Advanced Information Systems Technology (AIST) New Observing Strategies (NOS) Workshop

Summary Report

Jacqueline Le Moigne – NASA Earth Science Technology Office (ESTO)
Marge Cole – NASA ESTO – KBR, Inc.

*Edited by **NOS Workshop Participants***

Workshop held on February 25-26, 2020
Hyatt Place, Washington, DC

Workshop presentations and reference materials located on the
ESTO/AIST “NOS Workshop 2020” Website.

Table of Contents

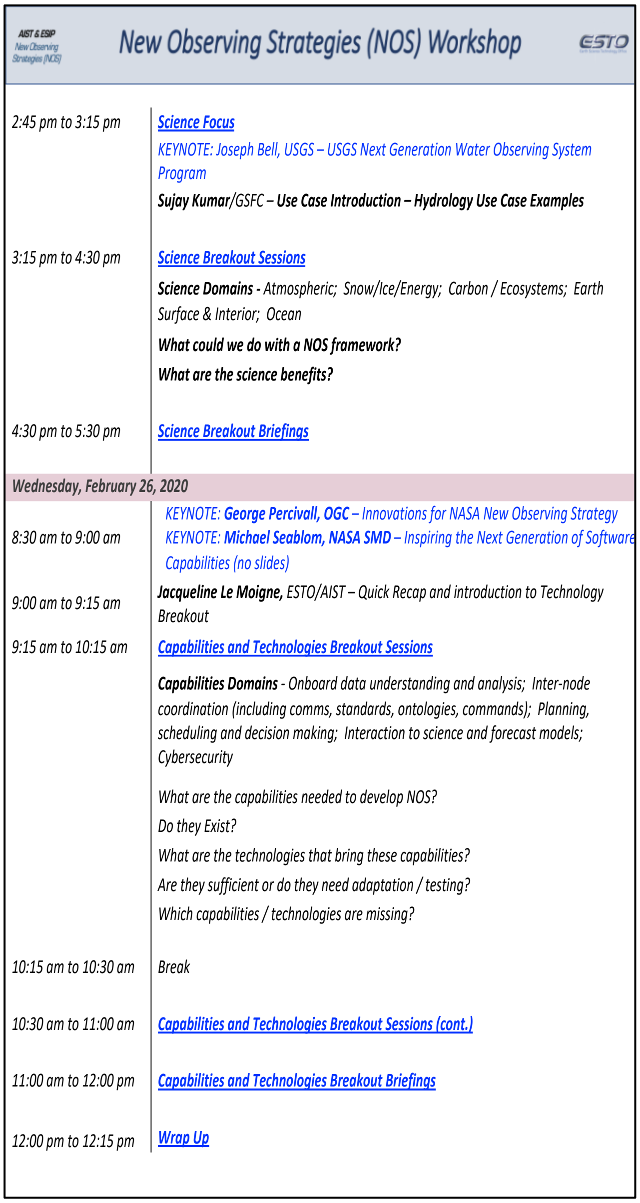
Workshop Agenda

AIST & ESIP
New Observing Strategies (NOS)

New Observing Strategies (NOS) Workshop

ESTO

Tuesday, February 25, 2020	
8:30 am to 9:00 am	**Arrival**
9:00 am to 10:45 am	**Welcome and Introductions** **Jacqueline Le Moigne,** ESTO/AIST – General Introduction to NOS and to the Workshop **Annie Burgess,** ESIP – General introductions **Tom McDermott,** SERC – NOS-Testbed (NOS-T) Framework KEYNOTE: **Sid Boukabara,** NOAA – NOAA Future Space Architecture
10:25 am to 10:45 am	Break
10:55 am to 11:35 am	**Project Briefs** **Daniel Cellucci & Chad Frost**/ARC – Ames Research Center Pilot Project: 'Tip' and 'Cue' Architectures for The New Observing System **Sujay Kumar**/GSFC – A Hydrology Mission Design and Analysis System (H-MIDAS) **Dan Crichton**/JPL – Data Driven Observations for Water Resource Management **Steve Chien**/JPL – Dynamic Tasking of Earth Observing Assets **Paul Grogan**/Stevens – Trade-space Analysis Tool for Constellations (TAT-C) **Sreeja Nag**/ARC&BAER – D-Shield: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions
11:35 am to 12:00 pm	**Group Discussions** - Attendees
12:00 pm to 1:00 pm	Lunch
1:00 pm to 2:05 pm	**Project Briefs (cont.)** **Matt French**/USC-ISI – Enabling New Observation Strategies Through On-board Computing and System Virtualization **Jim Carr**/Carr Astronautics – StereoBit: Advanced Onboard Science Data Processing to Enable Future Earth Science **Derek Posselt**/JPL – A Science-Focused, Scalable, Flexible Instrument Simulation (OSSE) Toolkit for Mission Design **Lorraine Fesq**/JPL – ASTERIA Amazon Ground Station Experiment **Ethan Gutmann**/NCAR – Preparing NASA for future Snow Missions: Integrating the Spatially explicit SnowModel in LIS **Joel Johnson**/OSU – Including On-Platform Sensor Adaption, On-Platform Resource Management, and Cross-Platform Collaboration in NOS Studies **Ruzbeh Akbar**/MIT – SoilSCAPE & SPCTOR: Summary of AIST Projects
2:05 pm to 2:30 pm	**Group Discussions** - Attendees



AIST & ESIP
New Observing Strategies (NOS)

New Observing Strategies (NOS) Workshop

ESTO

2:45 pm to 3:15 pm	**Science Focus** KEYNOTE: Joseph Bell, USGS – USGS Next Generation Water Observing System Program **Sujay Kumar**/GSFC – **Use Case Introduction – Hydrology Use Case Examples**
3:15 pm to 4:30 pm	**Science Breakout Sessions** **Science Domains** - Atmospheric; Snow/Ice/Energy; Carbon / Ecosystems; Earth Surface & Interior; Ocean **What could we do with a NOS framework?** **What are the science benefits?**
4:30 pm to 5:30 pm	**Science Breakout Briefings**
Wednesday, February 26, 2020	
8:30 am to 9:00 am	KEYNOTE: **George Percivall, OGC** – Innovations for NASA New Observing Strategy KEYNOTE: **Michael Seablom, NASA SMD –** Inspiring the Next Generation of Software Capabilities (no slides)
9:00 am to 9:15 am	**Jacqueline Le Moigne,** ESTO/AIST – Quick Recap and introduction to Technology Breakout
9:15 am to 10:15 am	**Capabilities and Technologies Breakout Sessions** **Capabilities Domains** - Onboard data understanding and analysis; Inter-node coordination (including comms, standards, ontologies, commands); Planning, scheduling and decision making; Interaction to science and forecast models; Cybersecurity What are the capabilities needed to develop NOS? Do they Exist? What are the technologies that bring these capabilities? Are they sufficient or do they need adaptation / testing? Which capabilities / technologies are missing?
10:15 am to 10:30 am	Break
10:30 am to 11:00 am	**Capabilities and Technologies Breakout Sessions (cont.)**
11:00 am to 12:00 pm	**Capabilities and Technologies Breakout Briefings**
12:00 pm to 12:15 pm	**Wrap Up**

Executive Summary

On February 25-26, 2020, the Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) Program conducted a successful New Observing Strategies (NOS) Workshop in Washington, DC. The main goal of the NOS concept is to dynamically optimize measurement acquisition using many diverse observing capabilities (space, air and ground), collaborating across multiple dimensions and creating a unified architecture. The workshop presented the current state of Earth observing system architectures in several U.S. organizations, including SmallSats and Distributed Spacecraft Missions (DSM); defined science use cases that could benefit from intelligent and collaborative distributed interactive systems architectures; and identified technology capability concepts required to achieve such future observing systems architectures. The workshop was attended by past and current AIST project teams as well as by a few relevant government agencies representatives.

Exceptional participation from all attendees enabled a productive workshop and beneficial outcomes. In reviewing the data gathered from the workshop, it was determined that additional mini-breakout sessions would supplement and substantiate the science and technology scenario information already collected, especially in those domains in which there were notable intersections. The virtual NOS mini-breakouts were held over a range of dates from June 10 to July 1, 2020.

This report includes:

1. The characteristics and benefits of NOS architectures;
2. A summary of all presentations made during the workshop;
3. Outcomes of the science use cases and mini-breakout discussions, including their relation to NASA's science requirements and to the objectives of the 2017 Earth Science Decadal Survey and;
4. A summary of the data gathered during the required technology capability discussions.

Additional data from the workshop including the full participant presentations can be found on the ESTO/AIST "NOS Workshop 2020" Website.

Enabling NASA's objectives through pioneering technology, dynamic interaction of assets, and public-private collaborations.

As previously stated, the New Observing Strategies (NOS) concept addresses NASA's science objectives by dynamically coordinating NASA and other organizations assets and capabilities, by leveraging multi-agency and private-public partnerships opportunities, and by improving and developing inventive and novel technology capabilities. Technology advances, such as instrument and spacecraft miniaturization, onboard intelligence and big data analytics, have created an opportunity to make new measurements, and to augment and complement current measurements in a less costly or more productive manner. Future science measurements will take advantage of capabilities such as SmallSats equipped with science-quality instruments, distributed spacecraft missions and generalized SensorWebs[1], as well as

---

[1] See SensorWeb definition in Section 5.

machine learning techniques that will enable processing of large data volumes and real-time, onboard decision making. Along with these capabilities, technologies such as well-defined and standardized interfaces, inter-spacecraft/inter-node secure communications systems, generic metadata and ontologies, onboard processing, intelligent data understanding and decision making will also be necessary to fully exploit the power of distributed, heterogeneous and coordinated observing systems. These capabilities and technologies will enable seamless interaction between NASA assets as well as with those from other organizations, e.g., academia, industry, and Other Government Agencies (OGAs).

This workshop is a first step in developing NOS science reference concepts and use cases, as well as in identifying corresponding technologies that will guide the development of a NOS roadmap.

While there is plenty of software and intelligent systems technology to be developed to ultimately achieve **rapidly adaptive, interactive and agile, distributed sensing objectives**, this workshop helped identify the path to those architecture developments, including technology gaps and required developments in capabilities such as:

- onboard data understanding and analysis;
- inter-node coordination (communications and commands);
- planning, scheduling and decision making;
- seamless interaction between sensors/observing systems and science/forecast models; and
- cybersecurity.

Science use cases targeted NASA's Earth Science Directorate's Research & Analysis and Applied Science focus areas and spanned research into multiple domains such as:

- Modeling of atmospheric pollution, cloud structure, environmental interactions, and falling snow;
- Study of the carbon cycle and various ecosystems such as monitoring the distribution of plant species, studying species habitats, monitoring illegal fishing or modeling the evolution of ocean color/temperature and its consequences;
- Study of Earth surface and interior, investigating land level change, landslides, volcano eruptions modeling and predictions, as well as wildfire-related land-cover and land-use (LCLU) changes;
- Modeling oceans algal blooms, coastal flooding, and carbon export and saturation point; and
- Study of snow, ice and energy balance, sea ice melting, water resources related to agriculture, as well as of atmospheric rivers and flood rain models.

Another outcome from the workshop and breakout sessions has been the identification of a variety of Earth science systems that can benefit from similar or same technology developments highlighting the efficiencies of pursuing such architectures as the one described in Figure 1.

Workshop attendees expressed interest in recurrent meetings such as this workshop, that would include an interdisciplinary community, partner agencies, industry and academia and would help better understand NASA’s objectives and where various organizations can work together to achieve these goals. In particular, attendees appreciated the broader scope, hearing from NASA, NOAA, and USGS, and discovering how these three agency requirements are similar and differ from each other and how they could collaborate when designing future Earth observing systems. Attendees also expressed that goals are much easier to identify when scientists, technologists and end users from various organizations that share the same domain space meet for face-to-face discussions.

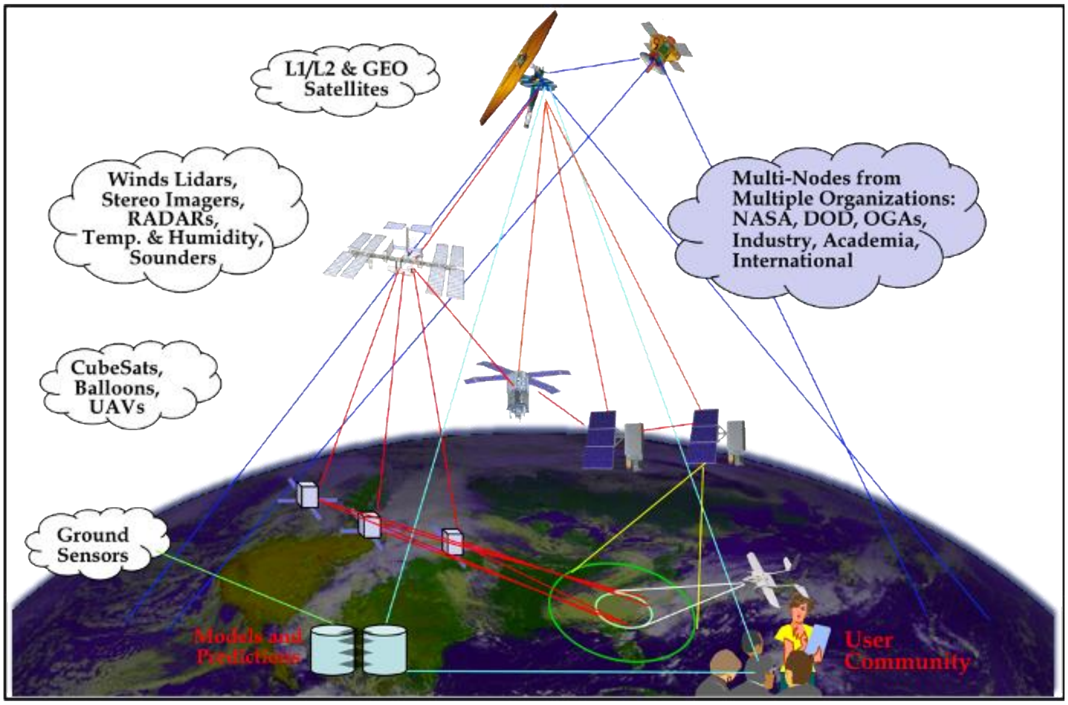


***Figure 1** – New Observing Strategies (NOS) will design systems with multiple, collaborative sensor nodes producing measurements integrated from multiple vantage points and in multiple dimensions (spatial, spectral, temporal, radiometric), providing a dynamic and more complete picture of physical processes or natural phenomena.*

1. NOS Workshop Summary

1.1. Introductions – Goals of the Workshop

ESIP's, Erin Robinson and ESTO AIST's Jacqueline Le Moigne opened the workshop with brief introductions to each of the organizations and summarized the objectives for the workshop.

NOS Workshop Objectives - The workshop is one of the first steps in developing NOS science reference concepts and use cases as well as identifying corresponding technologies that might guide the development of a NOS roadmap. This workshop only focuses on the AIST NOS thrust.

1.1.1. ESIP – Earth Science Information Partners

ESIP is a membership organization that facilitates grassroots community collaboration and Earth science data stewardship. ESIP's guidance in the workshop's discussions provided relevance to the general Earth science community as well as a broad dissemination of the outcomes of those discussions.

1.1.2. AIST – Advanced Information Systems Technology

NOS enables rapidly adaptive, interactive and agile, distributed sensing system architectures.

AIST is NASA SMD's Earth Science Technology Office Program which focuses on innovative software and information systems technology developments to enable: new and unique measurement collection capabilities through distributed sensing; optimizing science missions return on investment through flexible and rapid information integration; and agile science investigations through data analytics and artificial intelligence tools and algorithms. The AIST Program currently includes two thrusts: New Observing Strategies (NOS) and Analytic Collaborative Frameworks (ACF).

The New Observing Strategies (NOS) thrust focuses on optimizing measurement acquisition using many diverse observing capabilities, collaborating across multiple dimensions and creating a unified architecture. New observing strategies leverage Distributed Spacecraft Missions (DSM) and SensorWebs to observe phenomena from different vantage points, and coordinate observations based on events, forecasts, or science models. NOS concepts can include NASA data sources and services as well as non-NASA assets.

The Analytic Collaborative Frameworks (ACF) thrust focuses on enhancing and enabling focused Science investigations by facilitating access, integration and understanding of disparate datasets using pioneering visualization and analytics tools as well as relevant computing environments. This will be of particular interest when dealing with the large amount of diverse data that will be collected with NOS systems. ACF's intent is to:

- Allow flexibility/tailoring configurations for Science investigators to choose among a large variety of datasets and tools; and
- Reduce repetitive work in data access and pre-processing, e.g., developing reusable components.

This workshop focuses only on the AIST NOS thrust, although we envision that future NOS concepts will include one or several ACF as nodes of these generalized and dynamic

SensorWebs. Opening remarks introduced the role of NOS, its relevance to science as well as the validation of NOS technologies using the New Observing Strategies Testbed (NOS-T) Framework, which is described below.

1.1.3. NOS-Testbed Framework

Tom McDermott, Paul Grogan and Jerry Sellers (SERC) presented the objectives of the NOS Testbed. These are the following:

- Validate NOS technologies, independently and as a system
- Demonstrate novel distributed operational concepts
- Enable meaningful comparisons of competing technologies
- Socialize new technologies and concepts with the science community by significantly reducing the risk of integration.

NOS-T will be built around a re-usable framework which is being designed and developed by SERC. The main objective of this framework is to enable disparate organizations to propose and participate in developing NOS software and information systems. An early concept of the Testbed and of its development plan were described, and future directions were highlighted.

