb) producing measurements integrated from multiple vantage points and in multiple dimensions (spatial, spectral, temporal, radiometric)



Example: SAFE (Structure and Function of Ecosystems): First diurnal high-spatial resolution measurements of plant functional properties, i.e., of structure and functioning of vegetation provide the complete picture of plant productivity and stress. (POC: Jon Ranson/GSFC)

A SensorWeb is a distributed system of *sensing nodes* (space, air or ground) that are interconnected by a *communications fabric* and that functions as a single, highly coordinated, virtual instrument. It semi- or - autonomously detects and dynamically reacts to events, measurements, and other information from constituent sensing nodes and from external nodes by modifying its observing state so as to *optimize mission information return.* (e.g., EO-1 SensorWeb 3G). (Ref: Talabac et al, 2003)



New Observing Strategies (NOS)
=> New Observing and Exploration Strategies

New Observing Strategies (NOS):

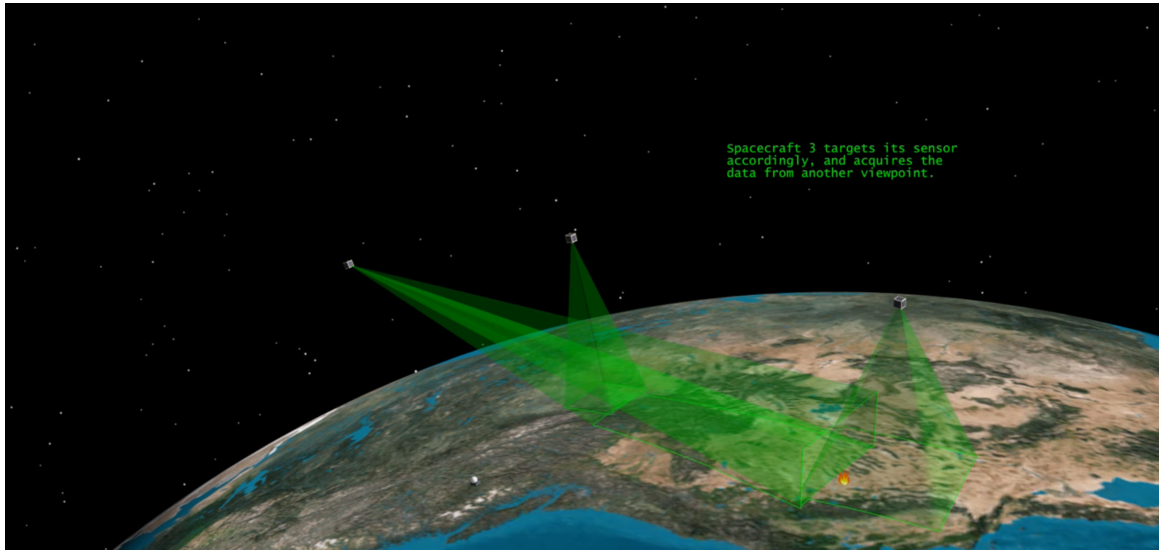
- Multiple collaborative sensor nodes producing measurements integrated from multiple vantage points and in multiple dimensions (spatial, spectral, temporal, radiometric)
- Provide a dynamic and more complete picture of physical processes or natural phenomena

NOS Similar to SensorWeb Concept where each Node can be Individual Sensor or DSM

DSM can be a general Constellation, Formation Flying, Fractionated, etc.

A special case of DSM is **an Intelligent and Collaborative Constellation (ICC)** which involves the combination of:

- Real-time data understanding
- Situational awareness
- Problem solving
- Planning and learning from experience
- Communications and cooperation between multiple S/C.



