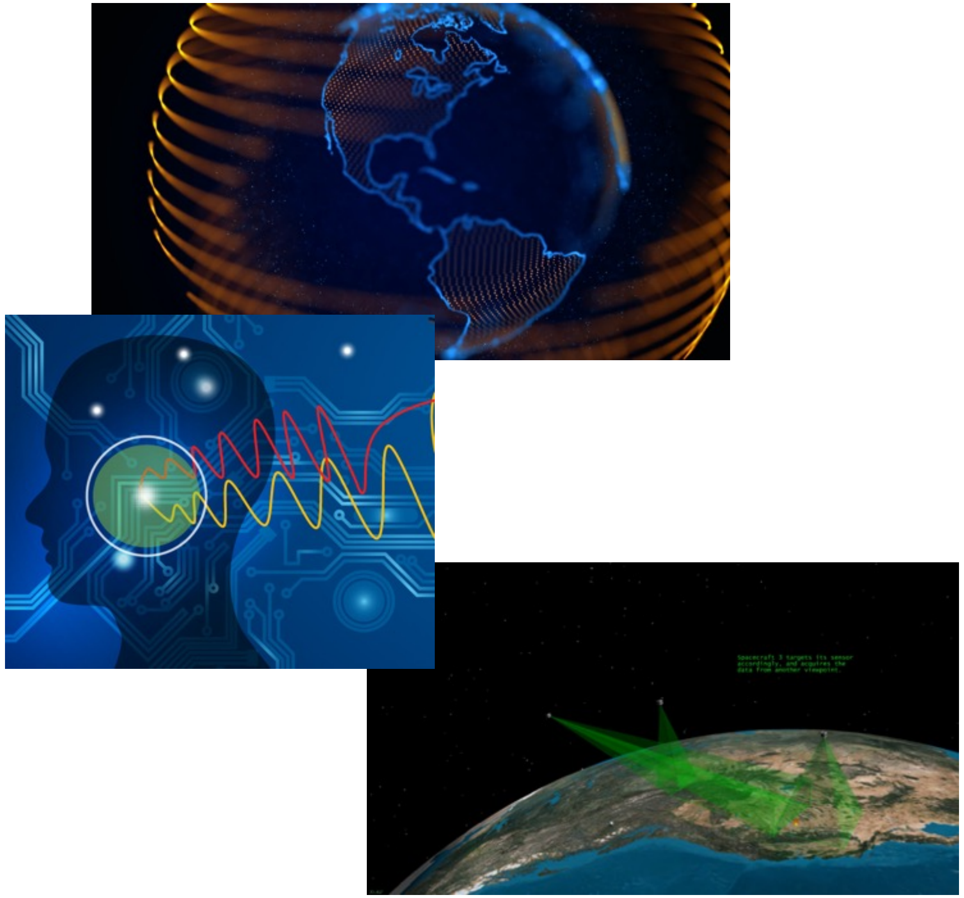


Novel Observing Strategies For NASA Future Earth Science Missions

Jacqueline Le Moigne
NASA Earth Science Technology Office

February 16, 2023

Earth Science Technology Office

ESTO leads technology development activities for the Earth Science Division. Through a science-driven competitive process it enables the next generation of instruments and information systems that advance our ability to study the Earth.

ESTO comprises five program lines:

ATIP	◉ Advanced Technology Initiatives Program
IIP	◉ Instrument Incubator Program
AIST	◉ Advanced Information Systems Technology
DSI	◉ Decadal Survey Incubation
FIRET	◉ Fire Technologies

AIST Objectives

Innovate in technologies that enable:

O1. New observation measurements and new observing systems design and operations through intelligent, timely, dynamic, and coordinated distributed sensing
=> **New Observing Strategies (NOS)**

O2. Agile science investigations that fully utilize the large amount of diverse observations using advanced analytic tools, visualizations, and computing environments, and that interact seamlessly with relevant observing systems
=> **Analytic Collaborative Frameworks (ACF)**

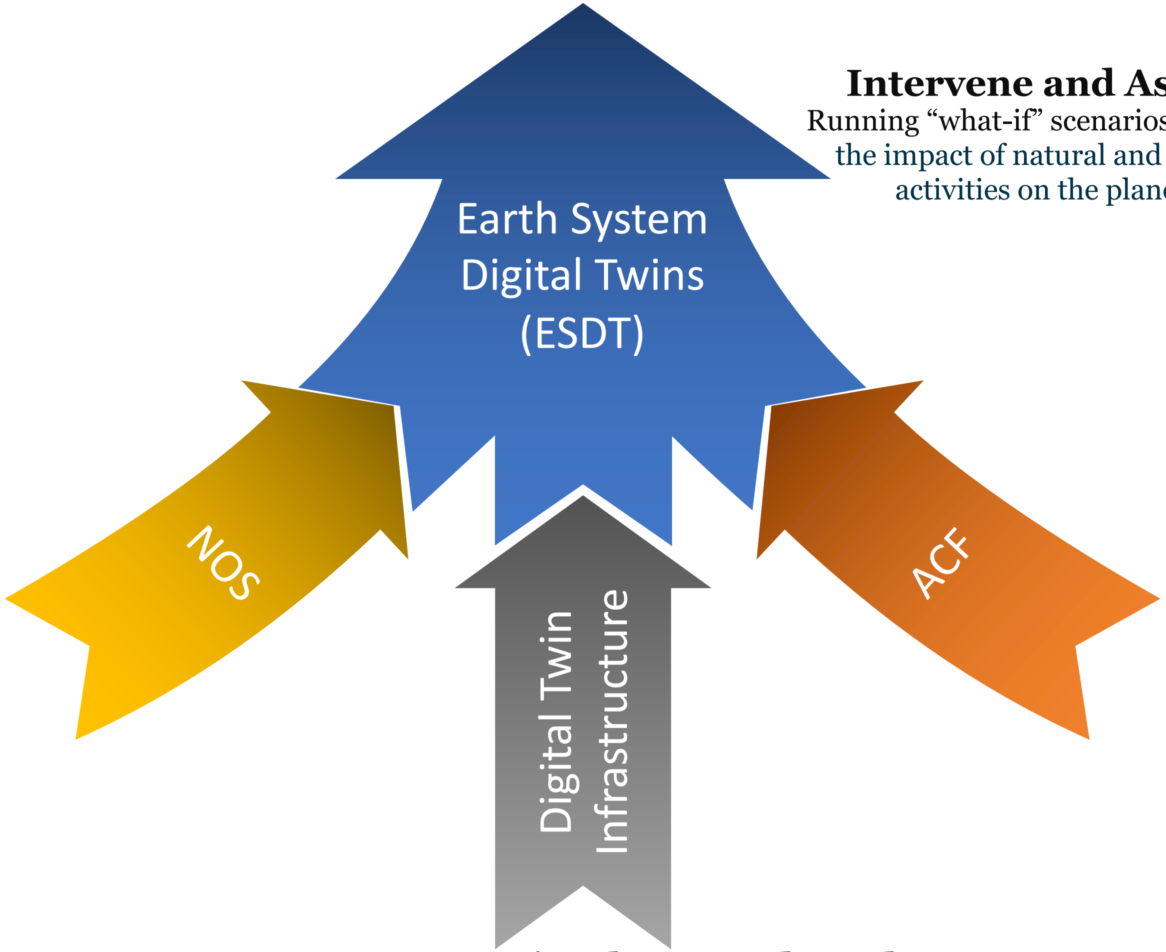
O3. Developing integrated Earth Science frameworks that mirror the Earth with state-of-the-art models (Earth system models and others), timely and relevant observations, and analytic tools. This thrust will provide technology for enabling near- and long-term science* and policy decisions
=> **Earth System Digital Twins (ESDT)**

More generally, provide "Science Data Intelligence"

* "Science decisions" including planning for the acquisition of new measurements; the development of new models or science analysis; the integration of Earth observations in novel ways; applications to inform choices, support decisions, and guide actions for societal benefit; etc.

