NEW OBSERVING STRATEGY (NOS) FOR FUTURE EARTH SCIENCE MISSIONS

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ABSTRACT

One of the new thrusts of the Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) Program is the New Observing Strategy (NOS) thrust. Its goal is to provide a framework for identifying technology advances needed to exploit newly available observational capabilities, particularly to enable the development of the information technologies needed to support planning, evaluating, implementing, and operating dynamic, multi-element sets of observing assets. In this paper, we will introduce relevant NOS terminology and some key concepts before describing the objectives, driving factors and technology goals of this new thrust.

Index Terms— Distributed Spacecraft Missions (DSM), Constellations, SensorWebs, Earth Science missions.

1. INTRODUCTION

The Advanced Information Systems Technology (AIST) Program is part of NASA's Science Mission Directorate (SMD) Earth Science Technology Office (ESTO). Its goal is not only to reduce the risk, cost, size and development time of future Earth Science missions and their corresponding information systems and to increase the use of Earth Science data, but also *to enable new observation measurements and information products.* In particular, with the emergence of new sources of observational data, including high-quality science instruments on CubeSats and SmallSats, and the development of commercial space platforms, phenomena that previously could not have been studied or would have been too expensive to study, can now be observed through a novel variety of measurements. Because of their relatively low cost and easy access to space these research instruments, hosted on small spacecraft and commercial satellites, enable observing strategies using multiple or even large numbers of similar platforms, yielding high revisit rates or multi- angle observations of the same phenomenon. In addition, the ability to point instruments, coupled with new high-performance onboard processing capabilities, enables high-density observations for specific phenomena of interest instead of operating in a fixed pattern. This new type of observation strategy will involve the coordination and integration of various instruments located at different vantage points from NASA and non-NASA sources, including in orbit, airborne and even in-situ sensors to create a more dynamic and complete picture of a natural physical process.

In this paper, we will introduce relevant NOS terminology and some key concepts before describing the objectives, driving factors and some of the technology capabilities required to make this new thrust a reality.

2. NEW OBSERVING STRATEGY DEFINITIONS, DRIVERS AND CONCEPTS

Generally, a New Observing Strategy is defined as:

- Multi-sensor nodes producing measurements integrated from multiple vantage points and in multiple dimensions (spatial, spectral, temporal, radiometric)
- Providing a unified picture of the physical process or natural phenomenon

These multiple (homogeneous or heterogeneous) nodes can be distributed in orbit within an actual or virtual distributed mission, with large or smaller spacecraft, or/and on aerial platforms and/or in-situ.

In order to further introduce NOS concepts, a few definitions need to be introduced:

– A ***"Distributed Spacecraft Mission (DSM)"*** is a mission that involves multiple spacecraft to achieve one or more common goals. A DSM can be defined from inception and we call it a "Constellation" (see below), or it can become a DSM after the fact, in which case we will call it an "ad-hoc" DSM or a "Virtual" mission. For all these types of DSM, we do not assume the spacecraft to be of any specific sizes, i.e., we do not restrict this study to CubeSats or SmallSats, although lowering cost considerations will involve choosing smaller spacecraft. Throughout this paper, a reference to a "CubeSat" is the class of satellites smaller than 10 kgs, "MicroSat" between 10 and100 kg and "MiniSat" from 100 to 180 kg.

– A ***"Constellation"*** is a space mission that, beginning with its inception, is composed of two or more spacecraft that are placed into specific orbit(s) for the purpose of serving a common objective (e.g., CYGNSS, TROPICS, Iridium). A constellation can be *Homogeneous* or *Heterogeneous.* It is called homogeneous if all member spacecraft employ functional identical bus, payload, and operational characteristics; heterogeneous, if not.

– An ***"Intelligent and Collaborative Constellation (ICC)"*** is a constellation that uses onboard intelligence to perceive its environment, takes actions that maximizes its chances of success in creating coordinated observations; it can potentially learn from its experiences. An ICC involves the combination of:

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

– A ***"SensorWeb"*** is a distributed system of *sensing nodes* (space, air or ground) that are interconnected by a *communications fabric* and that function 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 (e.g., predictive models) by modifying its observing state so as to *optimize mission information return.* (Note: a "communications fabric" is a communications infrastructure that permits nodes to transmit and receive data between one another) (e.g., EO-1 SensorWeb 3G) [Tal05, Man10].