Autonomy for Intelligent and Collaborative Constellations

- **What is an Intelligent and Collaborative Constellation?**
  - Intelligent:
    - Result of onboard processing of the data acquired from the different satellites is the basis for a decision taken autonomously and onboard
    - Real-Time Data Understanding; Situational Awareness; Problem Solving; Planning; Learning from Experience
    - How to characterize a constellation as “intelligent” or “autonomous”? What is the Threshold?
  - Collaborative/Cooperative:
    - Science Return Increased by Taking Advantage of Several Sensors Distributed on Several Platforms
    - Some Examples:
      - Processing on one SC triggers a command to another SC
      - Processing results and/or datasets sent to other SC for integration

When does it make sense For a Constellation to be Fully Autonomous?

- Observe events that are unpredictable in terms of :
  - Location
  - Start Time
  - Duration Time
  - Movement/Change throughout Duration Time

- Communication time to the ground vs. between spacecraft does not allow to optimally observe the event (time varies as a function of distance to the ground; "event" definition different for LEO or Deep Space or Planetary missions)

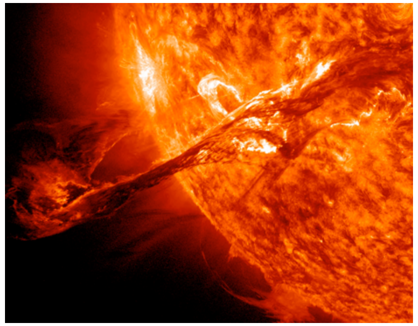
- Information obtained from multiple distributed sensors about the event is much smaller in terms of data rate compared to sending the full datasets

- Some Basic Conditions:
  - Area of interest observable by at least 1 SC in the constellation at all times of the event duration
  - {Onboard Processing + inter-SC communication} time small compared to event changes

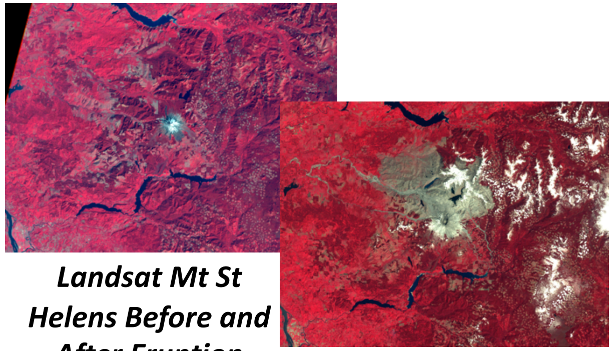
Autonomy Application:
Transient Event Observation

- Intelligent and collaborative sensing initiated by autonomous recognition of a science event of interest
- Earth Science or Heliophysics Constellation Example:
  - All spacecraft have a Wide Field of View (WFOV) sensor and one Narrow Field of View (NFOV) sensor with higher spatial resolution than the WFOV sensors
  - Desired area of observation viewed at good enough resolution and with short enough revisit time intervals such that transient events of interest (e.g. fires, floods, eruptions) can be detected quickly.
  - Onboard processing and inter-satellite communications capabilities
- Key Capabilities:
  - Recognize quickly and onboard science events of interest
  - Exchange data inter-spacecraft
  - Optimize data acquisition by targeting NFOV based on WFOV observations analysis to optimize science data return
- Benefits:
  - Follow fast-evolving events in real-time
  - No or minimal ground intervention
- Questions:
  - What should be the “speed” of events for an autonomous constellation to be beneficial?
  - Which computing capabilities needed onboard?