1.1.4. Discussions following the introductions

Topics and questions discussed after these first presentations included:

- *What would we have collected if we had been looking?*
    - *Quantifying science information losses is important.*
- *What is the utility case for NOS?*
    - *Collecting target data with discipline and inter-discipline goals.*
- *How to incorporate priorities from scientists in resource management – separate optimization from sociological & policy decisions.*
    - *Scientists could provide "observation policies".*
- *It is important to keep existing assets utilized as well.*
- *Good standards are very important, and interoperability is a key requirement.*
- *Baselines are important to be aware of; NOAA's existing constellation is their baseline, the ACCP (Aerosol and Cloud, Convection and Precipitation) Designated Observable is conducting a similar process.*
- *Observing System Simulation Experiments (OSSEs) for a single mission could be used as a "calibration tool" for evaluating a proposed constellation.*
- *Continuing to ask the correct questions and keeping a focus on the science goals is very important.*
- *NASA does not have a real-time planning system. The Missile Defense Agency (MDA) and other agencies do, and NASA will need one also.*
- *Difference between NASA and other agencies is the fact that NASA is driven by research and exploration while others are driven by their operational goals.*
- *The community needs to think about different ways to do data assimilation.*
    - *How to assign value across different science applications?*
    - *Looking at data from an economy point of view*

  - *Optimization when resources are scarce.*
  - *How to manage inter-organizational assets – a NOS architecture would enable the ability to use assets from multiple organizations including NASA, other government agencies, commercial, academia, and international.*

1.2. Keynote Addresses

Throughout the workshop, several keynote addresses summarized NASA's vision as well as other agencies' (NOAA and USGS) visions in terms of Earth Observing Systems and how the NOS concept relates to those visions.

1.2.1. Mike Seablom / NASA SMD Chief Technologist

Inspiring the Next Generation of Software Capabilities

In the early 2000's, ESTO led a study that proposed a next-generation weather prediction architecture that was the first step in defining the "SensorWeb" concept. In 2005, AIST began investing in SensorWeb development and implementation to advance our observation potential as well as support our missions with enhanced capabilities, such as for improved calibration and validation. Mike Seablom was one of the PIs working on SensorWeb simulation experiments, and over time some of the other 2005 & 2008 PIs implemented operational versions of SensorWebs, such as Mahta Moghaddam's SoilSCAPE (Soil moisture Sensing Controller And oPtimal Estimator). Additionally, the advances made through Dan Mandl's SensorWeb projects implemented with EO-1 laid the groundwork for the very software advances we are working on today.

NASA has always been a pioneer in science exploration; the commitment of this workshop attendees and the outcomes of those discussions will help us all, NASA, our partner agencies, and industry and academia reach our science objectives and better understand the Earth as a system. Some of these technologies will also help NASA by transitioning into other science divisions such as Heliophysics, Planetary, Astrophysics as well as Moon and Mars exploration.

1.2.2. Sid Boukabara / NOAA

NOAA's Future Space Architecture: Assessing & Optimizing the Value of Observing System

NOAA is planning for its next-generation space systems and future space architectures. The objective is to plan for the future by optimizing NOAA's space assets to maximize their value to users. Many tools such as Observing Systems Experiments (OSE), Observing System Simulation Experiments (OSSE), and Forecast Sensitivity Observation Impact (FSOI) are used to assess the impacts of various trades. Interacting successfully with industry is also critical to make sure the plans are feasible and cost-effective. An overarching objective (for accurate global forecasting) is to provide measurements "all the time everywhere" if possible, efficiently utilizing NOAA and its partner's capabilities (including commercial).

NOAA is utilizing the ASPEN system ("Advanced Systems Performance Evaluation for NOAA" assessment tool), which maps Earth systems into a set of standard variables that are observed from space, e.g., atmospheric temperature, surface parameters, etc., specifying environment and observables, including their attributes. ASPEN:

- Considers how applications map requirements on the listed Earth system components, overlays sensors capabilities onto this list of requirements to see how a given application domain gets covered, then adds entire observing systems.

- Defines the "Value of sensor 1 to application 1, to application 2, etc." This system can also account for forward looking aspects in emerging needs for more accurate product measurements.
- Combines geophysical requirements with technical priorities with sensor capabilities to assess mission candidates and plan the system.
- Ultimately will be accounting for costs to complete the cost/benefit analysis.

1.2.3. Joseph Bell / USGS

USGS Next Generation Water Observing System Program

The USGS NextGen Water Observing System (NGWOS) is an integrated set of fixed and mobile environmental monitoring assets that provide data to facilitate resource management challenges and decisions.

The program will select one basin per year to expand monitoring and observations: 30,000-60,000 sq. km per site. NGWOS goals include eventually working toward water availability and water observations made easy for users to access, along with getting data into prediction models for water forecasts and water quality knowledge.

Non-indigenous Aquatic Species (NAS) challenges to USGS include:

- "Fit for purpose" information. Enhance temporal and spatial collection of water quantity, quality, and water use data.
- Infuse citizen science into USGS collection activities, including soil moisture, flood notices, etc. Integrate fleets of drones communicating in an Internet-Of-Things (IOT) format; incorporate local farmers soil moisture and/or precipitation measurements and photogrammetry from drones. NCAR has 3-D printing weather stations for use.
- Develop innovative, intuitive, and web-based data analysis tools for the nation to better understand the status and trends of water resources.

USGS, NGWOS and NOS frameworks share many use case interests such as flood monitoring with ground and space sensors. Another interest is related to network monitoring over radio frequencies and taking traditional USGS stream gauges and turn them into a gateway with a possible goal of reducing the number of ground truth sites in the future. Sharing and coordination of datasets is also of great interest.

1.2.4. George Percivall / OGC

Innovations for NASA New Observing Strategy

The main objective of the Open Geospatial Consortium (OGC) is to improve access to *geospatial*, or *location* information. Using location, OGC connects people, communities, technology and decision making to create a sustainable future by making location more findable, accessible, interoperable and reusable. OGC is a membership organization that uses member collaboration and an agile process combining standards, innovation, partnerships and testbed projects to develop, advance and implement interoperability standards.

The OGC SensorWeb Enablement (SWE, [SWE]) standards were developed based on requirements from NASA ESTO and other OGC members. The resulting suite of SWE standards are now used in operational systems around the globe. OGC SWE standards include Sensor Model Language (SensorML), Sensor Observation Services, Sensor Planning Services, Observations and Measurements (O&M), etc. The O&M standard became the basis of joint projects and is now also published as an ISO and W3C standard. Sensor-web requirements are similar to many NOS requirements in pursuing:

- Quick discovery of sensors and sensor data
- Obtaining sensor specific information in a standard encoding that is understandable by software
- Readily access sensor observations in a common manner
- Tasking sensors in a common but secure manner
- Subscribe to and receive alerts when a sensor measures a particular phenomenon

OGC continues work towards NOS architecture capabilities with such projects as the SensorThings API that is a geospatial-enabled API to IoT devices, data, and applications and the DoD Sensor Integration Framework for sharing sensors across tactical and Enterprise environments, among other projects. OGC has also completed a cloud-native Earth Observation exploitation architecture pilot (see https://www.ogc.org/ogcevents/earth-observation-applications-data-architecture-presentation-webinar).

1.3. Summary of AIST NOS and NOS-T Projects

The next section of the Workshop focused on current or recent AIST projects dealing with the advancement of NOS or NOS-T technologies. These include a few Pilot Projects corresponding to essential capabilities required for NOS-T, as well as several projects developed under the AIST-16 and AIST-18 solicitations and corresponding to more general and more advanced capabilities and technologies.

1.3.1. Daniel Cellucci & Chad Frost / ARC

'Tip' and 'Cue' Architectures for The New Observing System

The team presented an example of an Oroville dam collapse as a hydrological application requiring better discharge predictions, including the need to focus on hydrology observations, and static vs. dynamic resources. Static includes satellite imagery, sensor networks, climate data, weather models, and ground-based radar. Fixed in space, fixed resource allocations are expensive but amortized across users; they usually cover a large area. Dynamic resources have a limited field of view and are resource-constrained. Dynamic resources can respond to new events and provide high data volumes over a small area. It is necessary to prioritize observations and assess the coverage needed. Static sources could tip and cue the dynamic resources. For example, static resources could command a UAV GPR to take a stream height measurement.

Other considerations are:

- IOT's crowdsourced data;
- Using interfaces to/from forecast tools;
- Addressing questions such as: How can we have enough advance notice to prepare/deploy dynamic observations? When is an impending event going to occur?;
- Developing a broker for cueing observations, that would task interfaces to sensors networks in NOS-T; and
- Implementing standards and ontologies to support these services.

1.3.2. Sujay Kumar / GSFC

A Hydrology Mission Design and Analysis System (H-MIDAS)

Hydrological events are driven by combinations of meteorological extremes and land surface conditions, and are best observed and studied through multiple science domains and vantage points (multiple sensors observing weather, soil, human interactions, etc.). The 2017 paper by McCabe et al. describes the changing nature of hydrology measurements from ground and remote sensing sensors. The H-MIDAS project is working towards a science-focused mission design environment to take advantage of distributed sensor observations. Such an environment requires observation operators for multi-platform, multi-angular measurements, tools for science translation of raw measurements, and data assimilation integration methods. It is also necessary to avoid single sensor only OSSEs. The system should include feedback to observing systems.

The project is using LIS (Land Information System) component and machine learning tools for forward modeling. It is also working with TAT-C and incorporating into a full OSSE system and considering ML-based forward models as alternatives to radiative transfer models.

1.3.3. Dan Crichton / JPL

Data Driven Observations for Water Resource Management

With the Western States Water Mission (WSWM) work, JPL is working towards an integrated view of hydrological processes to be used to support multiple observing assets having AI onboard.

Ten years from now observing assets will all be inter-connected, and ground systems will support longer term activity. We can also imagine changing roles for ground-based operations and advanced systems that plug nodes together to make an end-to-end architecture.

WSWM assimilates data with models to support hydrological sciences, focusing on such areas as depleting aquifers, impact on river flow, food supply, etc. This work includes uncertainty estimates and an end-to-end product drives a GIS system for data analysis.

Through this effort, the team is participating in the NOS-Testbed (NOS-T) focusing on rivers for the NOS-T simulations. Floods are peaks in river flow that can happen over a short amount of time only emphasizing the need for rapid response. We need to better forecast these effects and queue observations to support this. Peak river flow events need to be observed by re-tasking assets including satellites, UAVs, and in-situ sensors; all this includes Sentinel-3, altimetry, CYGNSS CubeSat, etc. This will also help support SWOT.

This effort is using the RAPID river model tool for US, working to extend it internationally to better predict river peak events.

The initial work focused on the Western United States with observational data from satellite, airborne, and ground-based sensors and included data from other sources such as ground wells, and the like.

1.3.4. Steve Chien / JPL

Dynamic Tasking of Earth Observing Assets

The goal of this project is to address the sequence:

Detection => Response => Produce data/model => Deliver to user.

The team is currently working on such prototypes with the NOS-T project team. This includes alert generation for volcanos and/or floods; auto-rescheduling of satellite observations; then continuous rescheduling. Assimilating alerts into existing scheduling and/or federated scheduling will be a must. On-board/ground-based product generation such as cloud screening, thermal summary, volcanic plume classification, and surface water event are all areas in which JPL has been doing work in the past. Additionally, the team is hoping to fly cloud screening on Planet DOVE instruments, and they are already releasing some data sets to particular groups. Additionally, they are looking for collaborations with ML researchers to look at classification problems for classification of alert status of a volcano.

They are performing detailed work on scheduling issues and working on demonstrations with Planet SkySat for volcano alerts. Alert-task-image is demonstrated with Planet; SkySats are not designed for thermal emission monitoring so there are challenges to address. Next, they will use these alerts to derive thermal output, and plume properties, etc. The plan is to experiment with other sensors such as ECOSTRESS, OCO-3, etc.; these sensors are on the ISS therefore it is somewhat difficult to task flexibly. The goal is to perform automated scheduling of these instruments.

The team is also performing "tailor-made" re-tasking, i.e., dynamic targeting, first with instruments having smaller swaths but accomplishing the majority of science at reduced costs. An Instrument Incubator Program (IIP) project led by Bill Deal will develop this capability for detecting storm centers.

1.3.5. Paul Grogan / Stevens Institute of Technology

Trade-space Analysis Tool for Constellations (TAT-C) [For16, Lem17, Nag16]

The project is integrating ML technologies in a trade-space tool to optimize distributed and multi-instrument mission planning. This tool enables mission concept evaluation with rapid trade evaluations including number of spacecraft, number of planes, altitude, inclination etc. TAT-C facilitates exploring mission concept optimization over a large trade-space. It also considers costs and launch vehicle options as well as assessing value through future data acquired by constellations.

TAT-C has a GUI front end for testing, modules built by multiple organizations in multiple languages including Java, C++, and Python and currently supports passive optical scanners and SAR. The tool uses JSON structures and a common object definition for data. It is anticipated that TAT-C's object schema will be transitioning to NOS-T for definition of interfaces between components. TAT-C interfaces are web-based (i.e., service oriented).

1.3.6. Sreeja Nag / ARC & BAER

D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions

This project is developing a suite of scalable software tools to help with scheduling payload operations in a large constellation, with each satellite having multiple heterogeneous payloads to enable constellations to make observations and downlink data to maximize science value. D-SHIELD schedules which payload turns on when and in which direction and is informed by a science simulator which provides a measurement value model for each measurement for a given sensor with a given set of parameters. It also evaluates results to predicted value to allow for feedback to science simulators and optimization tools.

This is not a trade-space tool to design the optimum constellation; it assumes a given constellation of instruments and optimizes science value using offline and on-board decision processes; modeling communication, instrument, and spacecraft control. Communications use delay tolerant networking to assign latency (inter-satellite and to/from ground) and have a power and data module to plan operations. Instrument models include SARs, radiometers and reflectometers in addition to previously available imagers.

A new science simulator will build on another AIST project, Mahta Moghaddam's soil moisture uncertainty quantification to improve measurement quality.

This project conducted some simulations using precipitation and flood prediction to queue satellites resulting in an example of improved Landsat-type coverage by re-orienting and pointing of multiple small satellites.

1.3.7. Project Presentations – Discussion #1:

Topics and questions discussed after these presentations included:

- *River focus? How does this connect to precipitation observations?*
    - *In a NOS scenario we could use observations from one sensor to train a simple onboard Machine Learning (ML) algorithm to try to predict other non-observed factors to queue sensors.*
- *What about loss of performance due to varying sensor operations?*
    - *We need to consider resource allocation. We will need to have prioritization of important observations, however, getting multiple scientists to agree on such as prioritization is a challenge. We need to work towards a better system than the current fixed sensing method. EO-1 did demonstrate having priority-guided observations.*
- *We should separate optimization from policy and science priorities. There are human factors that also need to be considered and quantified as well.*
    - *We do not necessarily know what is important early in the mission design, thus flexibility is desired in terms of priorities; continuity also becomes an issue in some cases.*
    - *A new preference may be to have scientists selecting observation policies rather than individual observations.*
    - *Currently, many autonomous systems have a "priority system" while science observation systems generally do not; however, this may need to be adapted in the future. Also, it is difficult to get consensus across an entire community, especially cross-cutting communities.*
    - *Additionally, the value of a given measurement varies dynamically given a past history of measurements.*
    - *There are also differences between agency science communities. The difference between NASA and other organizations is that NASA is research- and science continuity-focused while other agency missions are operationally focused.*
- *Designated Observables (DOs) such as ACCP, SBG (Surface Biology and Geology), and SDC (Surface Deformation and Change) all discussed flexible operations, but this might not be considered in the final designs.*
    - *With meso-scale weather observations it is already possible and can be targeted.*
    - *DOs trade studies seem to be investigating multiple architectures.*

- *We need to have a new vision of data assimilation as well. The usage needs to be quicker and more agile. Tools to do this exist, we just need to think differently. Smaller models can be trained by bigger models, for example.*
    - *Everyone agrees that there is an immense volume of data of which only a subset has high value for a given application at a given place/time.*
    - *This is similar to an economic problem in some cases. Commercial providers often make this kind of assessment. How do scientists assign value to a particular measurement? There have been proposals to use a market-based approach to assess value of science measurements, but this needs to be considered carefully. The goals of differing actors (science, industry, government, etc.) also need to be considered.*

1.4. Summary of AIST NOS and NOS-T Projects – Part 2

1.4.1. Matt French / USC-ISI

Enabling New Observation Strategies Through On-board Computing and System Virtualization

SpaceCubeX is a simulator for onboard computing and system virtualization. It enables better planning for on-board computing hardware, heterogeneous types of processors/compilers, FPGA code development, and portability across platforms. It also includes scalable verification methods and mapping of python applications to FPGAs. The project also developed SpaceCube 3.0 processor, as well as a simulator of the Virtual Constellation Engine in the Amazon cloud.

1.4.2. Jim Carr / Carr Astronautics

StereoBit: Advanced Onboard Science Data Processing to Enable Future Earth Science

This project is targeting CubeSat onboard science data processing, implementing Structure from Motion (SfM) tracking of clouds for Planetary Boundary Layer (PBL) and atmospheric science applications. Onboard science data processing will transform data to a stereo 3-D winds product, running on the SpaceCube processor. The future vision is a constellation of CubeSats that cooperate in pairs or fuse data with other weather satellites like GOES-R. The upcoming step is to perform hardware-in-the-loop testing of the processing algorithm.