AIST Thrusts – NOS, ACF and ESDT

Intervene and Assess
Running “what-if” scenarios to assess the impact of natural and human activities on the planet.



Observe, Target and Coordinate
Edge and on-the-ground intelligent planning, evaluating, coordinating and operating collections of diverse and distributed observing assets

Fuse, Analyze, Share and Collaborate
Simplify access to diverse and large amounts of data, analytics & modeling tools and advanced computational resources for collaborative science

Interrogate, Simulate, Trade and Visualize
Robust tools for interrogating, assessing uncertainties & causality, and for visualization, leveraging diverse data, models and products

NOS = Novel Observing Strategies

ACF = Analytic Collaborative Frameworks

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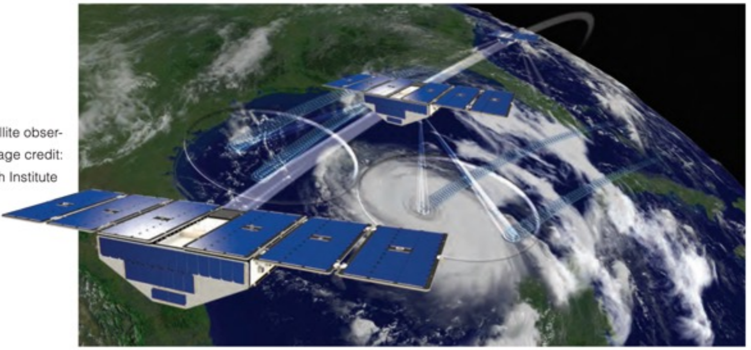
NOS for Optimizing Measurements Design & Dynamically Capturing full Science Events

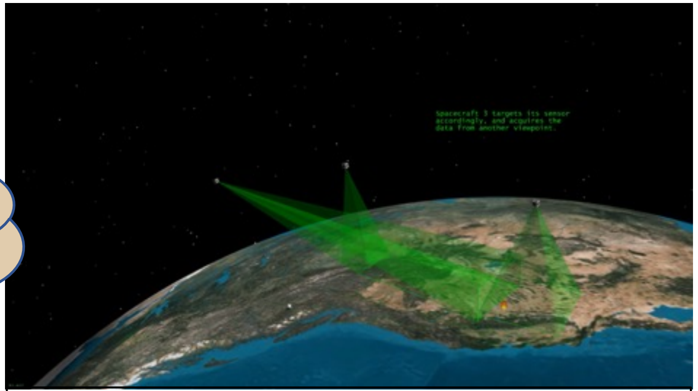
CYGNSS microsatellite observatories in orbit. Image credit: Southwest Research Institute



Distributed Spacecraft Mission (DSM): mission involving multiple spacecraft to achieve one or more common goals.

Provide complete picture of physical processes or natural phenomena

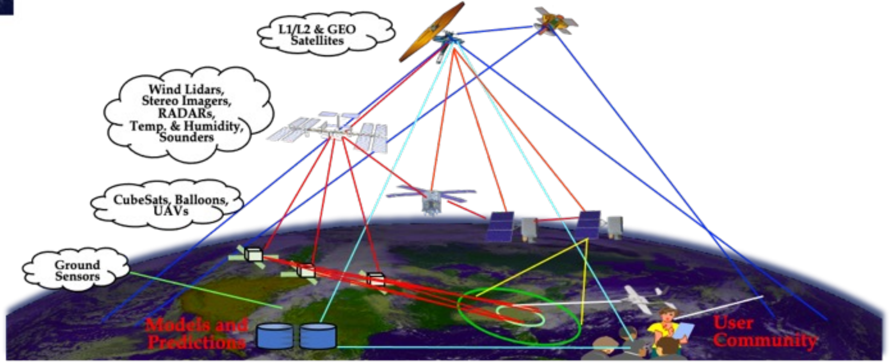
Increased understanding and predictability of dynamic events on Earth.



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

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

Multiple collaborative nodes from multiple organizations (NASA, OGAs, Industry, Academia, International) from multiple vantage points and in multiple dimensions (spatial, spectral, temporal, radiometric)



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.

Actively acquire data in coordination with other sensors, models in response to measurement needs and/or science events

OBJECTIVES:

1. **Design and develop New Observing Concepts:**
   - From Decadal Survey or Model; **Various size spacecraft;** Systems of systems **(*Internet-of-Space*); Various organizations**
   - **Perform trades** on sensor number/type, spacecraft, orbits; resolutions; onboard vs. on-the-ground computing; inter-sensor communications, etc.
   - System being **designed in advance** as a mission or observing system **or incrementally and dynamically over time**
2. **Respond to various science and applied science events of interest:** Various overall observation timeframes; Various area coverages; Dynamic/Timely; Scheduling, re-targeting/re-pointing assets, as possible

System-of-Systems NOS-Testbed for technologies & concepts validation, demonstration, comparison and socialization