EO-1 California Forest Fires



STEREO spots a Coronal Mass Ejection (CME) soaring into space



Landsat Mt St Helens Before and After Eruption

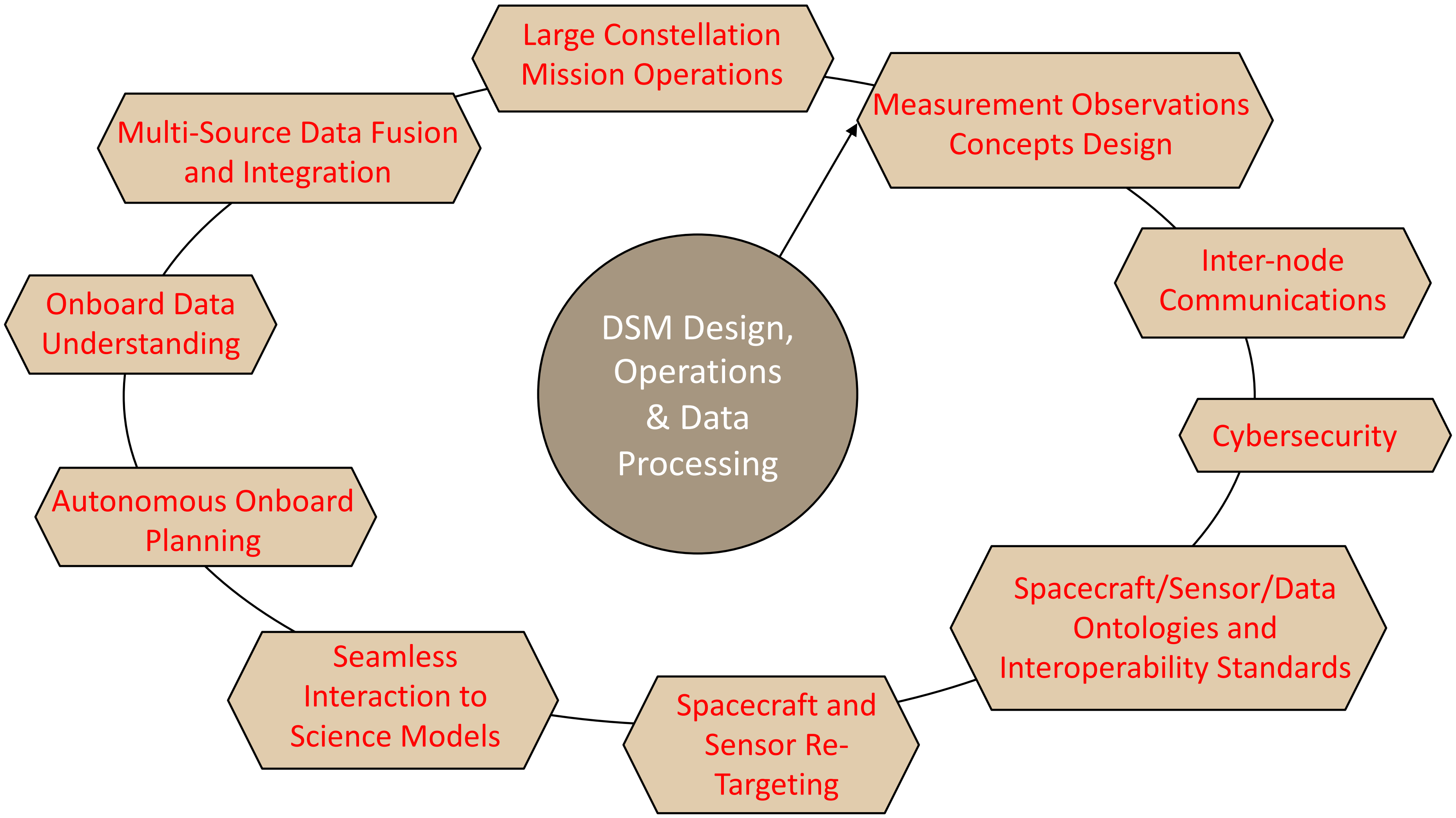
Technologies Needed for DSM

Some Examples of Capabilities Needed Onboard:

- Recognizing science events of interest
- Exchanging data inter-spacecraft
- Analyzing data for optimal science return
- Reconfiguring the spacecraft based on coordinated observations

Some Relevant AI Technologies:

- Explainable AI and Transfer Learning
- Onboard Computer Vision
- Onboard computing for data reduction, intelligent data fusion and interpretation
- Autonomous Decision Making
- Anomaly and diagnostic resolution