1.4.3. Derek Posselt / JPL

A Science-Focused, Scalable, Flexible Instrument Simulation (OSSE) Toolkit for Mission Design

The goal of this project is to develop a parallel OSSE toolkit to assess the science benefit of candidate observing systems. The specific application is focused on atmospheric convection, ranging from shallow cumulus through deep convection (thunderstorm-type systems). This OSSE system will enable quantitative assessment of measurement sufficiency by rigorously accounting for multiple sources of uncertainty, diverse measurement types, and multiple geophysical scenarios. Because it is a significant computational challenge to model uncertainties and trace them to science benefit for a large range of architectures, parallel computing is necessary. The infrastructure utilizes a parallel MapReduce framework and is designed for local cluster computing, High Performance Computing (HPC) systems, and Cloud Computing.

1.4.4. Ben Smith & Lorraine Fesq / JPL

ASTERIA Amazon Ground Station Experiment

The JPL ASTERIA CubeSat team conducted an experiment with Amazon to test the new AWS Ground Station as a Service (GSaaS) capabilities. The primary ASTERIA mission was searching for exoplanets. During the extended mission, ASTERIA conducted onboard technology experiments. They used GSaaS for communications and “on demand" connections, and AWS for processing. Based on the success of the experiment, ASTERIA subsequently transitioned to GSaaS as the primary communications mode for up and downlinks. A second experiment dealt with onboard “task nets” that enabled transition from “sequence-based” to “goal-based” tasking. All these tests were successful and easily performed without long schedule delays.

1.4.5. Ethan Gutmann / NCAR

Preparing NASA for future Snow Missions: Integrating the Spatially explicit SnowModel in LIS

The Land Information System (LIS) needs accurate snow information to improve future mission planning and model-data fusion. Snow is very heterogenous and changes rapidly, and current LIS snow models do represent the processes responsible. Adding wind redistribution and improved micrometeorology into LIS will create realistic heterogeneity to improve snow modeling. This capability will enhance planning to better quantify tradeoffs in a distributed system. This includes decisions related to sensor types and repeat times as well as when and where to make observations. Improved water resource management, climate change projection, avalanche forecasting, drought monitoring, and flood predictions are some of the societal benefits; along with that, defining what mobile applications and sensors are needed, or policies on how to deploy sensors are science and programmatic benefits.

1.4.6. Joel Johnson / OSU

Including On-Platform Sensor Adaption, On-Platform Resource Management, and Cross-Platform Collaboration in NOS Studies

Future Earth Observation missions will involve intelligent networks of adaptive sensors that coordinate their observations and optimize performance with sensors operating on resource constrained platforms (e.g., CubeSats). NOS simulations should include the capability to model on-platform sensor adaptation, on-platform resource management, and cross-platform communication and collaboration. The Simulation Toolset for Adaptive Remote Sensing (STARS) developed initial software components for simulating these capabilities. Capabilities to be considered include adapting sensor pulse repetition frequency in response to observed scenes; interrupting radar integration period when scene is assessed as not scientifically useful; managing sensor operations based on predicted platform power budget over future orbit and assigned science relevance; and sharing information among multiple satellites via optimized communications networks.

1.4.7. Ruzbeh Akbar / MIT

SoilSCAPE & SPCTOR: Summary of AIST Projects

Soil moisture is highly variable across the landscape due to topographic, weather, and climate effects. At the same time, remote sensing observations of soil moisture are made at a variety of spatial and resolution scale. To bridge this spatial discrepancy, in situ soil moisture sensors that yield "representative" landscape moisture content are required. The SoilSCAPE system is made of clusters of in-situ wireless sensor networks (WSNs) measuring and reporting near real-time surface-to-root soil moisture. This system provides ground truth data for NASA's related Earth Science missions as well as providing the data for use through the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). SoilSCAPE is working with the AirMOSS, SMAP and CYGNSS missions.

The SPCTOR (Sensing Policy Controller and Optimizer) project is being developed for multi-agent observation strategy coordination and to demonstrate integrated operations between in-situ WSNs and networks of UAV-Software Defined Radars (SD Radar) based on commands queued by SoilSCAPE. Mobile SD Radars are capable of gap-filling regions where static WSNs under sample soil moisture or yield upscaled soil moisture with high uncertainty. SD Radars flights on UAVs and measurement collections have already been demonstrated. SPCTOR is developing sensing policy coordination using classical optimization and well as Machine Learning techniques.

1.4.8. Project Presentations – Discussion #2:

Topics and questions discussed after these presentations included:

- *How does SpaceCube compare to emergent commercial processors targeting ML at the edge.*
    - *SpaceCube is a hybrid architecture with some rad-hard components and an overall rad-tolerant approach; others do not. The NextGen Xilinx is supposed to have ML and other additional features that might be tested on SpaceCube.*
- *How is GSaaS scaling?*
    - *There are four AWS GSaaS's now working, 2 in US, 2 outside the US, with another three sites coming on-line soon. AWS' intent is to have over one hundred in the future. In the US there are regulatory issues to be managed. Charges are by the minute, specified on the AWS webpage, ~ $10/minute. It was a savings for ASTERIA.*
- *Is there an application to request satellites to shut down in response to a space weather event?*
    - *Yes, that could be of interest and a space weather sensor network was previously proposed. These are other types of services a NOS type architecture would benefit from.*
- *Real-time experiments with UAVs and ground systems are needed. There is a USGS project looking at how several UAVs might communicate with one another. There was an AIST project from NASA Goddard Space Flight Center (GSFC) and the University of Maryland (UMD) that advanced autonomous UAV capabilities and was the first step to a swarm or constellation of UAVs for hyperspectral observations at the 10 to 100-meter altitudes.*
- *Avalanches might be a good high space- and time-resolution need that could be added as a use case.*

2. Breakout Sessions Introduction

After the background presentations, the Workshop separated into a series of Breakout sessions, focused on Science and on Technology. Five areas were identified for Science and five areas were identified for Technology with participants selecting which session(s) they preferred to participate in.

Globally, we are experiencing the emergence of many new sources of observational data, including high-quality science instruments on CubeSats and SmallSats, and the development of commercial space platforms. As a consequence, 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 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 as well as new computing capabilities (on the ground or onboard) to process and analyze large amounts of data, enables high-density observations for specific phenomena of interest instead of operating in a fixed pattern. Such a 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.

This new paradigm will require many new capabilities (most shown in Table 2) and it is important to work towards understanding the value, developing the capabilities, and sharing the outcomes of these advancing technologies and how they will impact and benefit Earth science as a whole.

The breakout sessions focused on identifying science scenarios that will benefit from NOS and the corresponding technologies that will be needed to design, implement and operate these scenarios.

2.1. Science Use Cases Breakouts

The following science domain areas that were identified for those breakouts were the following: Atmospheric; Carbon and Ecosystems; Earth Surface and Interior; Oceans; and Snow/Ice/Energy. In each case, the application to Designated and Targeted Observables was determined, e.g., ACCP, SBG, SDC, MC (Mass Change) and PBL.

To set the stage and provide a motivational use case, Sujay Kumar/GSFC presented examples of potential scenarios within the hydrology domain that could benefit from a future NOS demonstration.

2.1.1. Sujay Kumar / GSFC

Use Case Introduction – NOS Hydrology Use Case Examples

These use cases were selected by the NOS-Testbed (NOS-T) and are now being considered by the testbed team to define future NOS-T demonstrations. Hydrology events typically involve the complex interactions of cascading processes.

Water cycle monitoring requires multiple geophysical products and includes everything from precipitation, evaporation, soil moisture, water runoff, snow, groundwater, and vegetation. There are critical gaps in our ability to measure these processes. For example, no direct measurements of evaporation are available, though it is the second largest water budget term (after precipitation). Events such as fires and mudslide events often involve the interactions from multiple processes. The removal of vegetation from fires decreases transpiration (and evaporation) and increases the tendency for runoff.

Within a NOS framework the use of optical/multispectral data to monitor vegetation anomalies and fires could trigger active and passive observations plus ground observations to measure precipitation and soil moisture. Subsequently ground sensors for runoff measurements could be triggered. Data assimilation and machine learning is all part of this system as well.

Brown ocean effects represent the intensification of tropical cyclones after landfall due to sufficient moisture being present over land. This can lead to high soil moisture and by adding additional soil moisture measurements when cued by an approaching hurricane this data could be provided for decision making.

Other applications are depletion of water resources, fire at high elevations, and snow evolution. There are many hydrology examples of how one sensor queueing another might be valuable – mostly over longer time scales; for example, the impact of irrigation over land surface, which is not well observed by soil moisture sensors alone, and the amplification of heat waves and drought. All of these examples in just one science domain are examples of the need for distributed, interactive observing systems that will utilize NOS technologies to provide NASA the most relevant science data.

2.2. Technology Breakouts

Designing, developing, flying and operating an NOS-like architecture require the improvement and/or the development of all the technologies identified in Figure 2: these are detailed in [Lem18] and [Lem19].

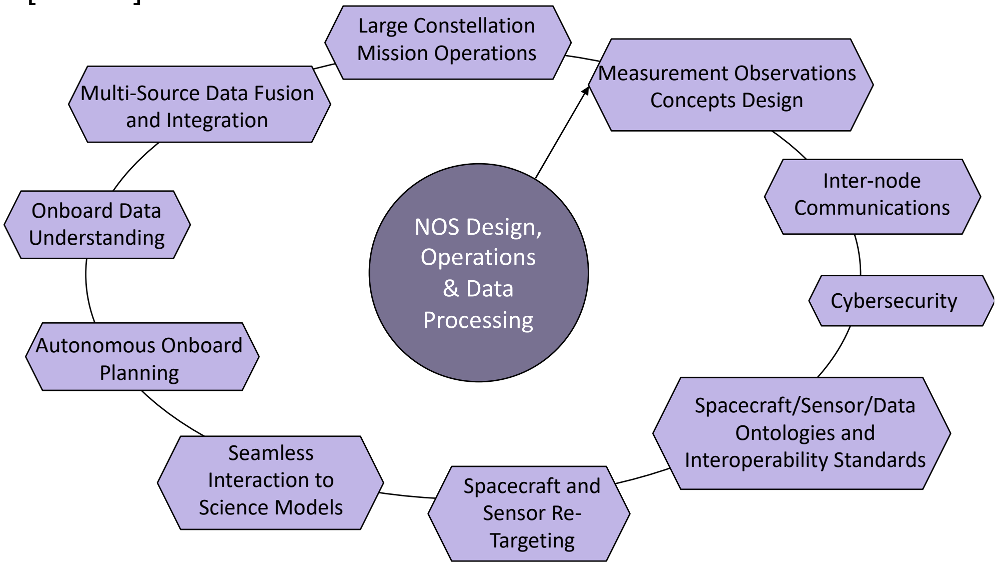


Figure 2 - NOS Capabilities Span the Entire Data Lifecycle, from Mission/Observing System Design to Onboard Processing, Analysis and Autonomy to Decision Making, Inter-Sensor/Inter-Spacecraft/Inter-Node Coordination to Cybersecurity and to Seamless Interactions with Science and Forecast Models.

In particular, the five NOS technology areas determined to be the most essential to focus initial developments on include: Onboard data understanding and analysis; Inter-node coordination; Planning, scheduling and decision making; Interaction to science and forecast models; and Cybersecurity.

Each of the science use cases/scenarios also include a *Capabilities* field to further highlight the overarching capabilities needed for each scenario.

The science use cases, and the corresponding capabilities and related technologies are further defined and detailed in sections 2 and 3. Below is a summary of the technologies needs that were identified during this NOS Workshop and the follow-on breakout sessions.

2.3. NOS Workshop Outcomes

A significant outcome of the New Observing Strategies Workshop and breakout sessions is the identification of the broad Earth science benefits that will be gained by the development of NOS capabilities and the corresponding required technologies that are often cross-cutting spanning all Earth science domains. Additionally, while the manner in which to gather new science observations may vary, the technologies to create NOS systems are highly applicable to other domains within and outside our Earth’s atmosphere and could be adapted to other domains such as planetary and deep space exploration.

Other significant outcomes of the workshop include a clear need for: Distributed Spacecraft Missions (DSM); dynamic, autonomous, and secure *Internet-of-Space (IoS)*[2] capabilities (i.e., seamless communications and interactions between various assets – space, air or ground); collaboration across broad sets of organizations, science domains, and technology features.

A summary of these outcomes includes:

- ***Overarching findings:***
    - Significant overlaps exist between various organization objectives and development paths (e.g., NASA, NOAA, and USGS as well OGA's, academia and industry).
    - There is a need for societal, management, mission, and technical changes and adoption of new capabilities and interactive systems.
    - There is a compulsory need for early formation of multi-disciplinary (when possible multi-organizational) teams, especially including software, science, security, and hardware.
    - Funding for comprehensive NOS projects is needed as opposed to projects focusing on specific science domains.
    - Further NASA implementation of SensorWebs is also needed.

- ***Science needs (see Section 3 for more details):***
    - Use cases are very valuable in identifying required technology gaps and cross-cutting technologies.
    - Desired cross-cutting capabilities were identified within each of the science use cases including the capabilities to:

---

[2] See IoS definition in Section 5.

        - Drive detailed observation decision making for in-formulation systems to optimize relationships between observing system design and science return.
        - Specify and execute a science observation policy that can adapt to sudden events (hierarchical and federated):
            - Federated planning including observation requests from other assets, and when and where to make acquisitions,
            - Probabilistic reasoning and ability to adapt the observing plan as requests are satisfied or rejected,
            - Pre-specified, nominal policies; reactive policies with an ability to activate a contingency policy or science team to quickly update a policy when an event occurs.
        - Unmanned vehicle flight policies - autonomy to follow boundaries – plumes, blooms, migration patterns, and independent exploration.
        - Determine the impact of observation results on future observation plans, e.g., when observations change the utility of the next planned observation(s) and triggering coordinated assets to observe phenomena, such as several CubeSats acting like a single large aperture:
            - Trigger UAVs to follow dynamic events, plumes, blooms, etc. while systems continue to adapt based on observation feedback.
        - Create observation-to-model-to-observation loops:
            - Select observations that reduce uncertainty and improve model forecasts by providing the most important parameters for initial state vector(s),
            - Assimilate observations into model(s) and use updated model(s) to inform new observation selections.
        - New and better science creates a greater desire/need for new and better technologies.
        - Science domains remain somewhat siloed and new technologies are broadening the capability to infuse different science aspects and inspire new science discoveries.
        - Infusing science data not historically included such as gravity waves for improved water and energy understanding can influence many science domains and systems.

- ***Technology requirements (see Section 4 for more details):***
    - Future architectures will evolve from single to multi-asset systems in which each asset is another node in the architecture including models, ground systems, constellations, Unmanned Aerial Vehicles (UAVs), etc.
    - Onboard/Edge computing, processing, and decision making will become essential.
    - Understanding New Observing Strategies architectures and standards that enable plug-and-play will help identify what are the technology gaps, and which new standards need to be developed.

- Requirements such as Artificial Intelligence (AI), Machine Learning (ML), autonomy, Internet of Things (IoT)[3], standards, protocols, data formats, calibration, among others, will need to be harmonized.
- There will be a more systematic incorporation of UAVs and Unmanned Underwater Vehicles (UUVs) into future observing system architectures.
- Data fusion and integration, advanced metadata development, and seamless model integration will play a significant role in the framework of these advanced systems.

3. Science Breakout Details

Science breakouts started during the February Workshop and continued in the following months with a series of targeted “mini workshops”. Workflows and triggers include stakeholder requirement analysis; problem frame analysis; functional analysis/ design synthesis; and required software and information systems analysis.

The subsequent pages summarize the results of these breakout discussions including details for the following science use cases:

Atmospheric Use Cases:
Use Case #1: Pollution transport between boundary layer and free troposphere
Use Case #2: Cloud structure and convection
Use Case #3: Falling snow
Use Case #4: Environment interaction due to explosion

Carbon and Ecosystems Use Cases:
Use Case #1: Monitor distribution of plant species and habitat protection
Use Case #2: Illegal fishing monitoring
use Case #3: Algal bloom

Earth Surface and Interior Use Cases:
Use Case #1: Land level change
Use Case #2: Landslides
Use Case #3: Volcanoes
Use Case #4: Land Use Land Cover Change - wildfires

Oceans Use Cases:
Use Case #1: Algal bloom tracking: fisheries and sea life
Use Case #2: Predicting coastal flooding due to hurricanes
Use Case #3: Ocean carbon export and sequestration

Snow, Ice, Energy (Hydrology) Use Cases
Use Case #1: Melting sea ice
Use Case #2: Water resources and agriculture
Use Case #3: Flooding - Rain and snow disasters

---

[3] IoT definition: see Section 5.