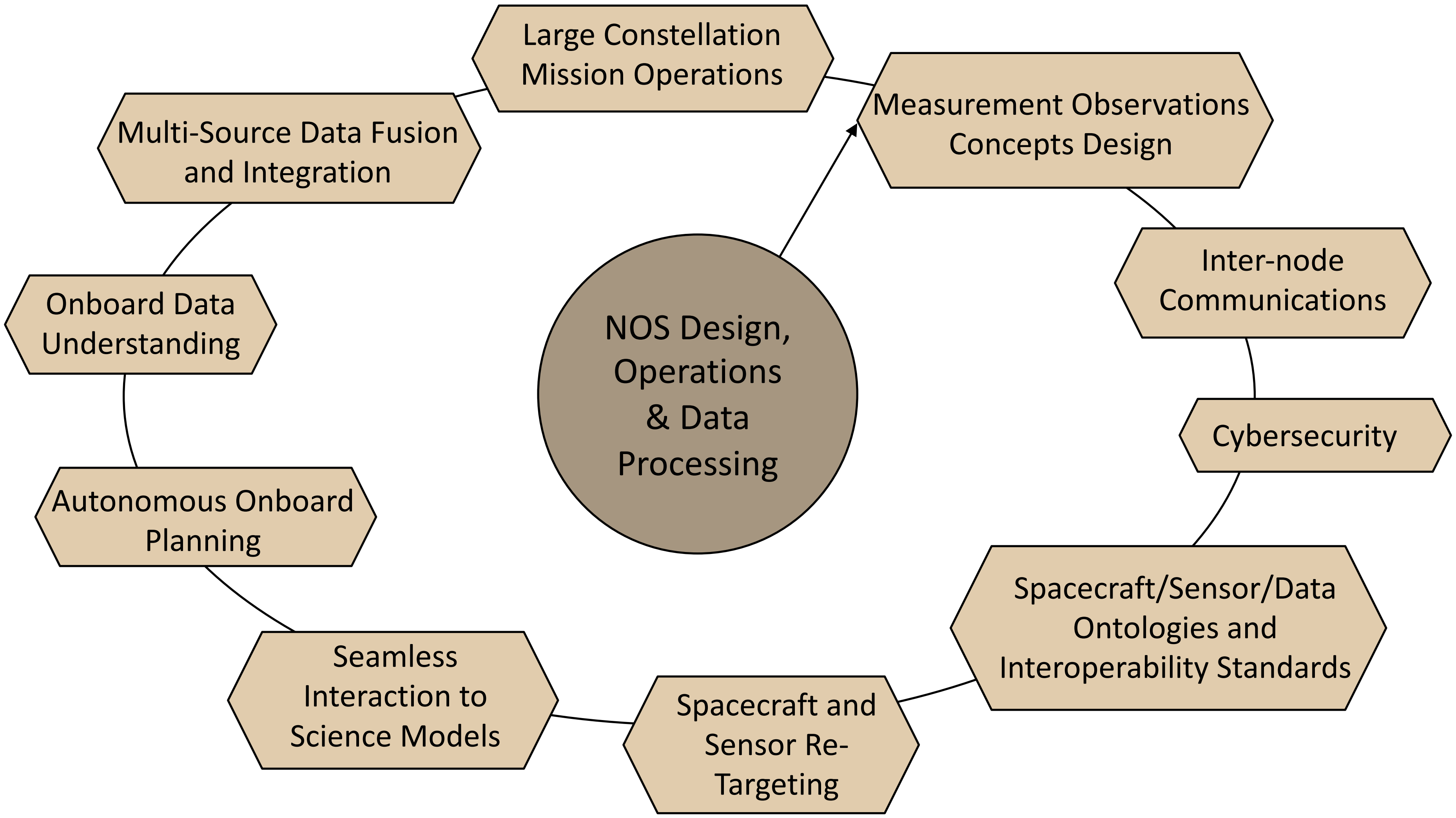
NOS Application Cases

Mission Type ***Timeframe*** ***Application***	**Tactical Observing System** ***Seconds-minutes*** ***Point event/phenomenon***	**Operational Observing System** ***Hours-days*** ***Spatial phenomenon***	**Strategic Observing System** ***Months-years*** ***Spatial-temporal phenomenon***
Example	*Detect and observe volcanic activity*	*Increase spatial observation of primary forest burning as input into long-term Air Quality and Climate models*	*Select observing strategy to optimize all measurements that will improve hydrologic estimates*
Functions	Detect emergent event Deploy observation assets	Deploy observation assets Digest information sources	Design observation system Digest information sources
Capabilities	• Responsiveness • Interaction • Dynamics • Adaptation	• Resource allocation • Coordination • Data assimilation • Prediction/ forecasting	• Platform selection • Coordination • Data assimilation • State estimation (belief)

Technologies Needed for NOS

Some Examples of Capabilities Needed Onboard:

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



2020 NOS Workshop and Report

https://esto.nasa.gov/wp-content/uploads/2021/02/AIST-NOS-Workshop-Report.pdf

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**

- General Context Talks:
  - NASA, NOAA, USGS
  - AIST and NOS Overview
  - OGC SensorWeb Standards
  - Examples of Science Use Cases
  - Introduction of NOS-Testbed
- Current AIST NOS and NOS-T Project Overviews
- Science Breakouts:
  - Atmospheric
  - Snow/Ice/Energy
  - Carbon/Ecosystems
  - Earth Surface & Interior
  - Ocean
- Technology Breakouts:
  - Onboard Data Understanding/Analysis
  - Inter-Node Coordination
  - Planning, Scheduling and Decision Making
  - Interaction to Science and Forecast Models
  - Cybersecurity

2020 NOS Workshop
Overall Findings

Needs from Science Use Cases:

- Rapid response
- Multi-assets, multi-angle observations
- Time series sensing as well as coincident measurements
- Event detection, trigger alert and targeted observations
- Autonomy to follow boundaries – plumes, blooms, migration patterns, and independent exploration
- 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
- Coordination of space assets with in-situ and airborne assets

2020 NOS Workshop
Overall Findings (2)

Science Needs => Required Technology Capabilities:

- Evolve from single to multi-asset systems with nodes including:
  - Models, ground systems, constellations, Unmanned Aerial Vehicles (UAVs), Unmanned Underwater Vehicles (UUVs), balloons, etc.
- Autonomous constellation Command & Control, e.g.:
  - Obstacle avoidance, leader/follower, formation flying
  - Adaptive pointing and targeting
- Onboard capabilities:
  - Onboard/edge computing, processing
  - Adaptive compression and downlink
  - Anomaly detection and decision making
- Uncertainty quantification/quality control of data
- Data Harmonization:
  - Standards, protocols, data formats, cross-calibration, etc.
  - Multi-source Diverse Data fusion and integration, advanced metadata development

AIST-18 NOS Awards

- **NOS-T Relevant**

PI's Name	Organization	Title	Synopsis
Mahta Moghaddam	U. of Southern California	SPCTOR: Sensing Policy Controller and OptimizeR	Multi-sensor coordinated operations and integration for soil moisture, using ground-based and UAVs "Sensing Agents".
Jim Carr	Carr Astro	StereoBit: Advanced Onboard Science Data Processing to Enable Future Earth Science	SmallSat/CubeSat high-level onboard science data processing demonstrated for multi-angle imagers, using SpaceCube processor and CMIS Instrument, and Structure from Motion (SfM).
Sreeja Nag	NASA ARC	D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions	Suite of scalable software tools - Scheduler, Science Simulator, Analyzer to schedule the payload ops of a large constellation based on DSM constraints (mech, orb), resources, and subsystems. Can run on ground or onboard.
Paul Grogan	Stevens Institute of Technology	Integrating TAT-C, STARS, and VCE for New Observing Strategy Mission Design	Inform selection and maturation of Pre-Phase A distributed space mission concept, by integrating: TAT-C: architecture enumeration and high-level evaluation (cost, coverage, quality); STARS: autonomous/adaptive sensor interaction (COLLABORATE); VCE: onboard computing and networking

- **OSSEs (Observing System Simulation Experiments)**

PI's Name	Organization	Title	Synopsis
Derek Posselt	NASA JPL	Parallel OSSE Toolkit	Fast-turnaround, scalable OSSE Toolkit to support both rapid and thorough exploration of the trade space of possible instrument configurations, with full assessment of the science fidelity, using cluster computing.
Bart Forman	U. of Maryland	Next Generation of Land Surface Remote Sensing	Create a terrestrial hydrology OSSE/mission planning tool with relevance to terrestrial snow, soil moisture, and vegetation using passive/active microwave RS, LiDAR, passive optical RS, hydrologic modeling, and data assimilation, using LIS and TAT-C.
Ethan Gutmann	UCAR	Future Snow Missions: Integrating SnowModel in LIS	Improve NASA modeling capabilities for snow OSSE, to plan and operate a future cost-effective snow mission by coupling the SnowModel modeling system into NASA LIS.