Some Technologies Required for ICCs

- **Onboard Processing**
  - High Performance Spaceflight Computing
  - Radiation-Hardened vs. Radiation Mitigation by Software (e.g., SpaceCube)
  - Neuromorphic Computing
- **Enabling and Supporting Technologies**
  - Multi-Spacecraft Flight Software
  - Real-Time and Onboard Image Processing and Analysis
  - Sensor Protocols and Secure Access
  - Semantic Representation (Bridge) of Disparate Observation Data
  - Precision Attitude Control Systems
- **Collaborative Systems Technology**
  - Dynamical and Fast Sensor/Inter-Spacecraft Communications
  - Sensor Fleet Management; Automated Tools for Mission Planning, Risk Analysis and Value Assessment
- **Knowledge Management for Decision Making**
  - Onboard Machine Learning and AI Technologies
  - Data/Information Fusion and Decision Systems

Current NASA DSM Tech Development *Distributed Spacecraft Autonomy (DSA)*

Game Changing Development (GCD) Technology – POC: Mark Micire/ARC:

- Objective: Demonstrate Autonomous Decision Making
  - For deep-space multi-spacecraft missions due to latency, bandwidth constraints, and mission complexity.
  - To increase the effectiveness of multi-spacecraft missions by operating them as a collective rather than individually.
- DSA Goals:
  - Advance command and control methodologies for controlling a swarm of spacecraft as a single entity.
  - Develop, mature, and demonstrate autonomous coordination between multiple spacecraft in the swarm.
  - Develop, mature, and demonstrate approaches for adaptive reconfiguration and distributed decision-making across a swarm of spacecraft.
- DSA will demonstrate autonomy with up to four spacecraft in conjunction with the Starling flight mission in the first 2 years, and independently from Starling on ground hardware with 100 spacecraft in the 3rd year.
- DSA will exclusively focus on the following technical areas related to scalable spacecraft autonomy:
  - **Reactive Operations**
  - **Distributed Resource and Task Management**
  - **Verification and Validation Techniques**

- DSA will partner with Starling flight mission on the following technical areas related to scalable spacecraft:
  - **Human-Swarm Interaction**
  - **Ad hoc Network Communications**
  - **System Modeling and Simulation**

Current NASA DSM Tech Development
Planning & Scheduling for Coordinated Obs

Earth Science and Technology Office (ESTO) – POC: Steve Chien/JPL

- Autonomous planning and scheduling framework to coordinate multiple observing assets (e.g. space, air, land) to perform coordinated and continuous measurements at varying scales (e.g. spatial, temporal).
- Relevant planning and scheduling capabilities include automated or autonomous:
  - Scheduling/resource management
  - Data interpretation
  - Multi-modal observations, and
  - Assimilation of information from other models, services, and nodes in the Constellation/Sensorweb.
- Builds on:
  - CASPER (Continuous Activity Scheduling Planning Execution and Replanning) which uses iterative repair to support continuous modification and updating of a current working plan in light of changing operating context.
  - ASPEN (Automated Scheduling and Planning ENvironment), based on AI techniques, which is a modular, reconfigurable application framework for complex planning/scheduling systems and to develop a sequence of commands for a system that achieves the user's objectives.

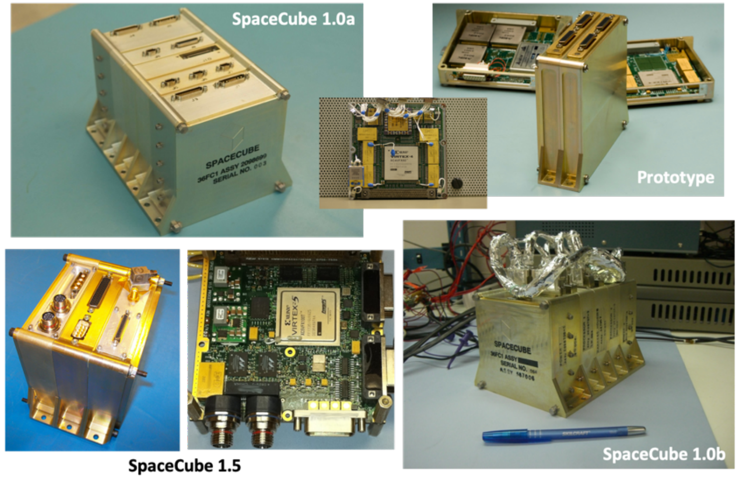
SensorWeb Experiments, POCs: Dan Mandl (GSFC, now Aerospace) and Steve Chien/JPL