3.1. Atmosphere Use Cases

ATMOSPHERE	
USE CASE #1	**Pollution transport between boundary layer and free troposphere**
Scenario:	Track transport of pollution from Planetary Boundary Layer (PBL) to free troposphere including flux, intensity, and boundary layer to free troposphere exchange.
Relevant Targeted Observables	PBL, ACCP
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing / tracking system on events.
Types of Data to be Gathered	Column data over time - Chemical compositions, humidity, wind, precipitation, cloud cover, temperature.
Workflows / Triggers	Scheduled observations (no trigger); trigger on detection of Air Quality (AQ) or convection events, e.g., from GEOCARB, local AQ sensors, and/or weather forecasts. Triggering based on concentration levels sending to appropriate measurement capabilities (UAVs, balloons, satellites, airborne, ground sensors); update models with data gathered.
Capabilities	Requires high spatial and temporal resolution, need rapid measurements of initial pollutant events and vertical and horizontal evolution of events; Uncertainty quantification and quality control of data is needed; Coincident measurements required; Measure concentration and chemical composition; Drones, UAVs, airborne, constellations of CubeSat lidars, balloons; Coordinate assets to observe phenomena (several X-Sats act like a single large aperture to observe, recruit cluster of ground sensors to get regional measurement). Edge sensors with local decision capabilities; onboard anomaly detection; imagery capabilities; detection and autonomous avoidance capability; system leader and follower coordinate to take joint observations; when, where, and how to find data. Observe an event, event detection triggers an alert, then process data onboard and downlink compressed or thumbnails of imagery.
All Technologies Required	Requires fine grained temporal and spatial scale observations of a dynamic event (plume transport) that evolves over minutes to hours; Multi-angle imaging, UAVs with hyperspectral capabilities; Autonomy, machine learning, onboard processing.
Gap Technologies	Dynamic control of cube-sat constellation with mixed instruments for larger scale; UAVs or Balloons for finer scale plume process; Ground sensors for initial detection and tracking; Data assimilation with high temporal and spatial resolution data into models.
Types of Sensors	Lidar, multi-angle spectrometer, visual (photogrammetry); Ground sensors (AQ, Meteorology); Tomography.
Models	Plume transport models
If Known, Current, In Development Technologies and Organizations	Swedish Space, K-space, Kepler communications, AWS; ASTERIA demo of using both ground stations for a given data dump, 5G cellular service

ATMOSPHERE	
USE CASE #2	**Cloud structure and convection**
Scenario:	Better understand the influence of boundary layer thermodynamic structure on development of clouds over time and on their processing and transport of aerosols/pollution. Determine 3D structure and time evolution of boundary layer clouds, and their processing of aerosols. Coordinated constellation targets clouds and reconstructs structure by combining multiple view angles; include photogrammetry and lidar.
Relevant Targeted Observables	PBL, ACCP, SBG, SDC, MC
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing and tracking system on events of interest.
Types of Data to be Gathered	Atmosphere, hydrology/soil moisture, snow, Earth Surface and Interior (ESI), carbon/methane, structures, convection, volcanoes; ocean pollution, field of clouds
Workflows / Triggers	Trigger based on scientific understanding rather than an extreme event; observations of the boundary layer should be taken at several times per day to capture the diurnal evolution of cloud and PBL development.
Capabilities	Tracking and measuring consistently over time, need consistent data; tracking low clouds day and night; Forecast models; Onboard capability, forward imager informs another imager to retarget; Networking of sensors, multi-resolution; integrate data sources; Uncertainty quantification and quality control; Timed/scheduled monitoring throughout the day; Data infusion of cloud, aerosol, weather, atmosphere, etc.
All Technologies Required	Constellation control and data fusion for reconstruction of 3D PBL structure and cloud time and space evolution; Coordinated observations to reconstruct the fine-grained time-evolving 3D structure of clouds and aerosols; Data fusion needed across multiple instruments and vantage points to produce an integrated 3D structure and its evolution over time; AI & ML for decision making of assets; Interface between PBL and atmosphere, as well as ground, oceans, and soil moisture to get entire PBL picture.
Gap Technologies	SmallSat formation flying, targeted observations of developing clouds and environment; Data fusion (and/or data assimilation) for data from various platforms with different resolution, different levels of uncertainty; Adaptive pointing/targeting.
Types of Sensors	Optical, LIDAR, IR, CYGNSS, soil moisture in-situ sensors
Models	Large eddy simulation models, global and regional weather models
If Known, Current, In Development Technologies and Organizations	PBL and atmosphere interfaces being developed on a Decadal Survey Incubation and University of Maryland, Baltimore County (UMBC) project using ceilometers

ATMOSPHERE	
USE CASE #3	**Falling Snow**
Scenario:	Measure snow as it falls; connect to water resource management especially in mountains; this is not snowpack measurement, it is snow as it is falling, to better understand frozen precipitation once on the ground as it is currently very difficult to measure and track. Determine the flux of snowfall from the atmosphere onto the surface with sufficient accuracy to quantify resulting change in snow-water equivalent (SWE).
Relevant Targeted Observables	ACCP, cloud specific objectives, atmospheric winds
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing/ tracking system especially for complex terrain and determining what is rain or snow, where it is falling.
Types of Data to be Gathered	Precipitation, snow vs rain, path of storm, location of storm
Workflows / Triggers	Forecast model shows an atmospheric river event along west coast; Task ground-based systems (they eventually degrade with storm movement); Continue using forecast models to show where the storm is headed; Task assets in specific regions.
Capabilities	Time and location specifications; Identify when snow is falling and location; Classification of snow type and measure amount; Tasking assets to look at specific storm and at specific latitudes; Multi-agency assets - USGS and Western Water ground-based systems; Coincident measurements
All Technologies Required	Local snow fall measurement as it is happening; Beam steering to further target instruments; Combine measurements - several radars to get a better picture; Spatial variability - in contrast to rainfall snowfall has unknown spatial variability
Gap Technologies	
Types of Sensors	Radar, GPM extends TRMM observations up to higher latitudes; GEOCARB, local AQ sensors, weather forecasts; CubeSat radars, RainCube, 300gHz to 800 gHz; TEMPEST-D; assets that can change frequency; different radar modes and pulse strategies, adaptable radar transmission;
Models	High resolution meteorological models, weather forecasts
If Known, Current, In Development Technologies and Organizations	

ATMOSPHERE	
USE CASE #4	**Environment interaction due to explosion**
Scenario:	Industry explosion with potential chemical consequences that need near and long-term tracking and impacts data. Regulatory agency or in-situ sensors alert to explosion, triggers multi-agency response, USGS, NASA, EPA, first responders. Identify potential chemicals with local data and in-situ sensors, trigger UAVs to begin creating 3D-structure of plume, trigger CubeSat constellations to image and track plume path; combine wind and atmosphere data to predict plume path; provide data to multi-agencies for near term responses. Depending on the situation consider other agencies, such as aviation. Continue tracking environmental impact over longer term with UAVs, satellites and ground/water way sensors.
Relevant Targeted Observables	Convection, ACCP, SBG, SDC
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing/tracking system for cascading events necessitating multi-agency responses.
Types of Data to be Gathered	Atmospheric, particulate matter, chemical compounds, pollution transport; convection; precipitation, snowfall; water resources, carbon, sulfur, methane; subsidence; land cover change, possibly aviation traffic data
Workflows / Triggers	Initial alert from agency or sensor; task multi-angle CubeSat constellation and UAVs to begin developing 3D structure of plume; downlink data to ground, model data, send forecasts to multi-agencies. Continue monitoring, modeling and updating path and sensing of UAVs in real-time; continue uplinking commands to satellite constellations for tracking. Goal is a system that is updating in real-time to monitor/forecast disasters data. Long term monitoring would uplink data to satellite constellations to measure certain areas potentially effected and trigger UAVs and in-situ sensors when appropriate.
Capabilities	Looped system that continues to update based on data gathered; alert triggers ground, UAV, airborne, and satellite systems that feed data to the models that in turn feed data to the sensing systems; GEO for early plume indication, LEO satellites, constellations, UAVs, airborne, ground sensors; Aviation as a sensing system and as an impacted system; Multi-agency and multi-sensor collaboration; water ways, transportation, land, human health; Precursor science data inclusion
All Technologies Required	Feature detection of convection in NOAA observations, tracking of convection centers (convective cores); coordinated observations of environment and in-cloud structure and dynamics, data fusion (and possibly data assimilation) to characterize 3D cloud structure and dynamics.
Gap Technologies	Dynamic control of SmallSat constellation; data fusion and/or data assimilation at convective scales; adaptive-resolution sounding of the environment, and different levels of uncertainty; adaptive pointing/targeting.
Types of Sensors	High spectral/high spatial resolutions (> 1km footprint) infrared spectrometers; doppler radar; doppler wind lidar and/or water vapor atmospheric motion vectors.
Models	Weather (e.g., WRF), Atmospheric models
If Known, Current, In Development Technologies and Organizations	NASA/EO-1, JPL/ASTERIA

3.2. Carbon and Ecosystems Use Cases

CARBON & ECOSYSTEMS	
USE CASE #1	**Monitor Distribution of Plant Species & Habitat Protection**
Scenario:	Monitor plant species patterns, abundance, and disturbances for the benefit of agriculture and human health decision makers, conservation, and national parks. Requires annual, seasonal, monthly and event-driven species movement measurements, impacts of negative invasive species; impacts on fruiting and pollination, and social-economic impacts, and preventing negative impact spread. Monitor and predict animal/insect species movements; specifically, locust tracking.
Relevant Targeted Observables	SBG
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing/tracking system of species events.
Types of Data to be Gathered	Wind, precipitation, river and water data, soil moisture, emerald changes, crop/canopy health, invasive species, pollinators, urban development, human health factors (disease spread); deforestation, fires, meteorological conditions such as hurricanes; resource usage such as water; monitor stress on the ground and how water use and fertilizer effects change over time, habitats, loss of species.
Workflows / Triggers	Anomalous emerald; Infestation scenarios, tree health and tracking; any rapid forest or agriculture changes; tree canopy changes, branches dying; soil moisture, rain and snow, precipitation; water resource changes and impacts; deforestation and related factors that affect human health (pandemics); use SBG or ECOSTRESS as a trigger; species structure changes; fertilizer, water, flood can trigger a response to see how ecosystem responds; chemical spills (what/where it is, where to target); monitor recovery or death, near term and long term recovery; human development, insect, bird migration; GIS location data and species movement.
Capabilities	High data rate and high resolution sensors; Onboard and edge processing (e.g., accurate cloud coverage detection); Timely capture of seasonal changes and events; dynamic timeliness as a function of seasonal and weather effects rapidity; Satellite and sensor re-targeting and multi-angle capabilities; High resolution and narrow vs. broad field of view => see large area spreading events and smaller area impacts; Autonomy and ML for satellite management and improved imaging/measurements, e.g. recognize clouds vs smoke vs fog; Decision making, recognize anomaly and trigger other systems based on issues; Detection of species movements, habitat infections, e.g., using SAR; Multi-asset imaging to understand photosensitivity of plants, forest health, how efficiently plants are using light (e.g., in forests); Spacecraft coordination; Track spread of crop or forest disease spread in real-time; Rapid in-situ and remote sensing disease outbreak discovery, triggering and response; Real-time incorporation of data and modeling: requires localized response to track and analyze what works or not; Feature tracking aspect - fertilizer, water, flood can trigger a response to see how ecosystem responds; Winds, pollinator and pesticide tracking.
All Technologies Required	Multi-sensor fusion such as GLIGHT at GSFC; hyperspectral signature changes; optical and thermal imaging; AI/ML; High resolution platforms; Radar, hyper/multi-spectral capabilities; In-situ sensing
Gap Technologies	AI and ML, citizen science incorporated; hyperspectral; radar; in-situ sensing
Types of Sensors	Hyperspectral, lidar; ground-based radar
Models	
If Known, Current, In Development Technologies and Organizations	NASA, USGS - https://www.nasa.gov/feature/goddard/nasa-goddard-technology-helps-fight-forest-pests/ - https://www.nature.com/scitable/knowledge/library/the-use-of-radar-in-the-study-84825627/ - https://www.icarus.mpg.de/en - https://www.nationalgeographic.com/science/2020/02/locust-plague-climate-science-east-africa/ - https://www.iceye.com/

CARBON & ECOSYSTEMS	
USE CASE #2	**Illegal Fishing Monitoring**
Scenario:	Monitor and track impacts of illegal fishing for improved species management. Require improved understanding and prediction of fish habitats and health for science research and economic impacts.
Relevant Targeted Observables	SBG
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing/tracking system of events capturing habitat, reproduction, and fishing changes and impacts across large areas as species migrate.
Types of Data to be Gathered	Agricultural runoff such as fertilizer, pesticides; sea life and coastal species; depleted and change in fish species; weather tracking; fish habitats and health
Workflows / Triggers	Model anomaly triggers; anomalous habitat protection changes, tracking species depletion; commercial fishing boats and personal watercraft triggers.
Capabilities	Specific area monitoring with regional changes as species move; Timeliness and rapid response to species movements on daily, monthly and seasonal timelines; Targeting specific areas to monitor and track fish across migration locations; Predict/track fish habitats and health of species; UAVs, SmallSats, CubeSats for faster cadence; Modeling and ML for tracking, e.g., use previous data to narrow scope to certain regions: Turn on exploratory behavior of first Sat telling next Sat where boat was to track trajectory of boat
All Technologies Required	Radiometric and spatial resolutions, nighttime radiance information from fishing vessels, location data, bathymetry, chlorophyl, sea surface salinity, sea surface height, sea surface temperature
Gap Technologies	
Types of Sensors	SAR, high resolution, active, small FOV Radar, Lidar, VIIRS
Models	Maximum entropy modeling (MaxEnt), OceanWorks, oceanographic modeling
If Known, Current, In Development Technologies and Organizations	NOAA’s Earth Observing Group and Global Fishing Watch (.org) - are currently tracking with SAR, meteorological satellites and AIS/VMS (Automatic Identification System / Vessel Monitoring Systems) data provides some of this info now with transponder that tells where a boat is European effort “Iceye”?

CARBON & ECOSYSTEMS	
USE CASE #3	**Algal Bloom**
Scenario:	Monitor and track impacts of algal bloom for improved water resource and human health as well as species management. This is a complex system with social-economic impacts that requires coverage of oceans and lakes with a faster cadence and a need to coordinate data with species depletion, water temperature changes, and other related science domains.
Relevant Targeted Observables	SBG, Aerosols, Mass Change
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, time series sensing/tracking system to capture events as they form and track events as they develop, spread, and dissipate.
Types of Data to be Gathered	Ocean color, temperature, winds and coastal species, sea life and grasses; agricultural runoff such as fertilizer and pesticides; aerosols tracking; depletion and change in species; weather tracking; fish habitats and health; human health and interaction/development along coasts and water lines and lakes.
Workflows / Triggers	Space based or in-situ trigger of bloom forming; Model anomaly triggers; Algal blooms, ocean color; Ocean temperature; Agriculture run off, aerosols and human impacts; Sea life and coastal species changes; Depleted species; Pesticide usage;
Capabilities	Specific area monitoring with regional changes as species move; Timeliness and rapid response to species movements on daily, monthly and seasonal timelines; Broad spectrum and multi-asset requirement; Track size and spread of a bloom, model analysis that triggers sensors to gather new data; Aerosol tracking for human air quality impacts; observations over a variety of water such as oceans, coastal area, lakes and reservoirs
All Technologies Required	AI and ML to predict fish location and habitats; night / dark observations; underwater observations; in-situ sensing
Gap Technologies	
Types of Sensors	MODIS, VIIRS, Sentinal 2 and 3, LandSat, Terra, Aqua, Suomi Nat. Polar Partnership (SNPP)
Models	OceanColor Web (oceancolor.gsfc.nasa.gov); Giovanni (Giovanni.nasa.gov/Giovanni); SeaDas (seadas.gsfc.nasa.gov)
If Known, Current, In Development Technologies and Organizations	Unknown

3.3. Earth Surface and Interior Use Cases

EARTH SURFACE & INTERIOR	
USE CASE #1	**Land Level Change**
Scenario:	Monitor land level change for decision making related to infrastructure and economic resolutions in relation to subsidence issues. Provide data for community design and infrastructure given subsidence; and how operations, maintenance, future investments, business decisions (stay, retreat) and insurance will be affected by subsidence.
Relevant Targeted Observables	SDC, ACCP, SBG
Why NOS vs Classic Mission	Requires coordinated constellation, sometimes rapid response, multi-asset, multi-angle, time series sensing/tracking system capturing dynamics of subtle changes over long periods and rapid changes due to sudden events. Complex, dynamic situation for which no one-system can provide all necessary overall data; needs sufficiently automated and smart system. Short- and long-term subsidence events, especially in regard to community impacts need interactive systems that can capture dynamics of subtle changes with surface deformation from a broad variety of human and nature induced impacts such as ground water pumping and injection, fracking, coastal degradations, extreme weather and earth interior events, among others.
Types of Data to be Gathered	ESI, atmosphere, hydrology, snow, weather events; ecosystem changes; Earth surface and interior events, human events - fracking, drilling, pumping, ingesting, building, etc.
Workflows / Triggers	Global Positioning System (GPS)/gravimeter triggered SAR acquisitions; weather events; ground water pumping/injection/fracking; coastal & sea-level rise; aquifer measurements; permafrost melting and related impacts (human, species, water flow, etc.); Flood predicted - trigger in-situ sensors to get different modalities, task CubeSats for after the fact analysis, also leading up to flood take better data to help with after the fact analysis; event analysis of historically unrelated data; e.g. Tsunami event, prior to Earthquake the tide gauges showed unusually high mark, some went underwater, had been subsidence by about 1 meter 4 minutes before event, never looked at tide data, coastal flooding, etc., didn't recognize as an indicator; could have predicted Tsunami; consider evolving predictive stories.
Capabilities	Subsidence changes, hydro, land, coastal changes in elevation; Coastal erosion, climate, sea level rise, aquifer hydrology, precipitation, snow measurements, etc. with rectified resolution and spatial aspects and manmade features (roads, drilling, military bases, etc.) included; Modeling and tracking of simultaneous changes (ocean, coastal, weather, earth surface, interior, manmade); Infrastructure layers from Department of Energy (DOE), Commerce, Census; Understanding disruptions to timelines, economies, science; (if we had a NOS system today we would have a different product for COVID info/dashboard); Understand downstream subsidence, what are effects when subsidence does happen; Need different timing, polarization, resolution; Need triggering and pull connections to other data sets, cannot wait for data to show up; Need model of how subsidence works and trigger systems to get updated data for model; ACF system identifies types of data needed to update models => ACF plug and play tools, models, and data analysis capabilities; Anomalous event analysis / triggering; tide sensors suddenly underwater, coastal sensors show anomalous subsidence is ocean event happening (e.g., tsunami)
All Technologies Required	Adaptive observation planning, AI / ML, data fusion, ensemble modeling, sensor networking; NISAR - SAR, UAVSAR, lidar; Deploy large radar antennas at low cost; Large swath coverage with lidar; Global precipitation, GNSS, GPS, Geodetic data for DEMs; SMAP for soil moisture; GRACE-like measurements with finer resolution;
Gap Technologies	Lightweight large (>10m) antenna; Large swath radar; 3D displacement; Atmospheric correction
Types of Sensors	Synthetic aperture radars (long wavelengths); lidars
Models	Risk Maps; Geophysical Models; USGS/MODFLOW forecasting
If Known, Current, In Development Technologies and Organizations	Unknown