AIST-21 NOS Awards

- **NOS for Smart Sensors and Onboard Intelligence**

PI's Name	Organization	Title	Synopsis
William Blackwell	MIT Lincoln Labs	Sensor-in-the-Loop Testbed to Enable Versatile/Intelligent/Dynamic Earth Observation (VIDEO)	Develops a methodology and test approach for a scene measured by a sensor to be able to configure the sensor in real-time during the scene measurement. Will significantly improve the resolution of the retrieved atmospheric fields in regions in which that improvement is most beneficial, while conserving resources in other regions. Includes two components: (1) Radiometric Scene Generator (RSG) using advanced metamaterial and its associated control software; (2) Intelligent processing and configuration software using feature detection and ML, running onboard the sensor, to detect and react to changes by dynamically optimizing the sensor response functions.
James Carr	Carr Astronautics	Edge Intelligence for Hyperspectral Applications in Earth Science for New Observing Systems	Will use the SpaceCube processor and its Low-power Edge Artificial Intelligence Resilient Node (SC-LEARN) coprocessor powered by Google Coral Edge Tensor Processing Units (TPUs) to implement two AI science use cases in hyperspectral remote sensing: (1) Use learned spectral signatures of clear-sky scenes to retrieve surface reflectance and therefore increase the efficiency of collecting land observations on ~68% cloudy planet (e.g., for SBG); (2) Classify artificial light sources after training against a catalog of lighting types. SC-LEARN will fly on STP-H9/SCENIC to the ISS with a Headwall Photonics HyperspecMV hyperspectral imager.
James MacKinnon	NASA Goddard Space Flight Center	Multi-Path Fusion Machine Learning for New Observing System Design and Operations	Proposes to develop a system based on data fusion and multi-path neural network ML to aid in the design and operation of multi-sensor NOS concepts. Will build ML-enabled analytic tools and advanced computing environment capabilities for NOS workflows that utilize large amounts of diverse airborne and satellite observations. Using multiple neural networks working in parallel, it will first be demonstrated with a forest productivity use case, with fusion of lidar, spectrometry, satellite-derived climatology and ecosystem modeling providing insights into the driving environmental factors that influence productivity. Then will be used for sensitivity studies to guide sensor and mission requirements traceability.
Daniel Selva	Texas A&M Univ.	3D-CHESS: Decentralized, distributed, dynamic and context-aware heterogeneous sensor systems	Proposes to demonstrate proof of concept for a context-aware Earth observing sensor web consisting of a set of nodes with a knowledge base, heterogeneous sensors, edge computing, and autonomous decision-making capabilities. Context awareness refers to the nodes' ability to gather, exchange, and leverage contextual information to improve decision making and planning. Will demonstrate and characterize the technology in a multi-sensor in-land hydrologic and ecologic monitoring system performing 4 inter-dependent missions: studying non-perennial rivers and extreme water storage fluctuations in reservoirs and detecting and tracking ice jams and algal blooms.

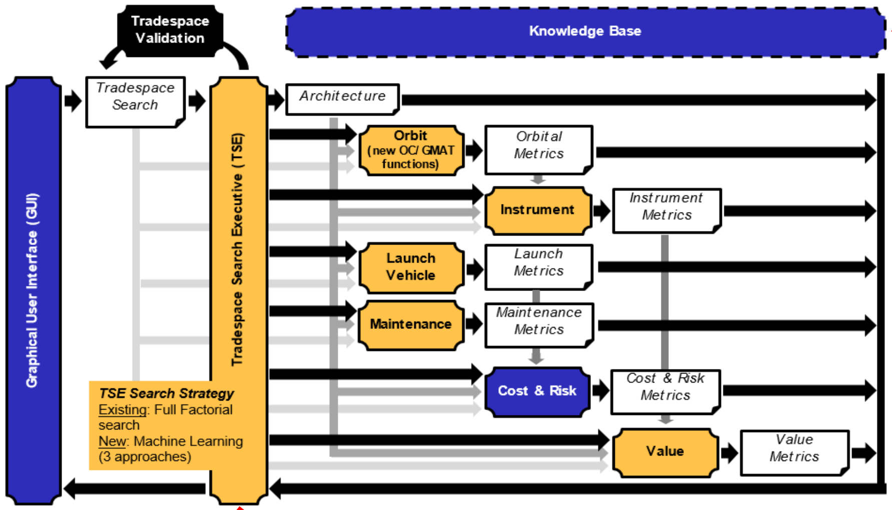
AIST-21 NOS Awards (cont.)

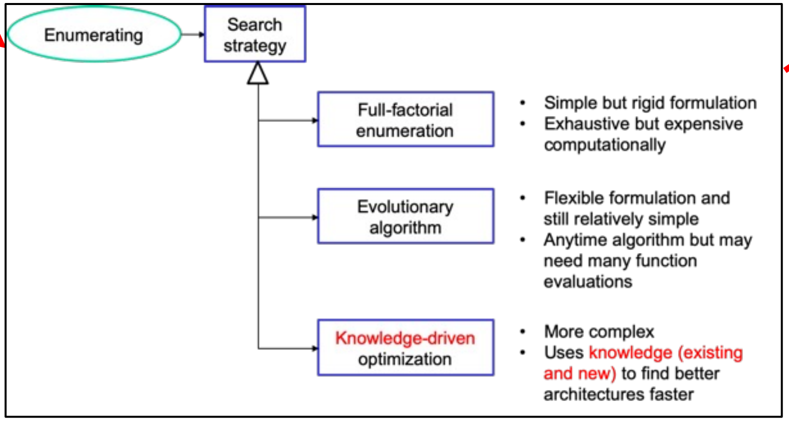
- **NOS for UAS Integration and NOS Prototypes**

PI's Name	Organization	Title	Synopsis
Meghan Chandarana	NASA Ames Research Center	Intelligent Long Endurance Observing System	Proposes the development of the Intelligent Long Endurance Observing System (ILEOS) to help scientists build plans to improve spatio-temporal resolution of climate-relevant gases by fusing coarse-grained sensor data from satellites and other sources and plan High-Altitude Long Endurance (HALE) UAS flights to obtain finer-grain data. ILEOS will also enable observations for longer periods and of environments not accessible through in-situ observations and field campaigns. 3 components: (1) the Target Generation Pipeline to identify candidate target scenes; (2) the Science Observation Planner using automated planning and scheduling technology to automatically generate a flight plan; and (3) a Scientists' User Interface.
Carl Legleiter	USGS	An Intelligent Systems Approach to Measuring Surface Flow Velocities in River Channels	Will develop a New Observing Strategy (NOS) for measuring streamflow from a UAS using an intelligent system. Using the USGS/NASA UAS-based payload for measuring surface flow velocities in rivers (USGS & NASA), consisting of thermal/visible cameras, a laser range finder, and an embedded compute (integrated within a common software middleware), it will address both quality control during routine streamgaging operations by quantifying uncertainty, as well as autonomous route-finding during hazardous flood conditions using inter-sensor communications. Will be implemented for real-time processing onboard the platform.
Carrie Vuyovich	NASA Goddard Space Flight Center	A New Snow Observing Strategy in Support of Hydrological Science and Applications	Will develop the Snow Observing System (SOS) considering the most critical snow data needs along with existing and expected observations, models, and a future snow satellite mission. It will estimate SWE and snow melt throughout the season, targeting obs with the greatest impact. It will: evaluate/combine observations from existing missions; create a hypothetical experiment to determine optimal observing strategy; assess value of new potential sensors, e.g., commercial SS for filling gaps and higher frequency obs. Higher density observations for early warning in regions where concerns for flood, drought or wildfires will also be studied.