Some of NOS drivers are the following:

- Respond to the requirement of measurement-based concept defined in the latest 2017 Earth Science Decadal Survey. NOS will enable missions to:
  - Take advantage of multiple modes (wavelengths and spatial, spectral, temporal resolutions), multiple vantage points, etc.
  - Create some transparent connections between science models and data acquisition.
  - Reduce costs: large flagship missions could be designed only when needed, after first leveraging existing government and commercial assets, ground sensors, Unmanned Air Vehicles (UAVs), balloons, instruments on the International Space Station (ISS) and various SmallSats and CubeSats.
- Create an "internet" of sensor data, from models up to in-orbit assets, via all intermediate levels. It would:
  - Link Earth and future space Internets to Earth Science sensor nodes
  - Link to other space networks (e.g., DARPA Blackjack)
  - Present mission interaction and partnerships with industry and academia.
  - Provide interoperability and accessibility to large flagship missions
  - Provide future links between an Earth SensorWeb (SW) to an Helio SW to a Lunar SW to a Martian SW, etc.
- Create an analog-like system to test future lunar, Mars or deep-space SensorWebs and constellations
- Facilitate societal applications by:
  - Responding quickly and on-demand to unexpected events (hurricanes, volcanoes, etc.)
  - Leveraging "out of network" assets for emergencies (DOD-, NOAA-, Foreign-, etc.).

An example of an NOS or SensorWeb concept is illustrated in Figure 1, in which an event of interest, for example a storm, is observed collaboratively with a variety of multi-vantage point heterogeneous sensors interacting with the models and the end users.

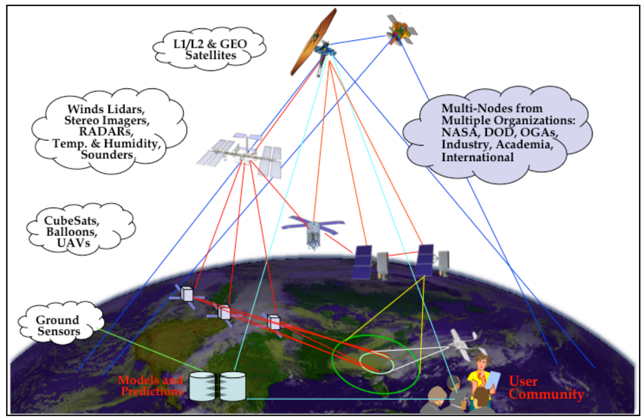

Figure 1 – ***Example of a New Observing Strategy for Acquiring Real-Time and Coordinated Observations of an Event of Interest***

Overall, this type of strategy will improve our response to the needs of various Earth Science domains; e.g., for hydrology, studying river flow and flooding, 3D snow fall and aquifer degradation, for cryospheric studies in glacier and sea ice changes, for urban air quality events, for biodiversity studying migrations, invasive species and transient spring phenomena, and for solid Earth Interior studying landslides, plate movement, volcanic activity and interior magma movement.

Additional NOS benefits to Earth Science users include the possibilities of reconfiguring groups of instruments to provide various measurements and customized products or of performing rapid prototyping of new products within hours. Ultimately increasing science timeliness, science knowledge and science application.

3. NEW OBSERVING STRATEGIES REQUIRED CAPABILITIES

In order to enable the New Observing Strategy described in Section 2, we identified 6 software technology areas corresponding to different steps of the Earth observation lifecycle:

1. **Concepts Design:**
   a. Develop tools for pre-Phase A/Phase A constellation mission design, optimizing various constellation variables such as number of spacecraft, number of orbiting planes, altitude, inclination, sensor characteristics, etc., as a function of the observation requirements.
   b. Tools for measurement observations concept design, combining existing assets with or without adding new nodes.
2. **NOS Systems Development and Validation:**
   a. Definition of ontologies; extension of existing and development of new standards, e.g., the Open Geospatial Consortium (OGC) Sensor Web Enablement (SEW) and Swath Coverage standards [Per13, Sim18]
   b. Development of testbeds and testing frameworks, e.g., hardware-in-the-loop systems and multi-node software testbeds.
3. **Inter-Nodes Communications:**
   a. Development of algorithms and protocols for inter-spacecraft communications and coordination.
   b. Cybersecurity
   c. Development of algorithms and protocols for science models to query and target sensors.
4. **Operations:**
   a. Algorithms for autonomous sensing and control.
   b. Algorithms for Coordinated pointing and measurement acquisition.
5. **Onboard Intelligence:**
   a. Onboard recognition of events of interest
   b. Onboard goal-oriented planning and scheduling
6. **Ground Data Processing:**
   a. Multi-node mission operation centers and ground data systems
   b. Solutions for multi-node/SensorWeb "Big Data" operations challenge
7. **Science Data Processing**
   a. Scalable data management for large multi-source science data
   b. High accuracy multi-platform calibration and registration
   c. Integration and fusion of disparate multi-source data.