- Namibian Early Flood Warning SensorWeb Pilot Project (NASA, UN-Spider, Namibia Department of Hydrology, Canadian Space Agency, Ukraine Space Research Institute, DLR (Germany) and others)
- Volcano SensorWeb Pilot Project
- Fire SensorWeb Pilot Project (with NRO, DIA, CEOS, Forest Service and NASA ARC)

Current NASA Tech Development for DSM
Onboard Processing

SpaceCube Family, POC: Gary Crum/NASA GSFC

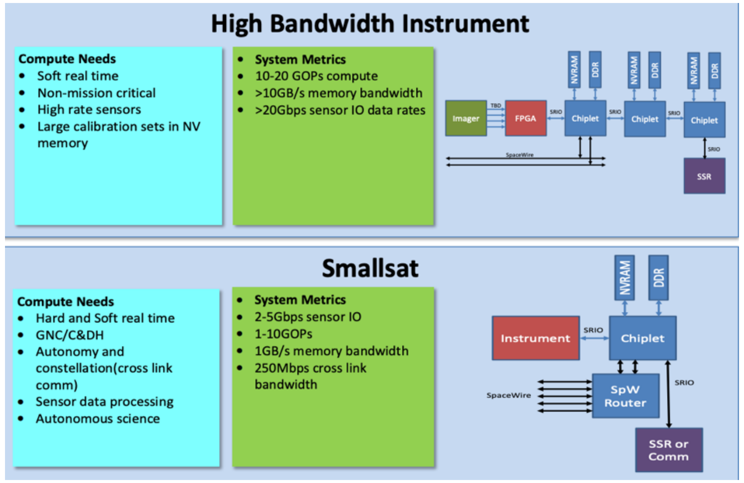
- SpaceCube: Field Programmable Gate Array (FPGA) based on-board hybrid science data processing system.
- Provides 10× to 100× improvements in on-board computing power while lowering relative power consumption and cost.
- “Order of magnitude" increase in processing power + Ability to "reconfigure on the fly" => Implement algorithms to detect and react to events, and produce data products on-board => Enable multi-platform collaboration.



SpaceCube 1.5

High Performance Spaceflight Computing (HPSC), POC: Rich Doyle/JPL and Wes Powell/GSFC

- Joint project between NASA and United States Air Force (USAF), which includes both AFRL and SMC.
- Goal: Develop a high-performance multi-core radiation hardened flight processor
- HPSC offers a new flight computing architecture to meet the needs of NASA missions through 2030 and beyond.
- Will provide on the order of 100X the computational capacity of current flight processors for the same amount of power, the multicore architecture of the HPSC processor, or "Chiplet" provides unprecedented flexibility in a flight computing system.