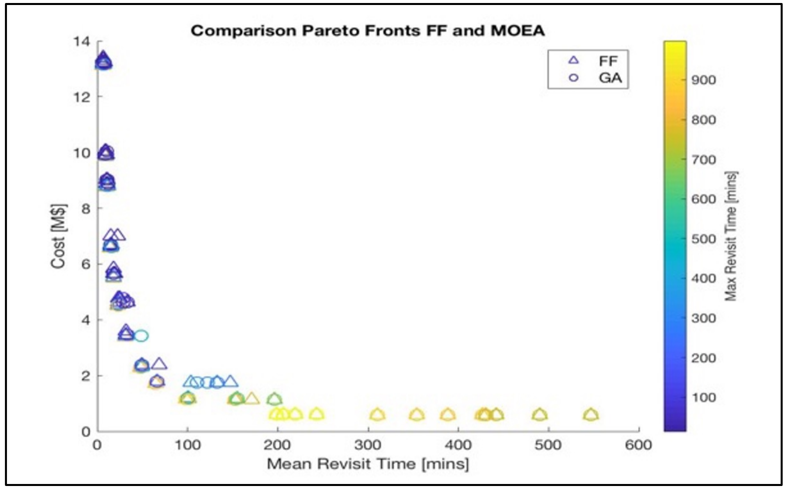
AIST-14 & -16/Grogan (Stevens) –
Trade-space Analysis Tool for Constellations (TAT-C)

TAT-C is a systems architecture analysis platform for pre-phase A Earth science (ES) constellation missions. It allows users to specify high-level mission objectives and constraints and efficiently evaluate large trade spaces of alternative architectures varying the number of satellites, orbital geometries, instruments, and ground processing networks. Outputs characterize various mission characteristics and provide relative evaluations of cost and risk. Machine Learning evolutionary algorithms are used for fast traversal of this large trade space using Adaptive Operator Selection (AOS) and Knowledge-driven Optimization (KDO) working with a Knowledge Base populated with information from historical ES missions.





Evolutionary algorithm finds a very similar Pareto front with an order of magnitude fewer function evaluations



Evolutionary algorithm enables searching much larger and richer design spaces with hybrid architectures combining satellites at various altitudes and inclinations.

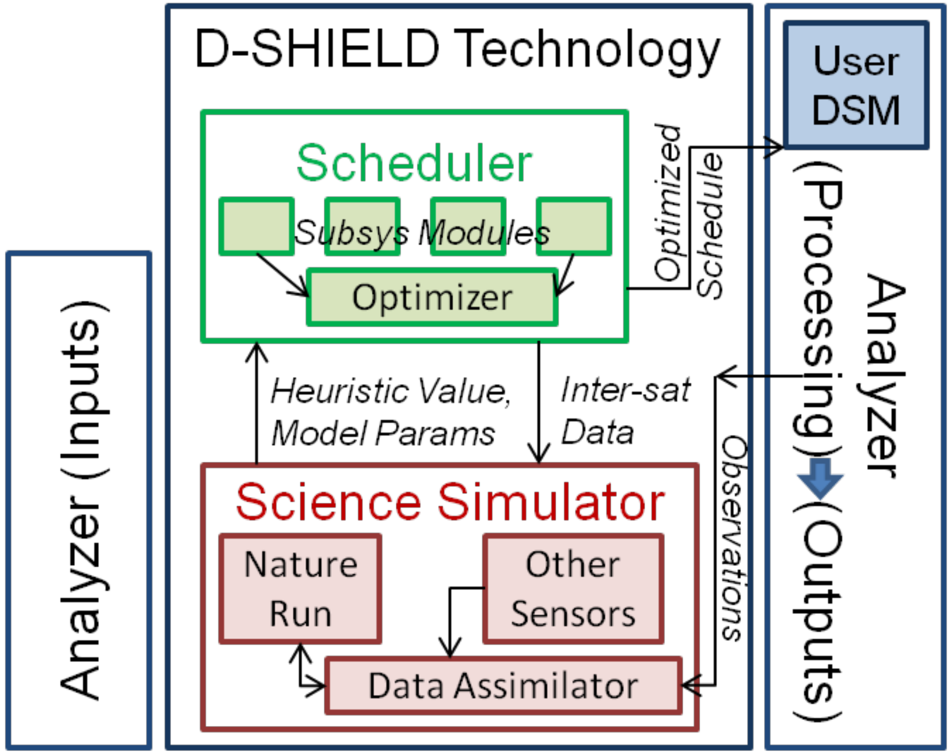
Delta heterogeneous Walker	
Decision	**Options**
# satellites	[1, 2, 3, 4, 6, 8, 10, 12]
# planes	[1, 2, 3, 4, 6, 8, 12]
Altitude	[400:100:800] km
Inclination	[0°,10°,20°,30° ISS, 90°, SSO]

Note: Previous PI's: Le Moigne & Verville @GSFC

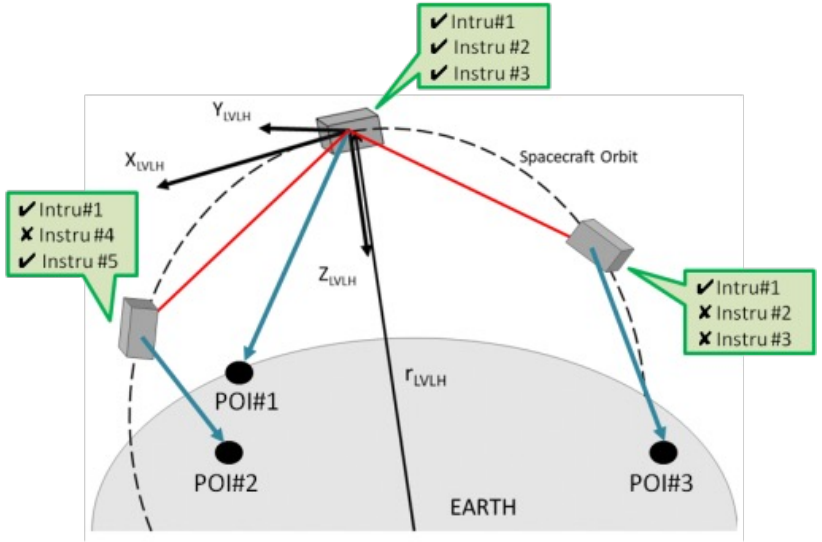
AIST-18/Nag (NASA ARC)

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

D-SHIELD is an operations design tool that will, for a given distributed space mission (DSM) architecture, plan re-orienting and operations of heterogeneous payloads, accounting for power/payload constraints while maximizing science value. It uses an iterative science observable simulator based on Observing System Simulation Experiments (OSSEs) adapted for real time planning and rapid mission design This project contributes to the New Observing Strategy (NOS) thrust area by developing an AI-based planning and scheduling-based DSM operations tool.