Figure 2 gives a graphical representation of these NOS capability areas.

4. CONCLUSION

This paper describes a new thrust in NASA Earth Science Advanced Information Systems Technology Program, namely the New Observing Strategy (NOS) thrust. It encompasses the use of multi-node sensor data coordination and integration for providing a multi-vantage, multi-resolution picture of a Science phenomenon. Definitions, driving factors, benefits, example concepts and required software technologies were highlighted. More details will be presented at the conference.

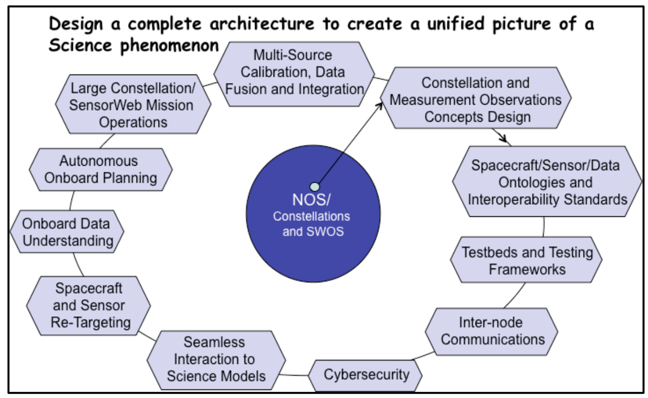

Figure 2 – *New Observing Strategy Lifecycle Software Technology Capabilities*

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New Observing Strategy (NOS) for Future Earth Science Missions

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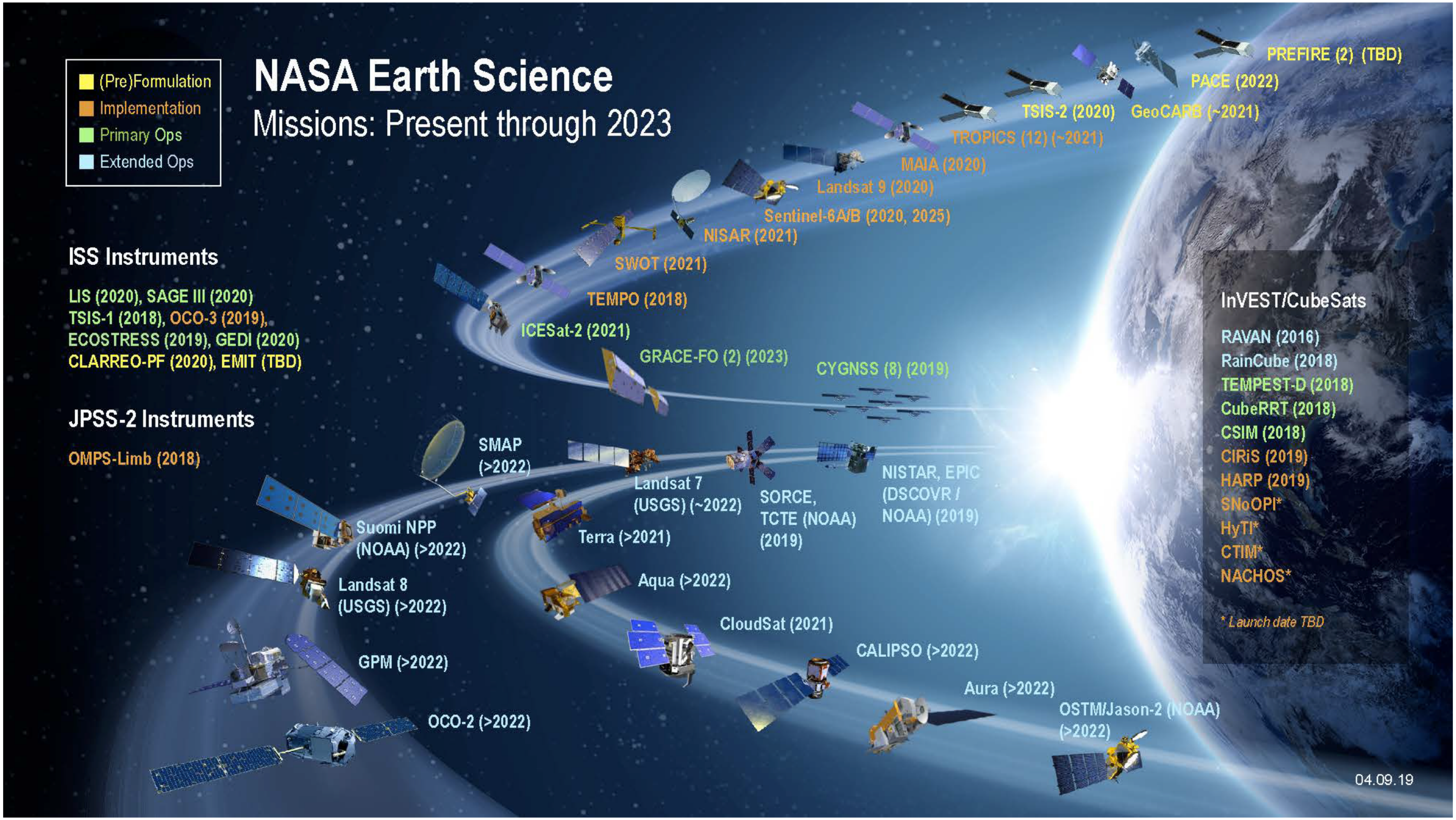
Advanced Information Systems Technology (AIST) Program