HPSC Chiplet Architecture Applications

New Observing Strategies Testbed

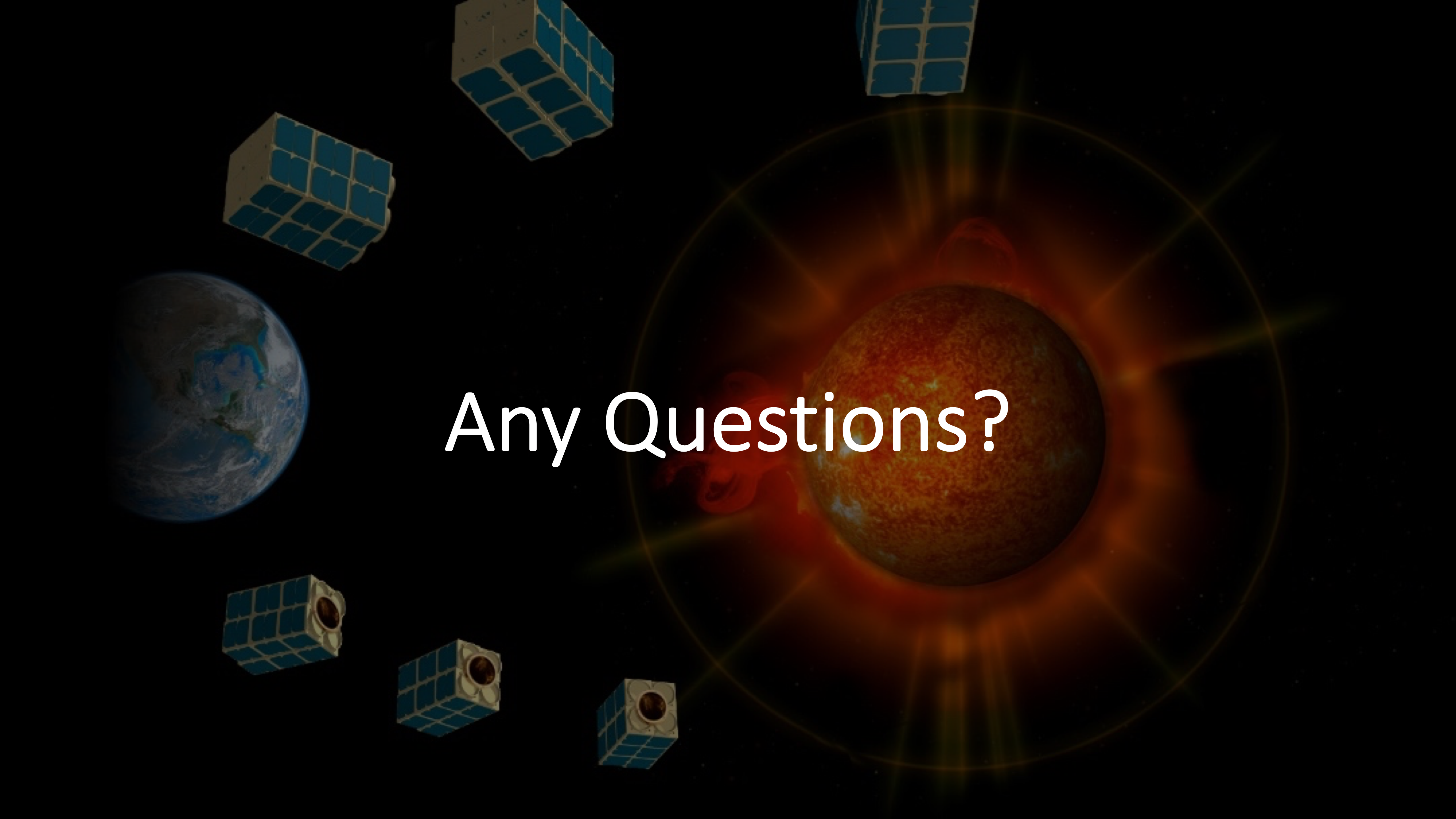
- Technologies to be deployed should be first integrated into a working ***breadboard*** where the components can be debugged and performance and behavior characterized and tuned-up.
- A system of this complexity should not be expected to work without full integration and experimental characterization as a "system of systems"

Testbed Main Goals:

1. Validate new DSM/NOS technologies, independently and as a system
2. Demonstrate novel distributed operations concepts
3. Enable meaningful comparisons of competing technologies
4. Socialize new DSM technologies and concepts to the science community by significantly retiring the risk of integrating these new technologies.

DSM and Autonomous ICC
Future Directions

- Develop Various **Use Cases and Design Reference Missions** Corresponding to Candidate Science and Application Needs
- Identify **Technology Needs and Gaps**, as well as State-of-the-Art Capabilities
- **Validate Novel Technologies** in the ESTO Testbed then in Tech Demo Missions (e.g., SMD/InVEST, STMD/SST)
- **Transition and Infuse** DSM and Autonomous ICC Technologies in Future NASA Missions and Projects



Any Questions?