EARTH SURFACE & INTERIOR	
USE CASE #2	**Landslide**
Scenario:	Tracking a risk area after a forest fire with atmospheric river, precipitation, snowpack, and Earth interior events over seasons and years for landslide risks or re-growth minimizing landslide risks. Also, monitor strain over slow-moving landslide to see when acceleration begins and track risk factors and change.
Relevant Targeted Observables	Surface Deformation and Change (SDC)
Why NOS vs Classic Mission	Requires coordinated constellation, sometimes rapid response, multi-asset, multi-angle, time series sensing/tracking system for events from disasters and over long periods of time.
Types of Data to be Gathered	Atmosphere & weather events, surface composition, hydrology/ soil moisture, snow, volcanoes; agriculture, forests, human impacts / development
Workflows / Triggers	Slow moving landslides: model triggers if a fire in an area, then amass data to measure and predict landslide susceptibility
Capabilities	Collaborative measuring with universities, governments, industry; Mapping data which triggers measurements for predicted landslide areas based on events, floods, fires, earthquakes, etc.; Monitoring events across range of time with susceptibility triggers- fire in one season followed by Earth movement and heavy rainfall in next season should trigger measurement system; Tracking and predicting slow-moving landslide - e.g., Kilauea, where will lava go and when will it affect a power plant downhill; Use of predictions to optimize observations; Interactive and predictive observation model
All Technologies Required	Hydrology sensing Geologic and subsidence sensing
Gap Technologies	
Types of Sensors	Global Precipitation Measurement (GPM), Synthetic Aperture Radar (SAR, variety of bands), Sentinel sensors RadarSAR; LIDAR; stereo imagery; thermal imaging; multi-spectral imagery
Models	Geophysical models
If Known, Current, In Development Technologies and Organizations	USGS; NASA; ARC Innovation centers Rainfall and Landslides in Northern CA project; r CEOS WG Landslide Pilot project

EARTH SURFACE & INTERIOR	
USE CASE #3	**Volcanoes**
Scenario:	Identify when a volcano might erupt, predict human and economic impacts, track plume and related impacts; better understand volcanos and their plumes.
Relevant Targeted Observables	Surface Deformation and Change (SDC)
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi/angle, time series sensing/tracking system for cascading events necessitating multi-agency responses.
Types of Data to be Gathered	Hydrogen fluoride / hydrogen sulfide; plume particulate matter and movement track, falling particulate matter location and amount, particulates dispersing to upper atmosphere; thermal anomaly data
Workflows / Triggers	Volcanic sensing, InSAR interferometric anomalies; gas and thermo changes over volcanoes; plume movement; lava/slow landslide movement
Capabilities	Retargeting of assets scheduled for other observations; Coordination of assets, government, academic, industry; Observations prioritization; Plume tracking and prediction - what particulate matter is in plume and size and distance/location it is traveling to; Need InSAR baseline (with same instrument in same orbit); Automated capability to trigger and command a vast array of systems then fuse data from MODIS, OMMI, AIRS, or like-sensors, etc. (Kilauea response required a huge variety of tools that had to be manually called and put together); More predictive modeling to direct where to do observations
All Technologies Required	Tomography, InSAR for interferometric changes; Thermal and gas emission sensing (hydrogen fluoride / hydrogen sulfide not yet monitored from space) and processing; Hyperspectral sensing (tradeoff between bandwidth/resolution) and processing
Gap Technologies	Water; CO2; hydrogen sulfide monitoring (requires finer spectral observations); LIDAR trace gas;
Types of Sensors	Tiltmeter SensorWeb; SAR, LIDAR; SO2 emissions; MODIS, OMI, AIRS, VIIRS; MISR GLISTEN and UAV SAR
Models	Magma source models
If Known, Current, In Development Technologies and Organizations	USGS Volcano Hazards Program; NASA/Disasters portal relevant to NOS: https://disasters.nasa.gov/central-and-east-africa-floods-2020

EARTH SURFACE & INTERIOR	
USE CASE #4	**Land Cover Land Use (LCLU) Change - Wildfires**
Scenario:	Measure and predict the risks and impacts of wildfires to humanity, species, and infrastructure by monitoring human and climate-based land cover – land use changes (LCLUC), percent of impervious surfaces; drought conditions and lighting events especially around airports, plants, and schools; triggers to define when green up changes, or drought increases to adapt models and predictions as seasons, climate, and weather changes.
Relevant Targeted Observables	Surface Biology and Geology (SBG); Terrestrial Ecosystem Structure
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing/tracking system for events followed by timely (seasonal, related events, near real-time) observations
Types of Data to be Gathered	Infrastructure changes and features; weather; drought; lightning; wildfire fuel sources; invasive species tracking (communities may clear cut due to invasive species destroying forests)
Workflows / Triggers	Forest fire risks, human impacts and percent impervious surface, soil moisture, forest fuel levels; lightening and storms
Capabilities	Infrastructure and human impacts in wildfire areas; Change in habitat of species, hyperspectral mapping for plants / animals; Ability to identify imbalance in models and anomalies to trigger measurements; Timely, dynamic systems to make measurements of short term events such as a severe drought over a short season; Fuel load measurements, location of growth, type of species, dryness of soil, abundance of fuel related to communities, types of buildings (schools); Seasonal / climate changes to predictive models; predictive models to track less monitored areas (e.g., wildfires that need to be tracked, while it was not needed in the past); Observation and data attribution and provenance (e.g., insurance companies cancel insurance due to risk based on old/inaccurate data); Disparate observation systems optimized for use to measure events when triggered and combined observations
All Technologies Required	Large swath coverage with lidar; Global precipitation, GNSS, GPS, Geodetic data for DEMs;
Gap Technologies	LIDAR for ladder fire mapping (e.g., vertical spread of fire)
Types of Sensors	Optical remote sensing; hyperspectral; NISAR, SAR, UAVSAR, lidar; SMAP for soil moisture; GRACE-like measurements with finer resolution
Models	Carbon emission model based on LCLUC
If Known, Current, In Development Technologies and Organizations	USGS California Climate and Wildfires; CA climate change maps Cal-Adapt.org

3.4. Oceans Use Cases

OCEANS	
USE CASE #1	**Algal Bloom Tracking – Fisheries & Sea Life**
Scenario:	Detecting and tracking algal blooms as they begin to occur and while they develop, spread, and decline at precise seasons, events, and times of the day due to high impact on fisheries, fisherman, coastal communities and any sea life within the algal bloom and better understanding difficult to detect algal blooms near the coast due to atmospheric changes.
Relevant Targeted Observables	Aerosols, MC, SBG, Ocean Surface Winds and Currents
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing/tracking system across random and ever-changing spatial regions and seasons.
Types of Data to be Gathered	Seasonal and tidal data, coastal data, atmospheric and water temperature changes.
Workflows / Triggers	Color changes in water, using NDVI index (used SeaWIFS data in the past); regulatory agency may send a trigger; city/state notifications; bloom location triggers; change in plant or fish species; commercial, international, NASA, etc. triggering; agricultural runoff events; (e.g., heavy rains in northern Mississippi region potentially affect Gulf of Mexico oxygen levels and cause a bloom)
Capabilities	Finding blooms with high accuracy; Capturing CO2 anomalies; oxygen levels in waterways; changes and affected marine life; 1 meter resolution; Feature tracking; Correlations of temperature, carbon, etc. to identify a potential bloom or one that is starting; Vertical structure of algal blooms; blooms need nutrients and light and towards the base are larger amounts of biomass; Salinity, temperature, winds, currents, ocean color measurements; Optimizing constellations for multiple science measurements; CubeSat constellations with Lidar and multispectral (with appropriate bands) pass once a day, see blooms, trigger next in constellation to measure again; Edge computing to recognize clouds and other coverage issues onboard; Low latency, need daily or every few days passes; Seasonal observations, especially in spring and fall for blooms; Phytoplankton changes; Cyano-bacteria - some partial instruments are missing some spectral nuances; Commercial agreement (data buy) might help; DESIS instrument would be useful
All Technologies Required	CubeSats with multi-spectral (MS) sensors (MS sufficient if critical bands included) and Lidar distributed on them; NOS would re-task sensors and determine which other in-situ measurements are useful; space measurements being from NASA, commercial or international)
Gap Technologies	
Types of Sensors	Space-based lidar; PACE, LandSat 9, MAXAR usable bands; Airborne; UAVs; Ship-based sensors, bio-geo-Argo floats, buoy sensors; NOAA data, commercial (MAXAR), foreign and academic data products (NASA data buy); Hyperspectral on space station; PRISM CubeSat; Lidar, blue lidar for coastal regions; Radar, Doppler scatterometers; MODIS for Chlorophyll and suspended sediment concentration (SSC) measurements
Models	NASA Ocean Biogeochemical Model (NOBM); MIT General Circulation Model (MITgcm); MIT Darwin Project; ECCO (Est
If Known, Current, In Development Technologies and Organizations	"Estimating the Circulation and Climate of the Ocean" (ECCO) consortium; JPL/Interactive Oceans State of the Oceans (SOTO); JPL/Oceanworks; Sail drones; LaRC High Spectral Resolution Lidar (HSRL) and Differential Absorption Lidar (DIAL); SeaWIFS-related projects

OCEANS	
USE CASE #2	**Predicting Coastal Flooding Due to Hurricanes**
Scenario:	Predict, monitor and identify effects of coastal flooding due to hurricanes and severe storms, monitor immediate hazards, needs and long-term change of effects on coastal flooding and metropolitan costs and spending; identifying potential risks of storms, hurricanes or mid-latitude cyclogenesis, and work with multiple agencies. Better understanding and improved El Niño predictions with data assimilation of many assets.
Relevant Targeted Observables	PBL, ACCP, SBG, SDC, MC, Ocean Surface Winds and Currents
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing/tracking system on dynamic events with potential human impacts.
Types of Data to be Gathered	Ocean currents; river data, precipitation, changes in tide and sea surface height; crowd sourcing identifying where flooding is happening; wind speed, intensity, direction, wind vector; water volumes; land composition and elevation, storm track to predict coastal and metropolitan flooding; vertical land motions and land models; sea level rise data; integrated water vapor, cloud top height, atmospheric pressure, storm surge
Workflows / Triggers	Hurricanes; aggressive storms; tidal anomalies; river & stream gauge anomalies; in-situ and crowd sourcing data; currents, sea surface height
Capabilities	Crowd sourcing capabilities to help identify flooding extent; Event driven redirecting of assets; Rapid revisit data; Rapid response & consistent tracking; Collect evidence of beginning of ENSO (El Nino Southern Oscillations); Utilize Japanese and NOAA buoys with data assimilation of many assets; Airborne assets to monitor and better understand and improve El Niño predictions with data assimilation of many assets; Sensors that penetrate cloud cover, manage in high winds and heavy precipitation; Before and after flood imaging; Ability to identify risk of flooding due to events, rain, snow, winds, etc.; Communication and data sharing with disaster response and first responder teams; Autonomous detection systems, AI/ML; Models and model triggering, regional, national, global models all communicating; Applications and advanced data mining techniques that enable crowd sourcing data to be deciphered and shared with models; Linking cell phones and other mobile devices (IoT) as SensorWebs, e.g., pointing a phone at something to take a measurement and share it
All Technologies Required	Rapid revisit data; floats, radar, SAR; GPS sensors, acquire live feed of measurements to guide tasking of sensors; constellations for continuous and timely measuring; airborne and in-situ SensorWebs for high resolution and specific region measurements; Small sat adaptive sensors incl. advanced GNSS-R capabilities and radiometer systems already under development by ESTO
Gap Technologies	On-board autonomy to adapt sensor operations and resource management; Communications among network of CubeSats, SensorWebs, etc.
Types of Sensors	Rapid response assets, gravitational sensors, Doppler; GNSSR; constellations, CubeSat radiometers, altimetry, floats, ships of opportunity; Tempest -D CubeSat; GPS sensors; Future SWOT mission; Small Sat wind sensors (e.g., GNSS-R as in CYGNSS); Larger wind vector missions, small sat radiometry for atmospheric properties (as in Rain Cube, Tempest-D); coordination of observations to increase space time resolution, in-situ sensors on ships (e.g., ADCP) or buoys.
Models	GEOS-5; ECCO; ENSO (NOAA CPC, IRI, NOBM, NHC forecast models and NOAA weather models
If Known, Current, In Development Technologies and Organizations	MSFC & JPL projects around forecasting;

OCEANS	
USE CASE #3	**Ocean Carbon Export & Sequestration**
Scenario:	Discovering and monitoring ocean carbon as it relates to acting as a carbon buffer. Measure how much carbon is sequestered out of the surface, discover when the ocean reaches saturation and how much carbon is being sequestered at any given time, as well as how much is exported and where.
Relevant Targeted Observables	Convection and Precipitation; ACCP; PBL; Ocean Surface Winds and Currents; Clouds; Atmospheric Winds
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing/tracking system to track transient events at particular but fluctuating times and seasons.
Types of Data to be Gathered	Ocean acidification, currents, winds, temperatures; composition of wetlands and phytoplankton's; arctic colors where release of carbon from melting permafrost; tidal, coastal, watershed measurements; coastal forests
Workflows / Triggers	Seasonal and climate changes such as melting permafrost carbon measurements; spring bloom in open ocean and on land; disruptions and anomalies in wetlands and permafrost regions; model triggering of anomaly or percent change of data; remote observations trigger other observables and models
Capabilities	Directable sensing to track transient events; Adaptable models; Tracking of seasonal changes, spring bloom in open ocean and on land; In-situ, SensorWebs, UAV, airborne and satellite measurements; Track which biological species take up more carbon and when they release it; Measure 3D structures and gas exchange across surface; Mesoscale measurements; Data sharing and buys from commercial entities; Tidal and coastal environment measurements, including coastal forests and watersheds; Blue carbon is a critical area
All Technologies Required	Bio-floats (trap sinking particles) are a critical component, floats catch raining of marine snow CAVIS sensor on WorldView-3 (30 m resolution); 1-meter optical data; SmallSat adaptive sensors including advanced GNSS-R capabilities and radiometer systems (already under development by ESTO); Improved systems for assimilating data and for on-board processing to enable rapid data analysis and response.
Gap Technologies	Onboard autonomy to adapt sensor operations and resource management; Communications among network of CubeSats
Types of Sensors	SmallSat wind sensors (e.g., GNSS-R as in CYGNSS), larger wind vector missions, SmallSat radiometry for atmospheric properties (as in Rain Cube, Tempest-D); Doppler; LIDAR; Radar; Scatterometers;
Models	NOAA weather models.
If Known, Current, In Development Technologies and Organizations	NASA and NOAA blue carbon expertise

3.5. Snow, Ice, Energy (Hydrology) Use Cases

SNOW, ICE & ENERGY	
USE CASE #1	**Melting Sea Ice**
Scenario:	Melting sea ice affects many aspects of science and supply chain management and transport, such as increasing ocean salinity, global ocean circulation patterns, and opening up northern sea shipping and transportation passages. Could this be predicted weeks ahead of time to determine if a tanker can pass through saving energy and time? Observations and models must be closely tied together, and new capabilities must be developed such as ships dropping/dragging measurement sensors.
Relevant Targeted Observables	MC; ACCP; SBG; SDC; Ocean Surface Winds and Currents; Ice Elevation; Surface Topography and Vegetation
Why NOS vs Classic Mission	Requires coordinated constellation, sometimes rapid response, multi-asset, multi-angle, time series sensing/tracking system on dynamic events over seasonal changes and decreasing current weather limitations.
Types of Data to be Gathered	Ocean surface winds, currents; ice elevation; surface topography and vegetation; atmosphere; hydrology; snow; carbon; sea ice melt and calving; hurricane forecasting; pollution; spills and contamination; ice formation or ice persistence; salinity; temperature
Workflows / Triggers	When does ice break up? Sea surface temperature and ice thickness; Ocean circulation; What signatures from other measurements indicate what is happening with sea ice? Elasticity of ice sheet; Ocean winds
Capabilities	Capability to combine measurements in models to observe and predict sea ice changes and feed model data back to sensing systems; Various polarized multichannel for metamorphosis of the ice; Need snow and ice properties at the same time; Ocean heat wave discoveries through airborne data and high-resolution modeling; Marine life changes and data integration into sea ice models; Opportunistic sampling with in-situ sensors on icebergs, ships; different frequencies/modalities; Rapid temporal observations and high-resolution spatial data Science research resolution data; Shipping and economic capabilities will advance faster than required research science data; Timely notice of transport lanes (large economic implications); Snow, ice and ice thickness require different frequency radars: snow higher frequencies, melting ice needs SAR; Timely notice of shipping channels (large economic implications); Coupling of snow and ice impacts many factors but acts differently with ice melt over the sea, it will require different models and data to accommodate different change scenarios; Discovering and tracking ocean heat waves, i.e., small scale features that cannot be captured by satellites alone, rapid in appearance and disappearance; Need to sense them as they develop and trigger rapid reaction sensing with multiple assets; Architecture: frequently, models discover the heat waves, period of time is generally over a few days and size is 10's of kilometers, short phenomena; ocean modeling of high-resolution data is looking for frequency of events, looking for how eddy transport is carrying heat to the ocean; rogue heat waves start small but become massive; high resolution modeling is necessary
All Technologies Required	Microwaves to track sea surface temperature; Radar for sea surface winds and more specific to snow and ice, correct frequencies; SAR - ice requires interferometry SAR, melting requires polarimetric SAR; Measurements from air, space, sea surface and below sea surface; Measurements within and underneath ice shelves; Gravitational measurements; Altimetry of surface; Data and video from ships to feed models; High resolution and rapid temporal data (<4 hours); Flexible System Support on the Ground (evolution and scaling); Steerable space vehicles (DoD currently does this); Constellations of SAR systems combined with in-situ, models, etc.; Ship sensors detect anomaly and trigger other ship sensors; Dynamic sensor pointing; Multi-variate (e.g., snow, soil moisture, vegetation) OSSE