ESTO/AIST Objectives

- **AIST**
  - Advanced Information Systems Technology Program
  - Part of the Earth Science Technology Office (ESTO) in NASA Science Mission Directorate (SMD)

- **AIST Goals**
  - Reduce the risk, cost, size, and development time of Earth Science Division (ESD) space-based and ground-based information systems;
  - Increase the accessibility and utility of science data; and
  - Enable new observation measurements and information products.

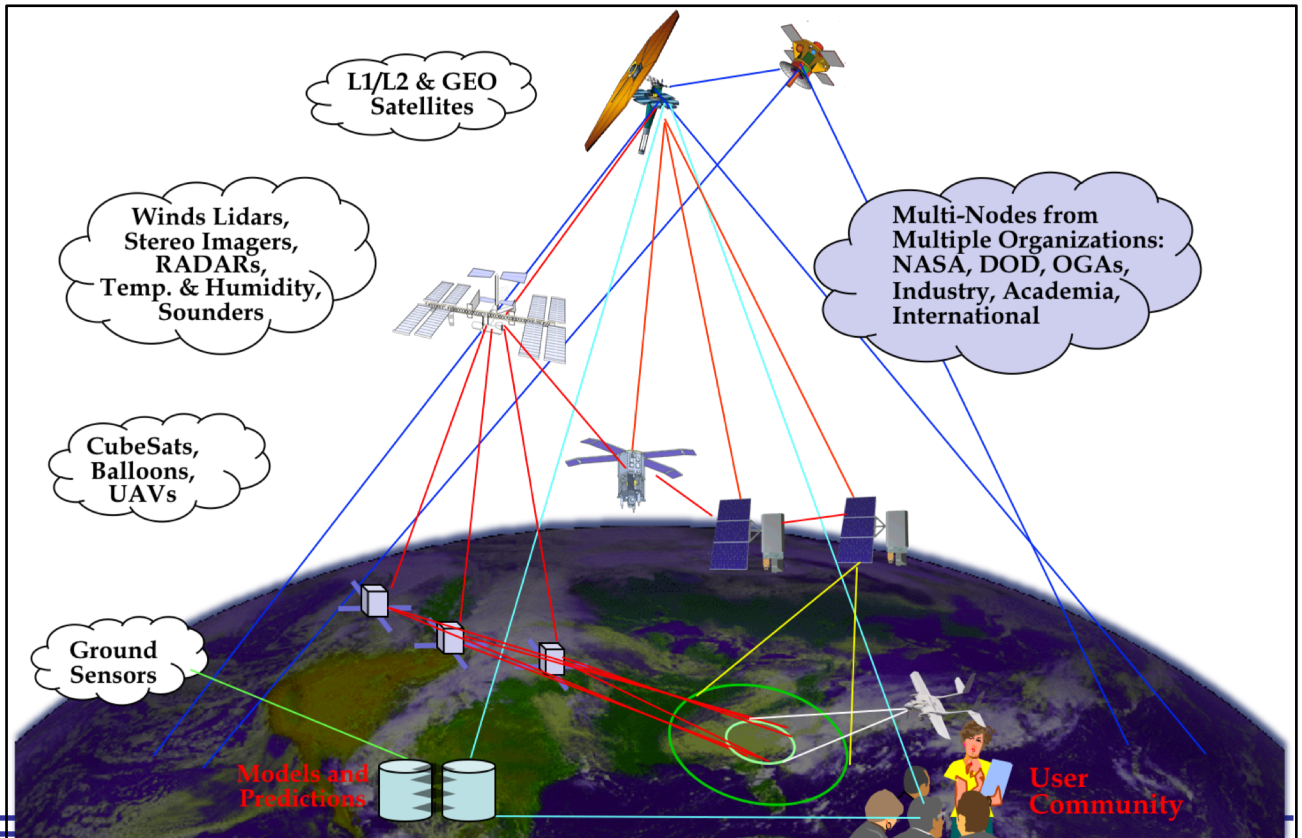
Current Observing Strategy



New Observing Strategies (NOS)

New Observing Strategies:

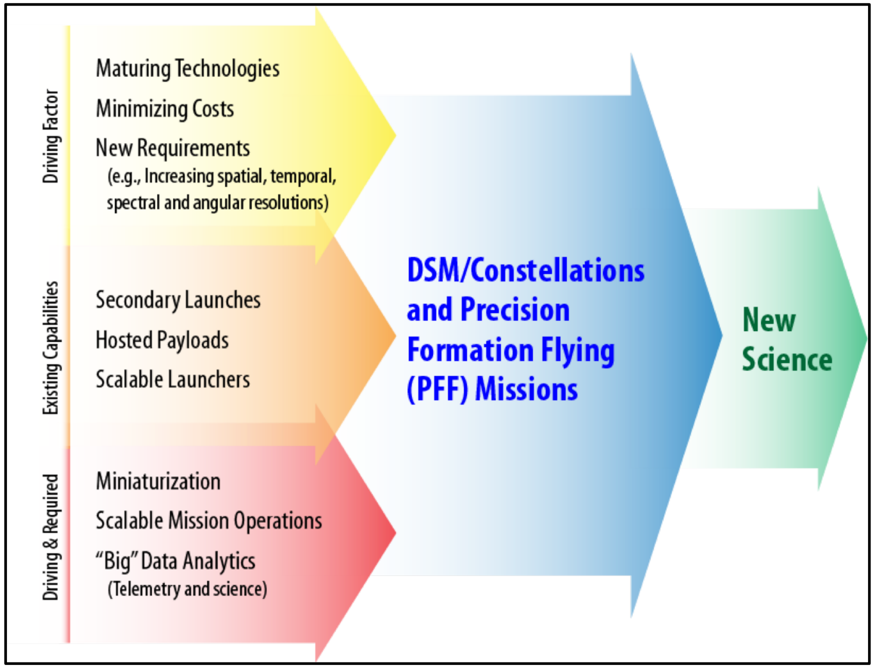
- Multiple collaborative sensor nodes producing measurements integrated from multiple vantage points and in multiple dimensions (spatial, spectral, temporal, radiometric)
- Provide a dynamic and more complete picture of physical processes or natural phenomena



ESTO Earth Science Technology Office

NOS 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*



NOS will:

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

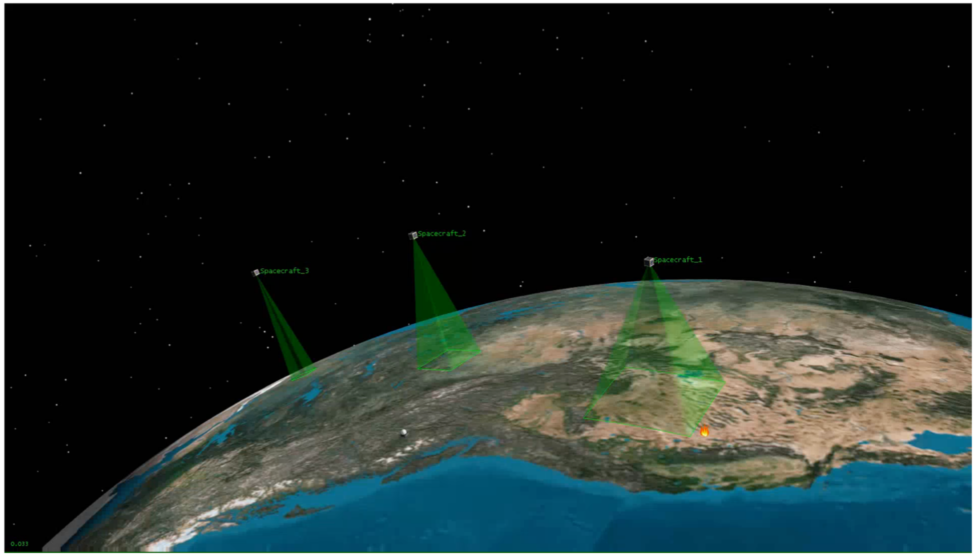
NOS Goals:

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

DSM/ICC and Sensor Webs

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.



A Sensor Web 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 (e.g., predictive models) by modifying its observing state so as to *optimize mission information return.* (Note: a "communications fabric" is a communications infrastructure that permits nodes to transmit and receive data between one another) (e.g., EO-1 SensorWeb 3G). (Ref: Steve Talabac et al, 2003)

NOS Drivers

- **Respond to new Earth Science Decadal Survey – Measurement-based:**
  - Utilize multiple modes (wavelengths, spatial, temporal res), multiple vantage points, etc. to create a unified picture of a physical process or natural phenomenon
  - Reduce costs: large flagship missions only when needed, leverage first existing govt and commercial assets, ground sensors, UAVs, balloons, instruments on ISS and CubeSats
- **Create an "internet" of sensor data, from models up to in-orbit assets, via all intermediate levels:**
  - Link WWW to Space-Internet
  - Link to other networks (e.g., DARPA Blackjack)
  - Provide interoperatibility-accessibility with/to large flagship missions
  - Future: link Earth SensorWeb to Helio SensorWeb to Lunar SensorWeb to Martian SensorWeb, etc.
- **Create an analog-like system to test future lunar, Mars or deep-space sensor webs and constellations**
- **Societal Applications:**
  - Respond quickly, on-demand to unexpected events (hurricanes, volcanoes, etc.)
  - Leverage "out of network" assets for emergencies (DOD-, NOAA-, Foreign-, etc.)