D-SHIELD system diagram including data flows.

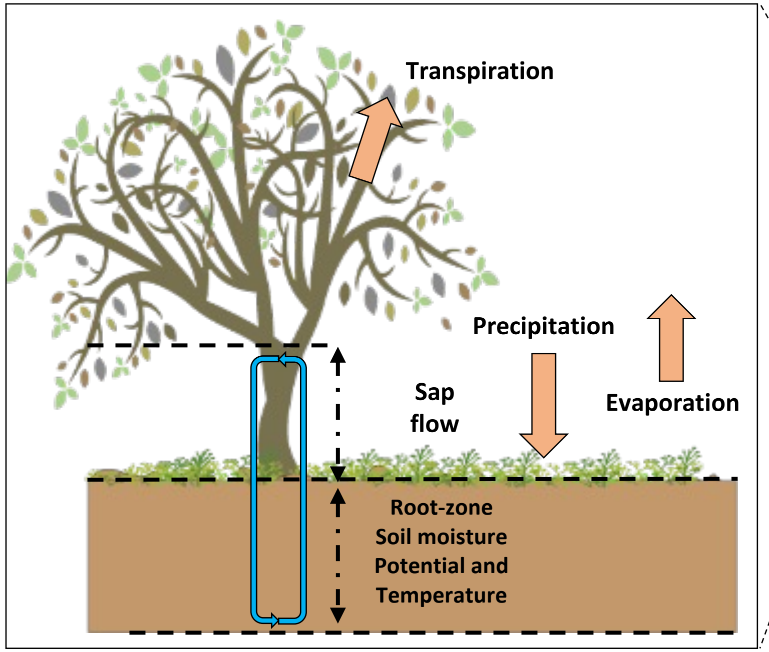


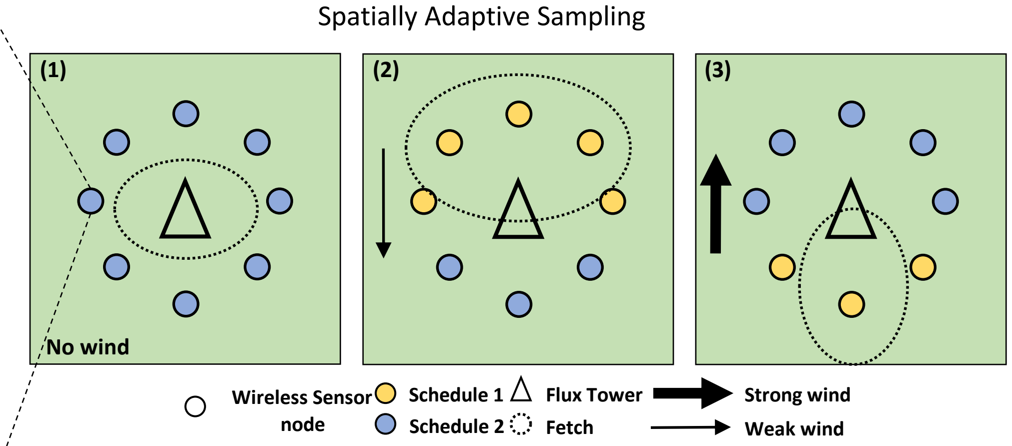
Cartoon of 3-satellite constellation with multiple instruments and D-SHIELD coordinated decisions

AIST-16/Entekhabi & Moghaddam (MIT & USC) –

Autonomous Moisture Continuum Sensing Network

Soil moisture is important for understanding hydrologic processes by monitoring the flow and distribution of water between land and atmosphere. A distributed, adaptive sensor network improves observations while reducing energy consumption to extend field deployment lifetimes .





Distributed wireless sensor network measures soil moisture, sap flow, and winds

Embedded Machine learning decides when and where to sample in order to optimize information gain and energy usage.

Evaluated alternative adaptive sampling strategies for performance (information) vs energy use.

- ✓ Information Gain vs. Energy Consumption optimization → present as Pareto Fronts
- ✓ An autoregressive ML will have superior performance $\theta(t) = f\big(\theta(t-1)\big) + g\big(X(t)\big)$
- ✓ Simple Policies can achieve superior RMSE performance with less energy consumption

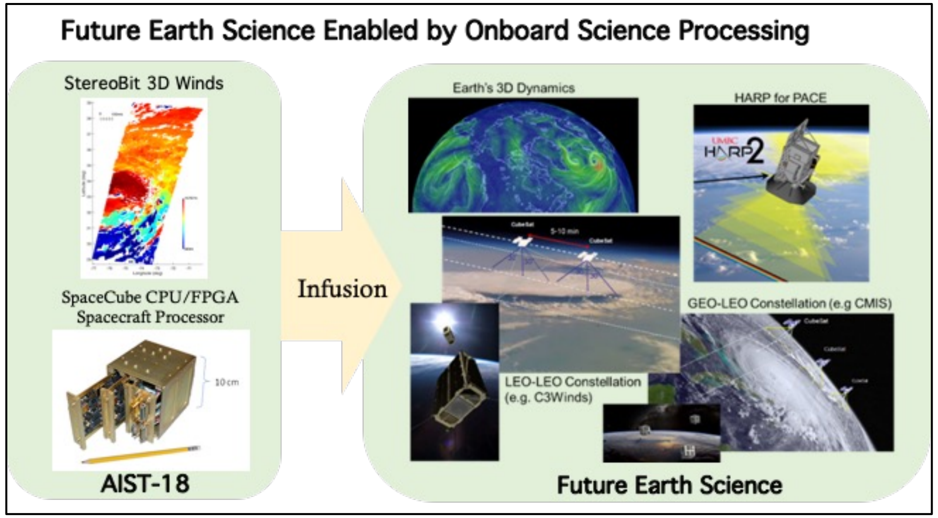
SoilSCAPE installation for CYGNSS Cal/Val

- SoilSCAPE Plan → Satellites Cal/Val
  - SMAP Cal/Val: Deployed 1 site at the Cary Institute of Ecosystem Studies (Millbrook, NY)
  - SoilSCAPE team (via. Co-I Moghaddam) collaborating with CYGNSS to provide *in situ* soil moisture for cal/val activities
  - Established a cal/val infrastructure for NiSAR