Gap Technologies	Multifrequency spaceborne sensors - K, C, L-band radar at multiple angles; (AirSar - stopped flying, NISAR cannot measure P and L bands); Software-defined radio for instruments; Constellations with multiple instruments each with individual sensors; Stable small spacecraft that do not drift; Autonomous cross-calibration among instruments and ML to correct calibration; Larger models with ML and related capabilities; Require GPU technology to keep up with fast paced SW changes; New chips optimized for neural network processing; Models that simultaneously analyze more than just snow and ice and tying models together to bring in-situ and remote sensing observations
Types of Sensors	SAR; LIDAR; Multiangle measurements; Bidirectional Reflectance Distribution Function (BRDF) measurements; UAVs to measure thickness of floating ice shelves; high resolution optical imagery to view differences in photos a couple of days apart; sensors that measure ocean waves; scatterometry; lower frequency, multi-angle, passive radiometers; high-resolution LIDAR; video from ships; permafrost measurements
Models	Models that predict how ice sheets form and break up; wind models that show wind pushing sea ice around; ice sheet thickness measurements; ICESat-2 models; shipping models
If Known, Current or In Development Technologies and Organizations	CubeSat VIS capabilities already available with Planet and commercial capabilities and data buys; AWS GaaS (Ground Systems as a Service); SmallSat constellation / swarm technology has been developed by NASA and industry; Space-qualified High Performance Computing (HPC) to enable ML, on-board processing being developed by NASA, DoD and industry; SmallSat SAR developed by DoD and industry; Currently, some iceberg tracking is being done, but not timely and not integrated with other remote sensing data; International Ice Patrol & North American Ice Service Coast Guard and NOAA all track and share data and models (international effort as well); Satellite SAR Data-based Sea Ice Classification: https://www.mdpi.com/2076-3263/9/4/152/pdf; Primer on ice & snow measurement using SAR: https://earth.esa.int/documents/10174/3166008/ESA_Training_Vilnius_07072017_SAR_Optical_Snow_Ice_Lecture_Schwaizer.pdf; Current USCG Navigation Center ice chart: https://www.navcen.uscg.gov/?pageName=iipCharts&Current; Example product: today's iceberg tracking for North Atlantic. https://www.navcen.uscg.gov/?Do=popImage&urlRef=images/iip/data/2020/20200615_NAIS65.gif AIST/NOS-T work uses the Atmospheric River probability models at https://cw3e.ucsd.edu/iwv-and-ivt-forecasts/ USGS modeling information at: https://water.usgs.gov/nawqa/modeling/ USGS integrated Water Availability assessments: https://www.usgs.gov/mission-areas/water-resources/science/integrated-water-availability-assessments-iwaas?qt-science_center_objects=0#qt-science_center_objects

SNOW, ICE & ENERGY	
USE CASE #2	**Water Resources and Agriculture**
Scenario:	Measure and monitor water resources and related affected systems to optimize water resource usage with consideration for the many divergent needs and rights. Dynamic system that updates models, farmers, communities, Indian reservations, etc., based on current and long-term water resource availability and different conditions/scenarios. Provide greater knowledge and information enabling immediate understanding and long-term impacts on environment, crops, communities, including all water resources, groundwater, snow melt, aquifers, etc.
Relevant Targeted Observables	MC, SBG, Snow Depth & Snow Water Equivalent; ACCP; Clouds, Convection, and Precipitation
Why NOS vs Classic Mission	Requires coordinated constellation, sometimes rapid response, multi-asset, multi-angle, time series sensing/tracking system for dynamic events across multiple science domains.
Types of Data to be Gathered	Water resources; agriculture and crop health; soil moisture; snow; precipitation; drought; wind; stream and reservoir data; atmosphere; carbon; PBL; atmospheric rivers; clouds convection
Workflows / Triggers	Underground water levels, where water coming from, what is the usage and replenishment forecast; day, season, weather events trigger snowmelt; groundwater changes and anomalies; drainage routes and changes; NASA to coordinate with USGS and other agencies to share triggers from sensors/models; snowpack density and moisture levels; glacier depth, freeze and thaw measurements and models. Model forecast, updated models from different sensors depending on time and changes over seasons (e.g., a satellite radiometer with daily info tracking dry or wet areas on a coarse scale identifies a dry area anomaly => UAVs deployed to measure dry area and update models); need a joint carbon and hydrologic model as crops grow PBL changes, heat and energy changes with crop growth
Capabilities	Seasonal water budget management with models being updated regularly, triggering sensors for new data and providing data to end users; models that can scale and with greater detail; data evaluation for models (how much, what kinds, and what granularity); models with synthetic inputs and able to accept a lot of variables for same location, e.g., snow, run off, groundwater, precipitation, storm sensors, atmospheric rivers; UAVs, airborne, in-situ and satellite constellations interacting as SensorWebs; co-located, high resolution, localized observations; measuring resources that would not be replenished quickly/easily is very important - ground water, snow pack; Cross-correlation of systems; Determine which points give the most information, do not need to measure every point of the ground, need efficient/effective measurements; Training approaches using images; 100 m-resolution for crops; Managed communications; Collect and integrate a wide variety of existing ground sensors and model forecasts, e.g., stream gauges, reservoir heights, rain gauges, atmospheric river forecasts, etc.; quantifiable, accurate data rather than estimated, much of snow pack is estimated; Autonomous systems with few humans in the loop; off-schedule, autonomous or human-induced new model runs when an "event" is discovered; Accurate aquifer measurements, e.g., fleet of drones with improved resolution; current gravity measurements are not useful for crops; need discovery of cracks in bedrock and loss of water, etc.; dynamic and small scale cannot be measured from space, e.g., slivers of high humidity streams of air that come and go; Optimized tasking of multiple satellites with various configurations (e.g., combined with previous sea ice scenario?); Systems that adapt from time-based to condition-based maintenance
All Technologies Required	Interferometer SAR; high resolution LIDAR (vertical & horizontal); low-cost photon-counting clusters; stereo depths (multi-angle or multi satellite); data-driven models; autonomy and ML; science model-driven observations; low frequency radars; low hundreds of MHz radar; radar on a CryoSAT for simultaneous measurements; satellite radiometer; UAVs; constellations
Gap Technologies	Space LIDAR; multi-angle, multi-frequency radar; turning radar on/off; model-data fusion; ML and related capabilities for better data assimilation; autonomous cross-calibration of systems
Types of Sensors	GRACE-like; airborne LIDAR; low-frequency radar; SAR; hyperspec; radiometer; UAV sensors
Models	GEOS; LIS; USGS National Hydrologic model, USGS/MODFLOW, Central Valley Model; Snowpack model; Atmospheric river models; https://cw3e.ucsd.edu/iwv-and-ivt-forecasts/
If Known, Current, In Development Technologies and Organizations	Networked sensors (some already developed by USGS and NASA)

SNOW, ICE & ENERGY	
USE CASE #3	**Flooding - Rain and Snow Disasters**
Scenario:	Measure and track atmospheric rivers, snowpack condition and rain on snow instances and related flooding events with an integrated, multi-asset, flexible sensing system across multiple agencies and organizations; use multiple assets to observe phenomena that would act like a single large aperture for forecasting/prediction resulting in a state-of-the-art forecast of floods.
Relevant Targeted Observables	Clouds, Convection, and Precipitation; Mass Change; SBG; Snow Depth and Snow Water Equivalent; ACCP; Water Resources; Agriculture and Soil Moisture
Why NOS vs Classic Mission	Requires coordinated constellation, rapid response, multi-asset, multi-angle, time series sensing/tracking system for cascading events necessitating multi-agency responses with large spatial and temporal scopes.
Types of Data to be Gathered	Clouds, convection, and precipitation; ocean data related to atmospheric rivers (AR), soil moisture and agriculture; atmospheric conditions, snowfall; subsidence, land cover-change; stream/river height and speed using gauges, rain gauge, precipitation radar, reservoir height, surface flow, AR probability, landslide probability; avalanches probability; rates of change
Workflows / Triggers	Atmospheric river tracking/modeling trigger systems; connecting to forecast informed reservoir and river operations; measurements of rain on snow for estimation of flood risks; flood detection triggers/alerts; AI systems determine when/where to make acquisitions (could be decisions that are hierarchical and federated); systems may include both smart/taskable assets and passive read-only assets; recruit multiple assets to observe phenomena with larger spatial or temporal scope; coordinate assets to observe phenomena (e.g., several CubeSats acting as a single large aperture and triggering ground sensors clusters for regional measurement).
Capabilities	Spacecraft clusters; constellation network decision making; Uncertainty quantification; Atmospheric river forecasts as important drivers for flood events, pulling various measurements, stream/river gauges, landslides, etc.; Address lag in deploying airborne assets and in getting satellite data; Capability to detect something which is about to happen and ability to spin up assets needed; Ground truthing on the fly, local observations streamed iteratively between airborne and satellites; improving next forecast instead of next storm event; Prediction modeling fed by ground truthing for hazard zones; modeling structural integrity for finding hot spots for failure; Better fidelity as AR data degrades rapidly; additional radars; Ability to rapidly perform trades of satellite systems to optimize science value and capture event value, especially with steerable satellites; Smaller, inexpensive systems able to fly in heavy rain, winds, snow, etc.
All Technologies Required	Edge sensing; instrument decision making; Spacecraft, clusters, constellation network decision making; enable recruitment of additional observing assets that are not part of the core mission (commercial, other missions and partners); UAV/UUV autonomy to follow boundaries of storm systems; Dedicated computer nodes in orbit to provide additional storage and compute power; Communications that can be shared among multiple missions; Steerable systems, DoD operates regularly steerable SmallSats and CubeSats - steerable satellites could reduce the number of needed CubeSats; Distributed, coordinated planning; centralized planning; distributed decision making; Planning in the presence of assets that could fail/drop out; Collaborative planning in distributed networks
Gap Technologies	
Types of Sensors	SAR, altimetry, imagery; UAVs and Airborne Snow Observatory type lidar for snow mass as related to rain on snow event; stress strain, debris flow
Models	AR forecast, landslide probability, watershed propagation, Atmospheric river forecast, landslide, watershed propagation models (how does rain event propagate over a watershed) river routing model HyMap, RAPID Model, LIS and variety of land models
If Known, Current, In Development Technologies and Organizations	Automated sensor tasking in advance of weather events (NASA, USGS); Onboard data processing (NASA, commercial); GeoSat has steerable capabilities and CubeSats with radiometers but no propulsion to physically steer them

4. Technology Breakouts Details

This section consists of two parts:

- First, we extract and summarize in a general manner all cross-cutting capabilities and technologies that were identified during the Science breakouts.
- Then, more details are provided for specific capabilities that were pre-selected to be discussed during the Technology Breakout sessions. The technologies listed under these tables mostly correspond to specific gaps that have been identified by the Technology community.

Although the NOS workshop was focused on Information Systems Technologies, NASA's Earth Science Technology Office provides opportunities for prototyping both the hardware and software aspects outlined in this workshop report, as well as potential in-space testing. The ESTO Instrument Incubator Program (IIP) and the Advanced Component Technology (ACT) Program solicit instrument and component advanced technologies; the In-Space Validation of Earth Science Technologies (InVEST) Program provides in-space flight validation and the Advanced Information Systems Technology (AIST) Program provides information and software advanced technology prototyping and testing. All of the ESTO solicitations are open to public and private proposals and provide many public-private partnership collaborations with academia and industry. Therefore, all the various technologies identified during the workshop are listed below, but for the remainder of this report, we will only focus on AIST-centric technologies.

A. Cross-Cutting Capabilities and Technologies Extracted from the Science Breakouts

These cross-cutting capabilities can be categorized as (a) general capabilities that relate to overall concepts, missions and instruments, and (b) capabilities and technologies specifically relevant to AIST.

(a) General Capabilities

(i) Overall

- Steerable systems
    - Steerable satellites could reduce the number of needed CubeSats (Note: DoD regularly operates steerable SmallSats and CubeSats)
    - Adaptive pointing/targeting; satellite and sensor re-targeting and multi-angle capabilities
    - Use sensor such as GPS, acquire live feed of measurements to guide tasking of sensors
    - Rapid revisit data/rapid response & consistent tracking of events
- Smaller, inexpensive airborne systems able to fly in heavy rain, winds, snow, etc.
- Collaboration with other organizations:
    - Collaborative measuring with universities, governments, industry
    - Enable recruitment of additional observing assets that are not part of the core mission (commercial, other missions and partners)
    - Commercial agreement such as data buys (e.g., for instruments such as DESIS)
    - For disasters, communication and data sharing with disaster response and first responder teams
- Crowd sourcing capabilities to help identify specific events

- Dedicated computer nodes in orbit to provide additional storage and compute power
- Edge sensing
- Communications that can be shared among multiple missions

(ii) Missions/Spacecraft

- Mission Trades:
  - Use drones/UAVs, airborne, balloons, in-situ and satellite (CubeSats, SmallSats and other) constellations or clusters interacting as SensorWebs
  - Spacecraft coordination and optimized tasking of multiple satellites with various configuration
  - Constellations for continuous and timely measurements
  - Acquire co-located, high-resolution, localized observations, coincident measurements, multi-angle imaging
- Low latency, using daily or every few day passes
- CubeSats and UAVs with multi-spectral (MS) or hyperspectral sensors (MS sufficient if critical bands are included)
- CubeSats/SmallSats with Lidars
- Obtain stereo depths with multi angles or multi satellites
- Communications among network of CubeSats, SensorWebs, etc.