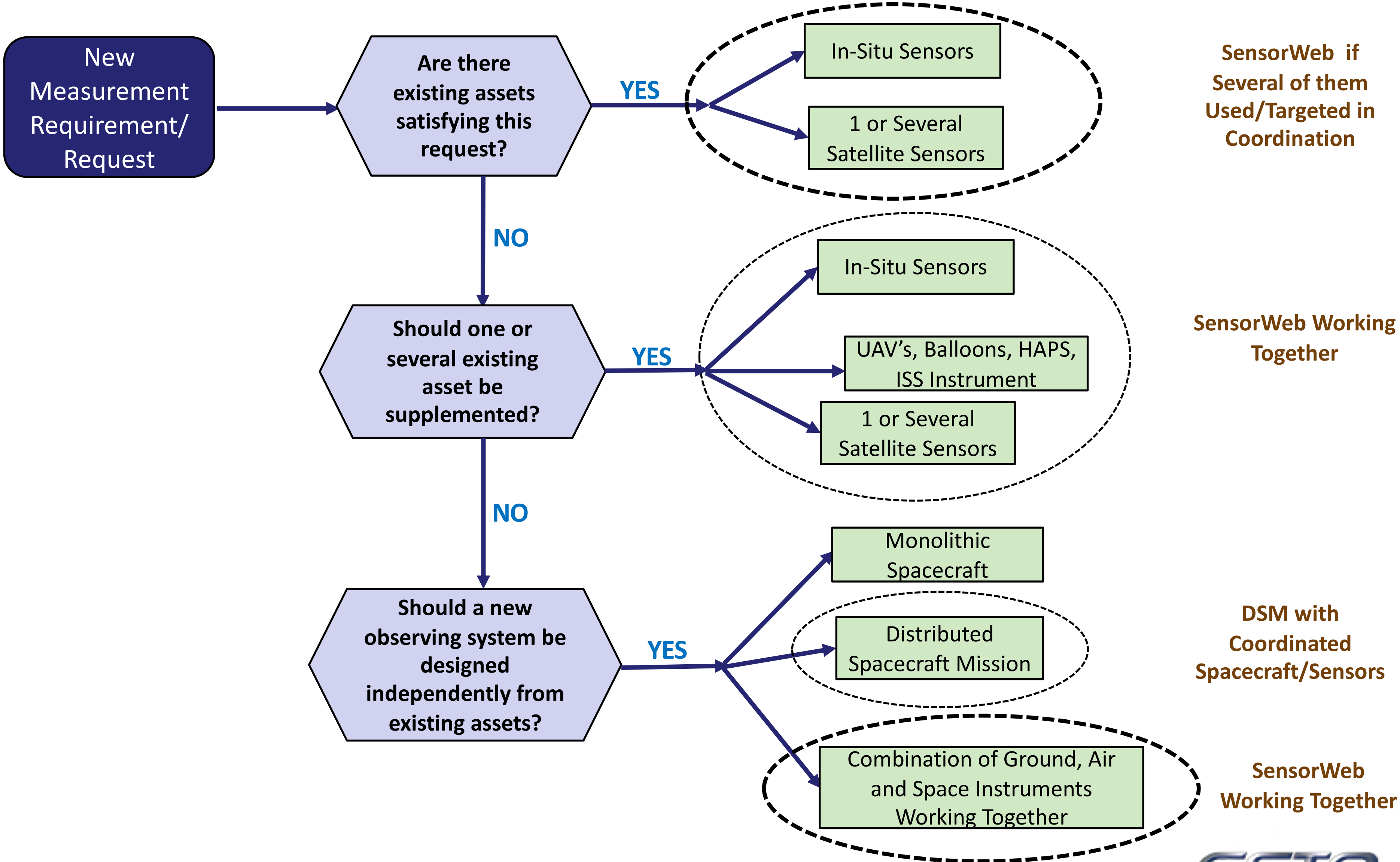
NOS Enables Earth Science

- **Improved Models that can Drive Observations**
  - Integrate models with in situ, airborne and orbital instruments
  - Continuously running models direct the observation system in collecting data