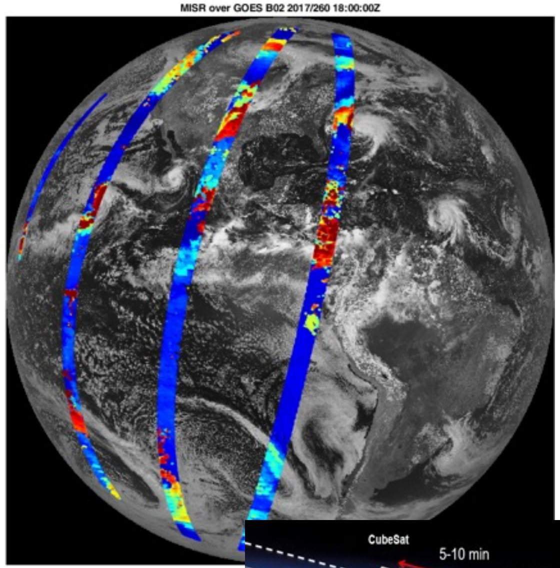
AIST-18/Carr (Carr Astronautics) –

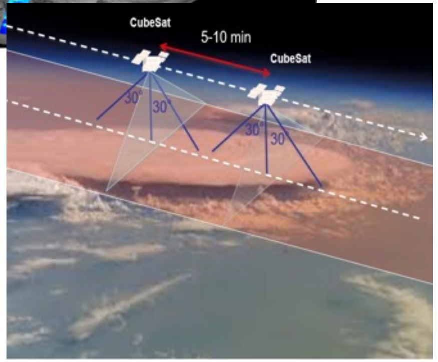
StereoBit: Advanced Onboard Science Data Processing to Enable Future Earth Science

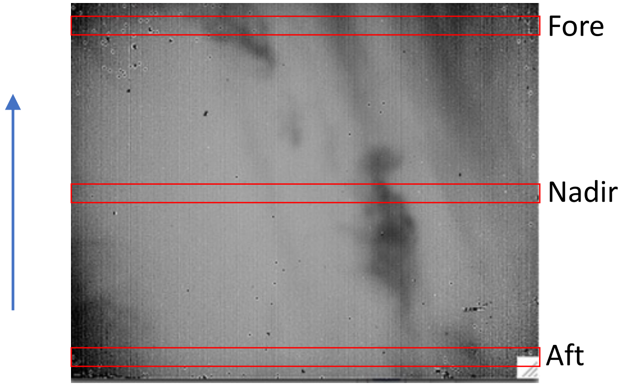
This investigation demonstrates higher-level onboard science data processing for more intelligent SmallSats and CubeSats to enable future Earth science missions and Earth observing constellations. Low-cost SmallSat architectures generally suffer from downlink bottlenecks and often result in lower data acquisitions per orbit. This project targets an objective relevant to the 2017-2027 Earth Sciences Decadal Survey - atmospheric dynamics with 3D stereo tracking of cloud moisture features using a Structure from Motion (SfM) technique called StereoBit that can be implemented onboard. This will lead to the development of a testbed to validate intelligent onboard systems.



SfM method from OpenCV implemented on SpaceCube 2.0 and flying on RRM3 using the Compact Thermal Imager (CTI)

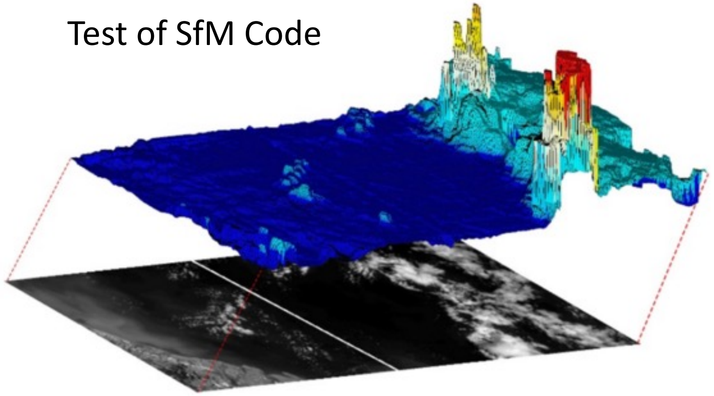






Early CTI Cloud Picture

Test of SfM Code



SpaceBorne-2 Experiments/Chien (NASA JPL) – *ISS Onboard Processing Experiment*

This project conducts both technology validation and TRL improvement experiments as well as it will demonstrate enhanced and enabling capabilities.

New Technology Demonstrations: *Validating New Hardware and Software Technologies*

- **Re-Tasking Demonstration :** using onboard data analysis to create alerts
    - Use onboard data analysis to generate alerts, NOS- or SensorWeb-like, e.g,: task other assets
- **Live-Instrument Data Feed :** run experiments with data generated on ISS, e.g., ECOSTRESS, EMIT, OCO-3
    - Using both pre-uploaded and potentially live data from onboard ISS instruments
- **Co-Processors Experiments:**
    - **Intel Movidius/Myriad Neuromorphic Processor**
        - Currently on ESA's Phi-Sat and terrestrial drones
    - **Qualcomm Snapdragon Processor**
        - Flying on Mars Helicopter
    - Gain tremendous in-space processing experience with 2 processors that are well on the path to mission use

Data Processing and Machine Learning Experiments

- **Radar Processing: l**everage NISAR and UAVSAR radar pipelines => data reduction, low-latency downlink
- **Thermal Infrared Processing :** experiment with TIR data from ECOSTRESS
    - Onboard pipeline: radiometric calibration, geolocation, land surface temperature, etc.
    - Applied Science Value: orders of magnitude data reduction, low-latency downlink
- **VSWIR Processing :** experiment with VSWIR data from EMIT
    - Heritage technology from HysPIRI Intelligent Payload Module (IPM)
    - Applied Science Value: data reduction, low-latency downlink, alerts for tasking other sensors
- **Machine Learning Demonstration** : perform ML/imagery classification techniques like HiRISNet, MSLnet, and Hirise

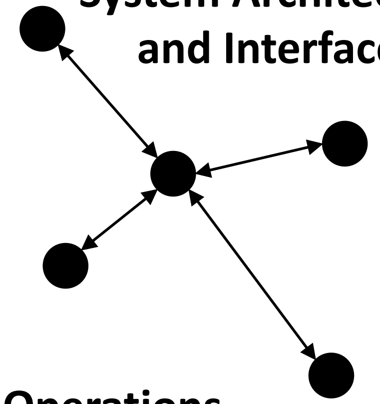
Novel Observing Strategies Testbed

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

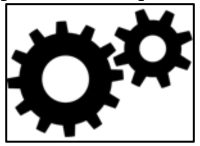
Testbed Main Goals:

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

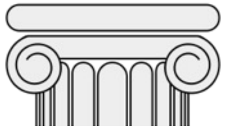
System Architecture and Interfaces



Concept of Operations



Governance Model

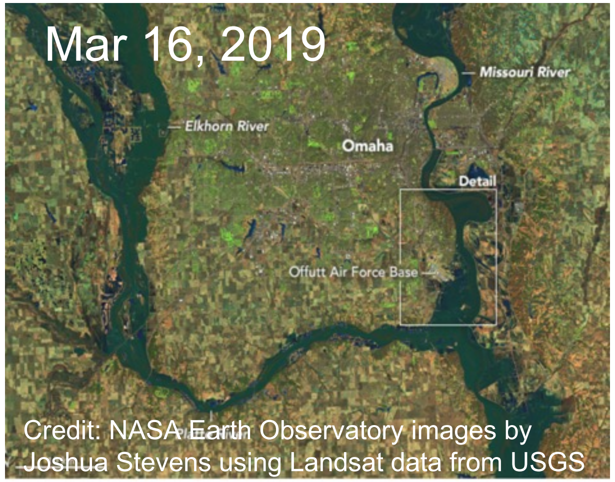


NOS-T framework objective:

Enable disparate organizations to propose and participate in developing NOS software and information technology