(iii) Instruments

- Resolutions:
  - High spatial and temporal (rapid repeats) resolutions of instruments
  - High resolution and narrow vs. broad field of view; enables to see large area spreading events and smaller area impacts
- Optical and thermal imaging
- Radar:
  - Multi-angle, multi-frequency radar
  - Low frequency radars, low hundreds of MHz radar
  - Radar on a CryoSAT for simultaneous measurements
  - Capability of turning radar on/off
- Interferometer SAR
- High resolution space LIDAR (vertical & horizontal)
- SmallSat adaptive sensors including advanced GNSS-R capabilities and radiometers (Note: systems already under development by ESTO)
- Low-cost photon-counting clusters

(b) AIST-Related Capabilities and Technologies

AIST Capabilities:

(i) Observing Systems/Missions Design

- Ability to rapidly perform trades of satellite systems to optimize science value and capture event value, especially with steerable satellites
- Looped systems:
  - Continuous updating based on data gathered
  - An alert triggers ground, UAV, airborne, and satellite systems that feed data to the models that in turn feed data to the sensing systems

- Multi-variate OSSE (e.g., snow, soil moisture, vegetation)
- Adaptive pointing/targeting
- Ability to integrate airborne and in-situ sensors for high resolution and specific region measurements
- Ability to link cell phones and other mobile devices (IoT) as SensorWebs, e.g., pointing a phone at something to take a measurement and share it

(ii) Assets and Constellation Coordination

- Spacecraft, cluster, or constellation network decision making:
  - Centralized planning
  - Distributed, coordinated and collaborative planning and decision making in distributed networks
  - Planning in the presence of assets that could fail/drop out
- Detection and autonomous avoidance capability
- Software systems for coordinated observations via:
  - Leader/follower sensor/spacecraft system coordination
  - Several satellites acting like a single large aperture
- Knowledge and information systems necessary to recruit a cluster of ground sensors to get a regional measurement based on space information: know when, where, and how to find the appropriate data
- Dynamic control of a CubeSat/SmallSat constellation with mixed instruments for both large- and fine-scale coordinated observations, e.g., for:
  - Tasking assets to look at specific storms and at specific latitudes
  - Reconstructing fine-grained time-evolving 3D structure of clouds and aerosols
- Software-defined radio for instruments

(iii) Strategy, Planning and Targeting

- Predictive modeling to target observations
- Event-driven redirecting of assets, e.g.:
  - Ability to identify risk of flooding due to events, rain, snow, winds, etc.
  - Ability to detect something which is about to happen and to spin up quicky required assets accordingly
- Timely, dynamic systems:
    - Measurements of short term events such as a severe drought over a short season
    - Triggering capabilities based on connections between datasets, not waiting for data to "show up"
    - Automated capability to trigger and command a vast array of systems then fuse data from multiple sensors (e.g., Kilauea response required a huge variety of tools that had to be manually called and put together)
- Adaptive sampling for efficient/effective measurements, i.e., determine which points give the most information; not every point of the ground need to be measured
- Address lags in deploying airborne assets and in getting satellite data
- Observations prioritization

(iv) Event and Feature Detection and Tracking

- Tracking and measuring consistently over time
- Timed/scheduled monitoring throughout the day or throughout the season, e.g.:
    - Tracking of low clouds day and night
    - Tracking of seasonal changes, spring bloom in open ocean and on land
- Specific area monitoring with regional changes
    - Predict/Track fish habitats across migration locations
    - Predict/track species health
- Dynamic tracking, many examples among which:
    - Coordinated observations of environment and in-cloud structure and dynamics, data fusion (and possibly data assimilation) to characterize 3D cloud structure and dynamics.
    - Feature detection of convection in NOAA observations and tracking of convection centers (convective cores)
    - Identify when snow is falling and location, followed by classification of snow type with corresponding amounts
    - Track spread of crop or forest disease spread in real-time
    - Track size and spread of a bloom with high accuracy, model analysis that triggers sensors to gather new data
    - Winds, pollinator and pesticide tracking
    - Aerosol tracking for human air quality impacts
    - Tracking and predicting slow-moving landslide
- Balance global, regional and local detection to global, regional and local tracking, e.g.:
    - Fertilizer/precipitation/flood can all trigger a response to see how the ecosystem responds
    - Discovering and tracking ocean heat waves, i.e., small scale features that cannot be captured by satellites alone, rapid in appearance and disappearance; Need to sense them as they develop and trigger rapid reaction sensing with multiple assets

(v) Autonomy

- UAV/UUV autonomy, e.g., to follow boundaries of storm systems
- Autonomy for satellite management and improved measurements, e.g., recognize clouds vs. smoke vs. fog
- Autonomous systems with few humans in the loop
- Off-schedule, autonomous or human-induced new model runs when an "event" is discovered
- Systems that adapt from time-based to condition-based maintenance

AIST Technologies:

(i) AI/ML

- AI and ML for autonomy, constellation management and decision making
- AI and ML for event and feature detection and tracking
- AI/ML for calibration, fusion and analysis
- ML for science and forecast models

  - AI/ML and Citizen Science integrated, e.g., Citizen Science providing ground truth or verifying AI/ML systems
  - Develop better training approaches for supervised ML techniques
  - Ground truthing on the fly, e.g., local observations streamed iteratively between airborne and satellites, therefore improving next forecast of next storm event
  - Model-based ML, e.g., for tracking, e.g., use previous data to narrow scope to certain regions

(ii) Uncertainty Quantification

- Uncertainty quantification and quality control of data
- Different levels of uncertainty, e.g.:
  - Original observations, e.g., location and/or radiometry uncertainty
  - Fused/integrated data uncertainty
  - Models uncertainty

(iii) Data Calibration and Data Fusion

- Multi-source data calibration, fusion and integration
- Autonomous cross-calibration of sensors and systems of sensors
- Data fusion (and/or data assimilation) for data from various platforms with different resolution
- Data fusion needed across multiple instruments and vantage points to produce an integrated 3D representation of the science phenomenon and its evolution over time, e.g.:
  - Reconstruction of 3D PBL structure and cloud time and space evolution
  - Combine measurements to observe and predict sea ice changes and feed model data back to sensing systems
  - Collect and integrate a wide variety of existing ground sensors and model forecasts, e.g., in hydrology, stream gauges, reservoir heights, rain gauges, atmospheric river forecasts, etc.; use quantifiable, accurate data rather than estimated (much of snowpack is estimated)
- Model-data fusion

(iv) Data Assimilation and Modeling

- Applications and advanced data mining techniques that enable crowd sourcing data to be deciphered and shared with models
- Data assimilation with high temporal and spatial resolution data into models
- Real-time integration of data and modeling
- Improved systems for assimilating data and for on-board processing to enable rapid data analysis and response (e.g., using ML)
- Adaptable models:
  - Integrate seasonal/climate changes to predictive models, e.g., wildfires that need to be tracked (while it was not needed in the past)
  - Identify types of data needed to update models => plug and play tools, models, and data analysis capabilities
  - Data-driven models as well as science model-driven observations
- Local, regional, national, global models all communicating; tying models together to bring in-situ and remote sensing observations

- Higher resolution and larger models with greater amounts of variables. e.g., integration of cloud, aerosol, weather, and atmosphere
- Models that can scale and with greater detail
- Data evaluation for models, i.e.:
    - How much data, what kind, and which granularity
    - Ability to identify imbalance in models and anomalies to trigger measurements
- Prediction modeling fed by ground truthing

(v) Data Analysis and Understanding

- Specific area monitoring and detection of regional changes:
    - Mapping data which triggers measurements on selected areas based on events
    - Monitoring events across range of time with susceptibility triggers
- Observation and data attribution and provenance
- Discovery of correlations, e.g., temperature and carbon to identify a potential bloom or one that is starting
- Hyperspectral data processing and analysis:
    - Detect signature changes
    - Create classification maps, e.g., for plants, animals, species, etc.
- SAR data processing and analysis, e.g., for detection of species and their habitats
- Anomalous event analysis/triggering
- Atmospheric correction, especially for onboard CubeSats and SmallSats
- Integrating multiple dimensions, e.g.:
    - Vertical structure of algal blooms
    - Measuring 3D structures and gas exchange across surface
- Understanding impacts, e.g., disruptions to timelines, economies and science (if we had a NOS system today we would have a different product for COVID info/dashboard)
- GPU, quantum and other high-end computing technology to keep up with fast paced software changes

(vi) Edge and Onboard Technologies

- Onboard anomaly detection, data processing and analysis, and decision making
- Dynamic control of CubeSats/SmallSats constellations
    - On-board autonomy to adapt sensor operations and resource management
    - On-board processing to enable rapid and dynamic data analysis and response
- Edge sensing/edge computing
    - For rapid instrument data processing
    - Local decision capabilities
    - Recognize clouds and other coverage issues onboard for optimizing observations
- Utilize new chips optimized for neural network processing

B. Output of the Technology Breakouts

In this section, we summarize all the technologies that were identified during the Technology Breakouts. Just like in section (A), the technology tables below mostly represent cross-cutting technologies that will benefit all science use cases identified in Section 3. They have been briefly listed in one or several use cases, and the tables below provide a few additional details and relevance background. These will be refined in the next few months.

Here are the technologies that were identified during the February Workshop:

Onboard Data Understanding and Analysis Needs:

- Capability #1: Future Proofing on Orbit
- Capability #2: Flexible System Support on the Ground
- Capability #3: On Orbit and Ground System Autonomous Decision Making
- Capability #4: Efficient and Near-Continuous Communications
- Capability #5: Onboard Processing for Knowledge Identification

Inter-Node Coordination

- Capability #1: Single Asset to Multi-Asset
- Capability #2: Model to Asset Coordination

Planet, Scheduling and Decision Making:

- Capability #1: Onboard Capabilities Including Edge and Autonomous Computing
- Capability #2: Spacecraft, Clusters, Constellation Network Decision Making
- Capability #3: Science Model-Driven Observations
- Capability #4: Novelty Detection and Investigation

Interaction to Science and Forecast Models Needs

- Capability #1: Forecast Models Interactions with Constellations

Cybersecurity:

- Capability #1: General Security Requirements
- Capability #2: Federated System Secure Access

Additional Technology Concept:

- Capability: Mission Formulation

4.1. Onboard Data Understanding and Analysis Needs

ONBOARD DATA UNDERSTANDING & ANALYSIS	
CAPABILITY #1	**Future proofing on orbit (evolution and scalability)**
Targeted Observables	ACCP, SBG, SDC
Science Domain	Atmospheric, Carbon and Ecosystems; Earth Surface and Interior, Oceans and Snow/Ice/Energy
Science Use Case Applicability	Pollution transport; convection; snowfall; water resources; snow albedo; ocean currents; methane; subsidence; land cover change; soil moisture
Capability Description	Recognizing payloads are physically fixed at launch, use of instrument output evolves as we move up the learning curve, we must make payloads (instruments + support+ onboard processing) as flexible as possible to accommodate future re-configurations or updates. Must accommodate ongoing cal/val adjustments. This also permits extension of mission life rather than launching a new platform. Flexibility for evolution of on-orbit systems that can improve their own capabilities over time and working with ground support systems.
Specific Technology	Software defined payloads and cognitive computing
Examples of Existing Specific Technologies	ASTERIA; EO-1;
CAPABILITY #2	**Flexible System Support on the Ground (evolution and scalability)**
Targeted Observables	ACCP; SBG; SDC; MC
Science Domain	Atmosphere; Hydrology; Snow; ESI; Carbon
Science Use Case	Snow/Ice/Energy use cases including sea ice melt and calving; Oceans use cases including hurricane forecasting, volcanoes, pollution, spills, and contamination
Capability Description	Most platforms continue to use the same ground support over the life of the flight. Frequently these become obsolete or degraded and need modernization. Successive generations of ground support enhancements as technology emerges to make them more effective or re-purposed. Enable changes to ground support with improving validation and risk reduction, i.e., evolving Science Data Processing (SDP)
Specific Technology	Development and operations
Examples of Existing Specific Technologies	Planet; AWS GSaaS (Ground Systems as a Service)
CAPABILITY #3	**On Orbit and Ground System Autonomous Decision Making**
Targeted Observables	ACCP, SBG, SDC
Science Domain	Atmosphere, Hydrology, Snow, ESI, Carbon
Science Use Case	Atmospheric, Carbon and Ecosystems; Earth Surface and Interior, Oceans and Snow/Ice/Energy including fishing, pollution, cloud structure & convection, convection & environment, falling snow, methane.
Capability Description	On orbit and ground systems that make decisions autonomously or semi-autonomously using a growing base of knowledge. As understanding of instrument performance and behavior evolves over time, the on-orbit and ground systems can either make or recommend improvements to observing systems.
Specific Technology	Cognitive computing
Examples of Existing Specific Technologies	EO1, Mars Rovers, IPEX, Rosetta. One overview from ESA: https://indico.esa.int/event/225/contributions/4289/attachments/3361/5388/OBDP2019-paper-DLR_Mess_Techniques_of_Artificial_Intelligence_in_Space_Applications-A_Survey.pdf

ONBOARD DATA UNDERSTANDING & ANALYSIS	
CAPABILITY #4	**Efficient and Near-continuous Communications**
Targeted Observables	ACCP SBG, SDC, MC
Science Domain	Atmosphere, Hydrology, Snow, ESI, Carbon
Science Use Case	Pollution, cloud & convection, convection environment, soil moisture, flooding, fishing, ocean circulation
Capability Description	Efficient, near-continuous communications between orbital and ground assets. Current ground station capacity is oversubscribed, and large data volumes cannot be fully transferred in a single contact thus improved orbital and ground communications are required.
Specific Technology	Software defined networks, cooperation among different types of satellites (i.e., some satellites in a constellation transmit to ground and others transmit to one another)
Examples of Existing Specific Technologies	Swedish Space, K-space, Kepler communications, AWS; ASTERIA demonstration of using 2 ground stations for a given data dump, 5G cellular service
CAPABILITY #5	**Onboard Processing for Knowledge Identification**
Targeted Observables	ACCP, SBG, SDC, MC
Science Domain	Atmosphere, Hydrology, Snow, ESI, Carbon (methane)
Science Use Case	Cloud structure & convection; convection & environs; methane; flooding; volcanoes; ocean pollution
Capability Description	The integrated system (onboard and ground science data processing and mission management/control) identifies patterns and anomalies to identify new insight and knowledge. Unsupervised learning, genetic programming, ML, computer-aided discovery, determining priority of downlinked data.
Specific Technology	Autonomous science data processing, onboard cognitive computing
Examples of Existing Specific Technologies	Mars rovers, especially AEGIS; EO1; Rosetta, Self-driving automobiles

4.2. Inter-Node Coordination Needs

INTER-NODE COORDINATION (including comms, standards, ontologies, commands)	
CAPABILITY #1	**Single Asset to Multi-Asset**
Targeted Observables	ACCP; SBG; MC
Science Domain	Water resources and soil moisture and others
Science Use Case Applicability	Water resource management and soil moisture measurements greatly enhanced by usage of multi-asset constellations and clusters to pull in snow, precipitation, drought, wind, stream, and reservoir data among other assets such as models.
Capability Description	A single observing asset coordinates with several others to achieve a science objective, e.g., a spacecraft observes a volcanic eruption, coordinates with a network of UAVs and ground sensors to track the plume. This capability requires coordination and communication technologies: Centralized or peer to peer systems; sensors and systems that communicate with one another; tipping and queuing; federation of networks and nodes; non-owned asset interactions including requesting data, interface access, linking to non-NASA protocols; delay tolerant protocols and node failure adaptations; addressing time and command software packet self-destruct capabilities in autonomous systems; collision avoidance detection and management; navigation and errors in location estimations; scaling capabilities
Specific Technology	Edge computing; distributed triggering; cause and action capabilities; messaging contact (observation description, ontologies, etc.); asynchronous vs synchronous; behavioral interfaces, protocols, structured interfaces, supporting infrastructure (buffers, brokers, computational pieces facilitate movement); sending data objectives descriptive observations; interfaces to multiple sensors; sending data to appropriate recipient; DTN, delayed disruption tolerant networking; onboard modeling for timely decision making; calibration and inter-calibration of nodes; detect and correct capabilities; protocol exchange negotiations / standards; standardizing requests including energy use, bandwidths, etc.; cognitive radio including dynamic frequency change and hopping; manage resource constrained networks to prevent overburdening CPUs;
Examples of Existing Specific Technologies	Leverage existing standards; Starling DDS layer; MIT thesis, 12 motifs for distributed satellites, MIT Publication- Olivier de Weck- Distributed Satellites
CAPABILITY #2	**Model to Asset Coordination**
Targeted Observables	ACCP; SBG; MC
Science Domain	Weather events for example
Science Use Case	Model does a self-assessment and realizes its weather data over the plain states is old and rapidly becoming insignificant while the uncertainty level increases. The model determines it needs updated wind, temperature, and precipitation data and makes a query for all three. An interface assesses the data request, types of instruments, location desired, timelines, resolutions, bands, etc., while assessing the nodes that could fulfill the data request. Once the data request and available assets are reconciled, a request is made to the nodes. Once the data is gathered, downlinked, and processed it is sent to the respective model;
Capability Description	A model informs an observing strategy for one or more observing assets. Elements include: models; ground system, and sensor standards and protocols for communications; sensor planning capabilities; web processing services with bootstrapping (tell me what algorithms to use); security protocols for sharing data, commanding, etc.; data or sensor subscriptions;
Specific Technology	Edge computing, uncertainty estimations for inputs going into and out of models; calibration confirmations; cloud computing; sampling a point; data fusion techniques; create new data, transform data; prioritization for tasking and requests; autonomy and explainable AI through systems; ground vs space messaging standards; communications standards including call numbers, ontology models, asset identifiers; sensor planning services; asset resource management for decision making

4.3. Planning, Scheduling and Decision Making Needs

PLANNING, SCHEDULING & DECISION MAKING	
CAPABILITY #1	**Onboard Capabilities Including Edge and Autonomous Computing**
Targeted Observables	SDC for example
Science Domain	Volcanic eruption; cloud detection as examples
Science Use Case Applicability	Volcanoes
Capability Description	Onboard decision making and data processing implemented at the 'edge' nodes of an observing system, such as onboard an in-situ sensor, UAV, or satellite. This enables the edge node to respond autonomously, which reduces latency and communication bandwidth as compared to centralized control. Elements of autonomous edge computing include: edge sensors with local decision capabilities; onboard anomaly detection; imagery capabilities; cloud detection and autonomous cloud avoidance capability; system leader and follower coordinate to take joint observations; when, where, and how to find data. Observe an eruption then process hyperspectral data onboard and downlink compressed or thumbnail of imagery. Specification and execution of a science observation policy to adapt to sudden events
Specific Technology	Federated planning including observation requests from other assets, requires some probabilistic reasoning and ability to adapt the observing plan as requests are satisfied or rejected; Onboard satellite and airborne processing; SensorWebs; adaptation to observing systems failing or being unavailable. Pre-specified, nominal policies; reactive policies (when an event occurs need ability to activate a contingency policies or ability for science team to quickly update a policy. Human over-the-loop strategies.
Examples of Existing Specific Technologies	Onboard automated planning, scheduling and execution; ground-based planning and scheduling for mission planning; event recognition.
CAPABILITY #2	**Spacecraft, Clusters, Constellation Network Decision Making**
Targeted Observables	Clouds, Convection, and Precipitation; Mass Change; Surface Biology and Geology; Snow Depth and Snow Water Equivalent
Science Domain	Flood, precipitation, snow melt as examples
Science Use Case	Water Resources and Agriculture and Soil Moisture
Capability Description	Develop and execute a coordinated observation strategy for an observing system, such as a constellation of satellites. Decisions about when and where to make observations can be centralized or made in a hierarchical and federated fashion distributed across the system. The observing system may include both smart/taskable assets as well as passive read-only assets. The observing strategy may recruit multiple assets to observe phenomena that have larger spatial or temporal scope. The strategy can coordinate assets to better observe a phenomena, for example several CubeSats could be coordinated to act like a single large aperture, or a cluster of spatially distributed ground sensors recruited to get a regional measurement.
Specific Technology	Edge sensor; instrument decision making; spacecraft, clusters, constellation network decision making; enable recruitment of additional observing assets that are not part of the core mission (commercial, other missions and partners); distributed, coordinated planning; centralized planning; distributed planning and decision making; planning in the presence of assets that could fail / drop out. UAV / UUV autonomy to follow boundaries. collaborative planning in distributed networks; dedicated compute nodes in orbit to provide additional storage, compute power, comms that can be shared among multiple missions.