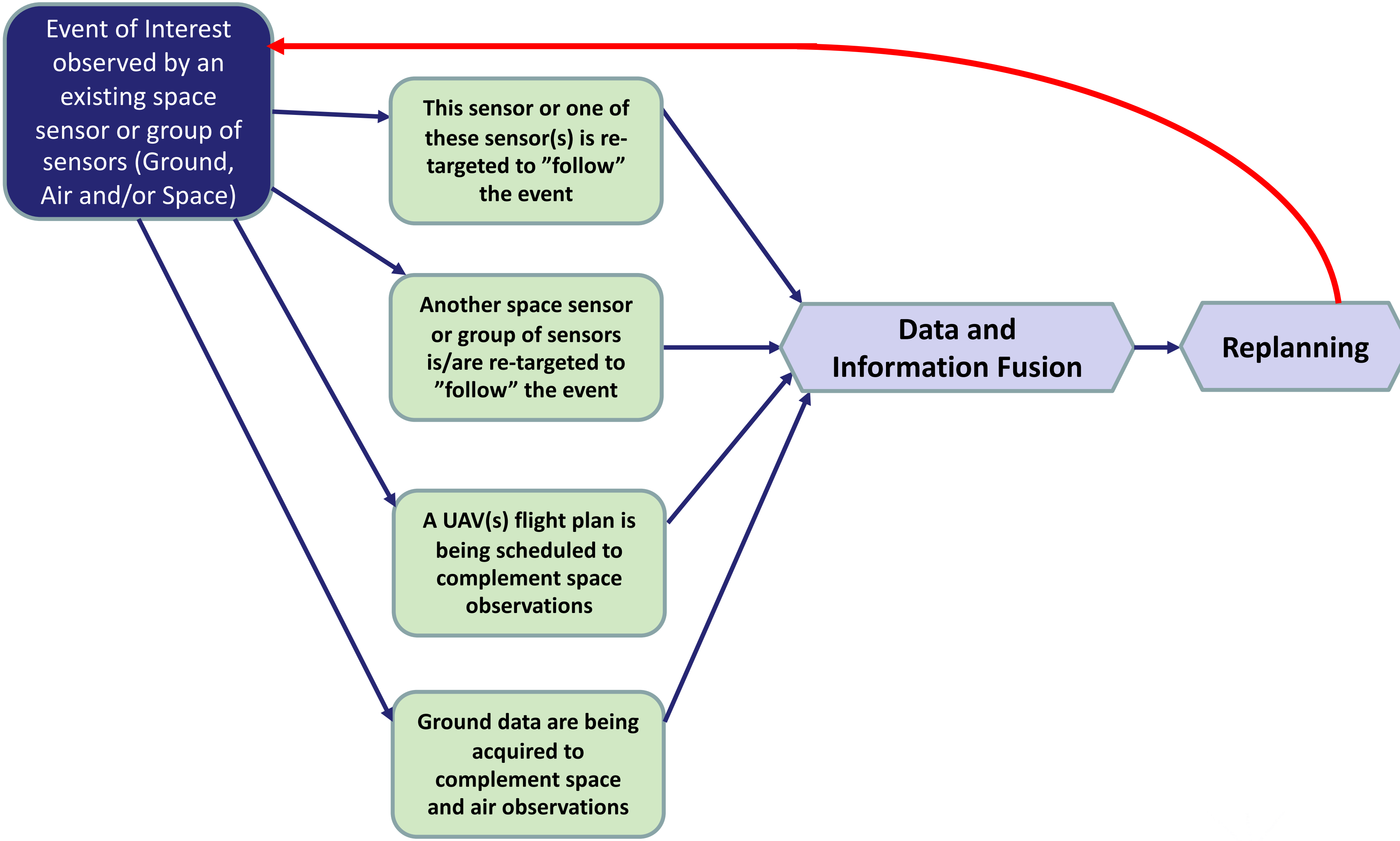
- **Real-time targeting of transient and transitional phenomena**
  - In situ triggering of observing system
  - Train configuration prolonging observation of an event
  - Viewing an event from multiple angles
  - Autonomy in focusing the observational system on the event

- **Coordinated arrays of sensors (station keeping)**
  - Reduce error with statistics
  - Improve resolution with multi-node instruments in phased arrays
  - Viewing of phenomenon from multiple angles and directions

New Observing Strategies (NOS) – *Measurement Acquisition ("Mission" Design or Model-Driven)*



New Observing Strategies (NOS) – *Observation Planning or Rapid Response to Event of Interest*



NOS for Candidate Science Needs

- **Hydrology**
  - River flow and Flooding
  - Snow fall in 3D
  - Aquifer degradation
- **Precipitation**
  - Extreme precipitation events
- **Cryosphere**
  - Glaciers changes
  - Sea Ice changes
- **Urban Air Quality Events**
  - At a resolution (vertical and horizontal)
- **Biodiversity**
  - Migrations
  - Invasive species
  - Transient spring phenomena
- **Solid Earth and Interior**
  - Landslides
  - Plate movement
  - Volcanic activity
  - Interior magma movement
- **Disaster Management**
  - Floods
  - Earthquakes
  - Volcanic Eruptions

Example of an Hydrology Use Case

Flood Monitoring with Space and Ground Sensors

1. A weather forecast or radar image indicates the potential for flood-inducing precipitation.

2. This triggers a network of ground-based sensors measuring changes in overland flow to begin telemetering data at high frequency.

3. When the ground sensors detect change in overland flow, they trigger a series of additional measurements:
   a. Space-based measurements, e.g., combination of space-based optical and radar, to determine surface water extent.
   b. In-situ measurements taken by either USGS technicians or future in-situ or UAS-mounted sensors, to measure high water level.
   c. A constellation of radar CubeSats is tasked to take targeted multi-angle measurements

Next Steps – Future Directions

- Develop Various **Use Cases** Corresponding to Candidate Science and Application Needs
- Define Required **NOS Technologies** Required to Develop Future NOS Concepts
- Establish an **NOS Testbed (NOS-T)** to Test and Validate NOS Technologies and Concepts
- **Transition and Infuse** NOS Technologies in Future Earth Science Missions and Projects:
  - Integration with Science and Forecast Models
  - Augmentation of Spaceborne Missions with Ground and Airborne Sensors
  - Definition of ISS Experiments or CubeSat Constellations