PLANNING, SCHEDULING, & DECISION MAKING	
CAPABILITY #3	**Science Model-Driven Observations**
Targeted Observables	ACCP; MC; SBG; Snow Depth and Snow Water Equivalent
Science Domain	Soil moisture (example)
Science Use Case	Water Resources and Agriculture; Soil Moisture
Capability Description	Select observations that reduce uncertainty, improve model forecasts (by providing most important parameters for initial state vector) assimilate observations into model and use updated model to inform new observation selections
Specific Technology	Models that communicate with utilities; detection across a sensor network; data fusion across different instruments, resolutions, calibrations, etc.
CAPABILITY #4	**Novelty Detection and Investigation**
Capability Description	Detect novel, high-interest science events and plan observations to investigate them further. If the result of an observation changes the utility of other observations, the observation plan can take that feedback into account. For example, if we have already seen several novel events of type X, but none yet of type Y, then the priority of Y could go up.
Specific Technology	Adaptive, utility-driven observation planning; development and execution of contingent plans; UAV / UUV autonomy to follow boundaries, plumes in the atmosphere, algal blooms, migration patterns and independent exploration.

4.4. Interaction to Science and Forecast Models Needs

INTERACTION TO SCIENCE & FORECAST MODELS	
CAPABILITY #1	**Forecast Model Interactions with Constellations**
Targeted Observables	All
Science Domain	All
Science Use Case Applicability	A need to update forecast models on actionable time scales and onboard modeling when communications are not sufficiently timely for centralized decision making. What parameters are most sensitive and how would sampling improve them? What is driving uncertainty in models: adjoint modeling, ensemble modeling,
Capability Description	A forecast model estimates when an event is about to occur, and coordinates with a constellation to obtain new relevant observations. Those observations could be designed to increase forecast skill, validate the model, and/or better characterize the event. Considerations for this capability include: estimating uncertainty of inputs to forecast / science models, what is driving uncertainty; what level of uncertainty is in the grid and what does it need to drive down that error; large ensembles; onboard and model decision making; calibration/inter-calibration of calibration-challenged sensor nodes (small satellites, remote sensors); capability to detect and correct for RFI; models with very high resolution will need capabilities to match observation resolution to model resolution; reconcile sensitivities from models and the uncertainty in the observation; stable and consistent baseline for observations
Specific Technology	ML approaches; data fusion from multiple measurements, different sources/modalities; uncertainty quantification; adjoint and ensemble modeling; satellite calibration; low power edge computing; adaptive mesh capabilities; cloud computing; onboard computing; adaptive sampling to avoid sampling RFI; techniques to match observation resolution to model resolution; translation of spaceborne measurements into geophysical variables' instrument and variability error capture; precise and standardized metadata

4.5. Cybersecurity Needs

CYBERSECURITY	
CAPABILITY #1	**General Security Requirements**
Targeted Observables	All
Science Domain	All
Science Use Case Applicability	Security is cross-cutting, needs to address all science domains, and appropriate systems aspects. Security is under-appreciated and with NOS type highly asymmetric and complex system-of-systems, it is highly required and valuable. The science community does not generally consider security and frequently considers it a constraint. Some nodes will be "worker nodes" (mainly Virtual Machines) that are more ephemeral in nature and will come and go within days or even hours, these may be exempted for some or all security requirements. What will be logged and how will logs be archived.
Capability Description	General security capabilities needed to ensure the integrity of an observing system that has several nodes and may involve multiple projects or organizations. Engage science and technology communities early in security needs and vulnerabilities (potential issues with third party software); multiple domains need to participate in security standards, gov, public, DoD, academia; use commercial off-the-shelf components where possible; leverage standards, Application Programming Interfaces (APIs), best practices (not in a prescriptive way); collaboration with systems designers, scientists to determine roles, authorizations, priorities to implement security in the system design.
Specific Technology	Standard Internet Protocol (IP) devices approach; support NASA and non-NASA access to nodes; access security roles for government, non-government, foreign nationals, foreigners, etc.; security level adaptation depending on system / access/ product (e.g. security for uplinking, commanding, onboard - all strict, data product - access loose); commercial cloud computing with security roles; collaborations with DoD such as Blackjack project; security updates to nodes capabilities; security exemptions; autonomy / autonomous vulnerabilities identification, notification, tracking; asymmetrical types of authorizations; secure logs and log archives and automated analysis and inspection of logs.
CAPABILITY #2	**Federated System Secure Access**
Targeted Observables	All
Science Domain	All
Science Use Case	Support multi-factor access for certain user types with elevated privileges in a federated system supporting enhanced device authentication. Requires inter-node and ground station communications as well as potential to securely interface with a non-government node and then successful end the communication while maintaining security. What organizations and individuals have secure access to which nodes, software / model capabilities, etc.
Capability Description	Access control technologies and policies for a federated observing system, in which nodes can span organizational boundaries. Among key considerations: security adapts to systems / node failures; adapts to linking and un-linking from non-government nodes; system threat level ranking (e.g. a satellite ranks high if it is hacked, a river sensor measuring water depth, ranks low, assuming it is not connected to internal NASA / Government systems); understanding the features of systems, especially commercial and non-government to enable security for all features (a weather station sensor may also have a camera, if camera is not used by system is it disabled, is system manager aware of it, what are rules if it is exploited)
Specific Technology	Security standards used by Government and non-Government systems developers; system failure security adaptation; secure linking and un-linking from nodes; detecting and evaluating threats with system threat levels; human overrides of security settings access roles; commercial and non-government node feature awareness and unused feature policies; ML and AI security functions

	Additional Technology Concept
CAPABILITY	**Mission Formulation**
Capability Description	Drive detailed observation decision making for a simulated, in-formulation system to understand relation between observing system design and science return. Approaches include more capable planning, execution, decision making that can operate in any environment; improved communications and protocols.
Specific Technology	DTN (delay tolerant networking) could help with communications among SensorWeb; AIST-funded Tradespace Analysis Tool for Constellations (TAT-C); AIST-funded Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions (D-SHIELD)

5. Definitions

- **Internet-of-Space (IoS):** Based on the definition of the Internet-of-Things (IoT) listed below, for the purpose of this report, we define the ***Internet-of-Space (IoS)*** as an IoT in which all the connected objects can be on Earth or in space in a seamless fashion.

- **Internet-of-Things (IoT):** The internet of all the "things", i.e., physical objects that are equipped with sensors and software and other technologies that can connect and exchange data. The definition given in [Dor15] is the following: “Group of infrastructures interconnecting connected objects and allowing their management, data mining and the access to the data they generate.” with *connected object(s)* being “Sensor(s) and/or actuator(s) carrying out a specific function and that are able to communicate with other equipment. It is part of an infrastructure allowing the transport, storage, processing and access to the generated data by users or other systems."

- **SensorWeb**: 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 (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) ([Man10], [Tal05]).

6. References

[Akb20] R. Akbar et al. “Wireless Sensor Network Informed UAV Path Planning for Soil Moisture Mapping”, IEEE TGRS.

[Bal19] C. Ball, G. Smith, A. O’Brien, J. Johnson, J. DeLong, M. Shattal, R. Linnabary, S. Musko, “Enabling Multi-Platform Mission Planning and Operations Simulation Environments for Adaptive Remote Sensors”, IEEE National Aerospace and Electronics Confernece (NAECON 2019)

[Bel19] J. Bell, “USGS Next Generation Water Observing System”, ESIP Federation Meeting, July 2019.

[Bou19] S. A. Boukabara, " Thoughts on the Future of NOAA's Satellite Remote Sensing for Weather Forecasting and Environment Monitoring," Proceedings of SPIE 11127, Earth Observing Systems XXIV, 112702, Sept. 12, 2019. https://doi.org/10.1117/12.2534370.

[Car20] J. Carr, C. Wilson, D. Wu, M. French, M. Kelly, “An Innovative Spacecube Application for Atmospheric Science”, IEEE IGARSS Conference October 2020.

[Cel20] D. Cellucci, N. Cramer, J. Frank, “Distributed Spacecraft Autonomy”, AIAA American Institute of Aeronautics and Astronautics, November 2020.

[Chi20a] S. Chien, J. Boerkoel, J. Mason, D. Wang, A. Davies, J Mueting, V Vittaldev, V Shah, I Zuleta, “Space Ground Sensowebs for Volcano Monitoring”, AGU, December 2020.

[Chi20b] S. Chien, A. Davies, J. Doubleday, D. Tran, D. Mclaren, W. Chi, A. Maillard, “Automated Volcano Monitoring Using Multiple Space and Ground Sensors”, Journal of Aerospace Information Systems, April 2020.

[DiP20] P. Di Pasquale, K. Hughes, A. Babuscia, L. Fesq, “Flexible Operations on ASTERIA with Cloud-based Ground Station Services”, Aerospace Ground Systems Architectures Workshop, March 2020.

[Dor15] B. Dorsemaine, J-P. Gaulier, J-P. Wary and N. Kheir, "Internet of Things: A Definition and Taxonomy," 2015 9th International Conference on Next Generation Mobile Applications, Services and Technologies.

[Fab14] N. Faber, Y. Nakamura, R. Alena, D. Mauro, C. Frost, G. Bhat, J. McNair, "Heterogeneous Spacecraft Networks: General concept and case study of a cost-effective, multi-institutional Earth observation platform," 2014 IEEE Aerospace Conference, Big Sky, MT, 2014, pp. 1-16, doi: 10.1109/AERO.2014.6836297.

[Fam17] J. Famiglietti, C. David, J. Reager, C. Oaida, D. Stampoulis, S. Levoe, P. Liu, A. Transgsrud, R. Basilio, G. Allen, D. Crichton, C. Emery, T. Farr, S. Granger, J. Hobbs, S. Malhotra, G. Osterman, M. Rueckert, M Turmon, “The Western States Water Mission: A Hyper-Resolution Hydrolocial Model and Data Integration Platfrom for the Western United States”, AGU Conference, December 2017

[For16] V. Foreman, J. Le Moigne and O. de Weck, 2016, “A Survey of Cost Estimating Methodologies for Distributed Spacecraft Missions,” *American Institute of Aeronautics and Astronautics (AIAA) SPACE 2016*, Long Beach, CA, September 13-16, 2016.

[Fre19b] Andrew G. Schmidt, Vivek Venugopalan, Marco Paolieri, Matthew French, “Constellations in the Cloud: Virtualizing Remote Sensing Systems,” 2019 IEEE International Geoscience and Remote Sensing Symposium, July, 2019.

[Fro11] C. Frost, Chapter 11 “Challenges and Opportunities for Autonomous Systems in Space” from National Academies book, “Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2010 Symposium(2011)”

[Gei19] A. Geist, C. Brewer, M. Davis, N. Franconi, S. Heyward, T. Wise G. Crum, D. Petrick, R. Ripley, C. Wilson, and T. Flatley, “SpaceCube v3.0 NASA Next-Generation High-Performance Processor for Science Applications,” 33rd Annual AIAA/USU Conf. on Small Satellites, SSC19-XII-02, Logan, UT, August 3-8, 2019.

[Gro16] Le Moigne J., P. Dabney, O. de Weck, V. Foreman, P. Grogan, M. Holland, S. Hughes, and S. Nag (2016). “Trade-space Analysis Tool for Constellations (TAT-C),” 2017 American Geophysical Union Fall Meeting, Dec. 12-16, San Francisco, CA.

[Gro17] P.T. Grogan, P. Dabney, O. de Weck, V. Foreman, M. Holland, S. Hache, S. Hughes, J. Le Moigne, S. Nag, A. Siddiqi (2017). “Knowledge Base for Distributed Spacecraft Mission Design using the Trade-space Analysis Tool for Constellations (TAT-C),” 2017 Earth Science Technology Forum, June 13-15, Pasadena, CA.

[Kim20] R.S. Kim, S. Kumar, C. Vuyovich, P. Houser, J. Lundquist, et al. Snow Ensemble Uncertainty Project (SEUP): Quantification of snow water equivalent uncertainty across North America via ensemble land surface modeling, submitted to JAMES, August 2020.

[Gut20a] E. Gutmann et al., 2020, Heterogeneity of Mountain Snow: Measurement, Modeling, and Implications. 19th annual Mountain Meteorology Conference Thursday, July 16, 2020.

[Gut20b] E. Gutmann et al., 2020 Multi-scale Snow-Atmosphere Interactions Over Mountain Snowpack for Climate Applications (Invited) AGU Fall meeting December 2020.

[Kum14a] S. Kumar et al., (2014), “Assessing the Impact of L-Band Observations on Drought and Flood Risk Estimation: A Decision-Theoretic Approach in an OSSE Environment”, Journal of Hydrometeorology, Special collection on SMAP applications, 15, 2140-2156.

[Kum14b] S. Kumar et al., (2014): “Science and applications-driven OSSE platform for terrestrial hydrology using the NASA Land Information System”, AGU fall meeting, San Francisco, CA.

[Kum19] S. Kumar, M Jasinski, DM Mocko, M Rodell, J Borak, B Li, HK Beaudoi, “NCA-LDAS land analysis: Development and performance of a multisensor, multivariate land data assimilation system for the National Climate Assessment” Journal of Hydrometeorology 20 (8), 1571-1593.

[Lem17] J. Le Moigne, P. Dabney, O. de Weck, V. Foreman, P. Grogan, M. Holland, S. Hughes, and S. Nag, 2017, “Tradespace Analysis Tool for Designing Constellations (TAT-C),” *2017 IEEE International Geoscience and Remote Sensing Symposium, IGARSS'17,* Fort Worth, TX, July 23-28, 2017.

[Lem18] J. Le Moigne, 2018, “Distributed Spacecraft Missions (DSM) Technology Development at NASA Goddard Space Flight Center,” *2018 IEEE International Geoscience and Remote Sensing Symposium, IGARSS'18,* Valencia, Spain, July 22-27, 2018.

[Lem19] J. Le Moigne, M. Little and M. Cole, “New Observing Strategy (NOS) for Future Earth Science Missions,” *2019 IEEE International Geoscience and Remote Sensing Symposium, IGARSS'19,* Yokohama, Japan, July 28-August 2, 2019.

[Man10] D. Mandl et al, “SensorWeb 3G: Extending On-Orbit Sensor Capabilities to Enable Near Realtime User Configurability,” 2010*Earth Science Technology Forum (ESTF)*, Arlington, VA, June 2010.

[Nag16] S. Nag, S. Hughes and J. Le Moigne, 2016, “Streamlining the Design Tradespace for Earth Imaging Constellations,” *American Institute of Aeronautics and Astronautics (AIAA) SPACE 2016*, Long Beach, CA, September 13-16, 2016.

[Pos20a] D.J. Posselt, B. D. Wilson, R. L. Storer, E. L. Nelson, N. Niamsuwan, and S. Tanelli, *Observation-Based Cloud and Precipitation Properties from Spaceborne Measurements Using a Parallel Bayesian Retrieval Framework*. Talk presented in the 26th Conference on Probability and Statistics at the 2020 American Meteorological Society Annual Meeting, Boston, MA, 12-16 January 2020.

[Pos20b] D.J. Posselt, B. D. Wilson, R. L. Storer, M. D. Lebsock, G. Duffy, B. Chen, N. Niamsuwan, and S. Tanelli, *Exploring Uncertainty in Bayesian Retrievals of Cloud and Precipitation Properties*, Poster presented at the 2020 Fall American Geophysical Union Meeting, Virtual, 1-17 December 2020.

[Pra20] S. Prager, M. Haynes, and M. Moghaddam, “Wireless Sub-Nanosecond RF Synchronization for Ultra-Wideband Coherent MIMO Software Defined Radar,” IEEE Trans. Microwave Theory and Techniques, vol. 68, no. 11, pp.4787-4804, Nov. 2020, DOI 10.1109/TMTT.2020.3014876.

[Rav20] V. Ravindra, S. Nag, A.S. Li, "Ensemble Guided Tropical Cyclone Track Forecasting for Optimal Satellite Remote Sensing", IEEE Transactions on Geoscience and Remote Sensing (TGRS), July 2020, DOI: 10.1109/TGRS.2020.3010821.

[San09] J.A. Santanello, Jr., C.D. Peters-Lidard, S.V. Kumar, C.A. Alonge, and W.-K. Tao, 2009: A modeling and observational framework for diagnosing local land-atmosphere coupling on diurnal time scales Journal of Hydrometeorology, 10, 577-599, DOI:10.1175/2009JHM1066.1.

[Sea08] M. Seablom, S. Talabac, J. Ardizzone, J. Terry, “A Sensor Web Simulator for Design of New Earth Science Observing Systems”, IEEE IGARSS 2008.

[SWE20] “Open Geospatial Consortium (OGC) SensorWeb Enablement,” consulted on 12/05/2020, https://www.ogc.org/node/698.

[Tal05] S.J. Talabac, M.S. Seablom, G.J. Higgins and B.T. Womack, “A Sensor Web Observing System Simulator,” *InfoTech@Aerospace, AIAA 2005-6945*, Arlington, VA, September 26-29, 2005.