NOS-Testbed Hydrology Demonstrations

March 2021 – Historical Nebraska Flood + Live Mid-West Flood



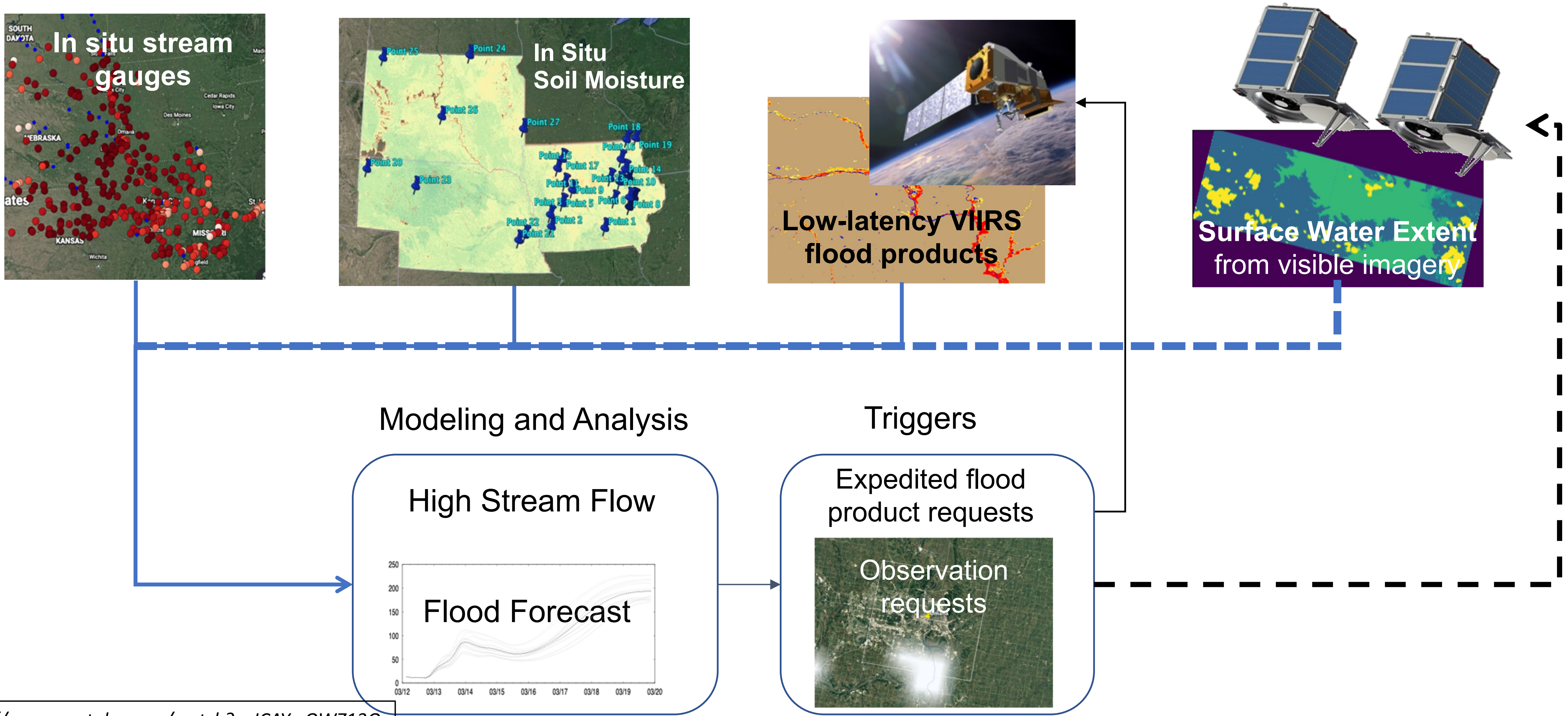
Credit: NASA Earth Observatory images by Joshua Stevens using Landsat data from USGS

Offutt Airforce Base Neb, Mar 17 (Air Force)

Flooding of Eastern Nebraska began on March 14, 2019, due to heavy precipitation, snow melt and river ice jams and resulted in mass evacuations from the area.

NOS-Testbed Hydrology Demonstrations

March 2021 – Historical Nebraska Flood + Live Mid-West Flood



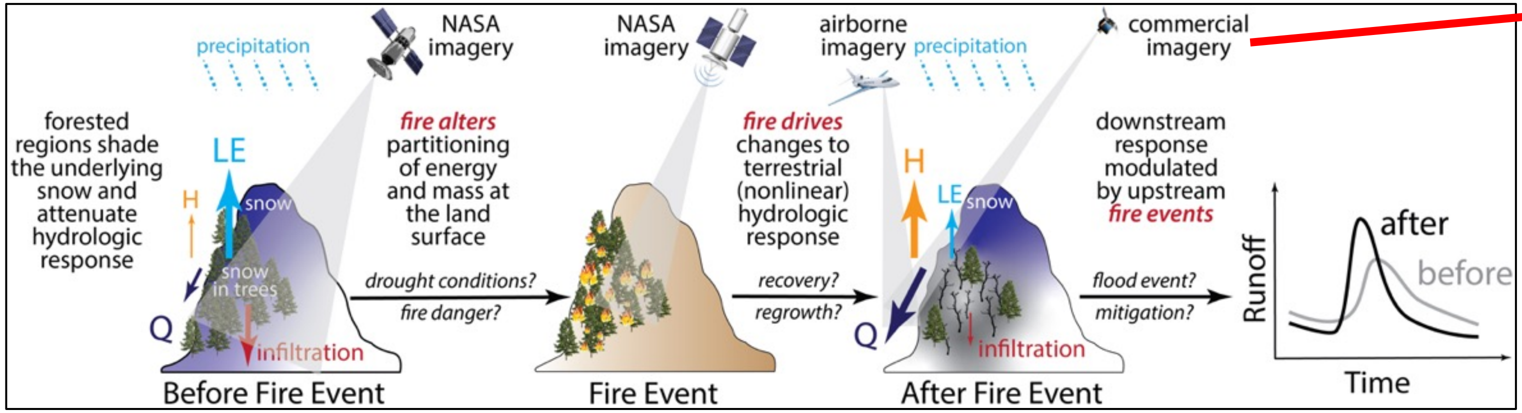
https://www.youtube.com/watch?v=ICAYwOWZ13Q

NOS-Live (NOS-L)

Autonomous, Model-driven Tasking of Flood Events

Live demonstrations of optimized surface water measurement acquisitions in responses to large fires over the Western U.S.

Vegetation disturbance triggered hydrology impacts for NOS-live demonstration



Planet and Capella

Large vegetation disturbances such as fires lead to significant changes in the local hydrology, typically by decreasing evaporation and increasing runoff in post-fire conditions. Such cascading impacts have been responsible for large flooding events in several parts of the world. Targeted remote sensing observations of the relevant processes would likely be of significant utility to capture fire-driven flooding instances.

- *High resolution multi-decadal model retrospective (2003-2021) and short-term over Western U.S., informed by RS precipitation, soil moisture, terrestrial water storage, and leaf area index estimates using the NASA LIS system => Fine scale vegetation disturbances from fires + associated hydrology impacts.*
- *Identification of target locations based on river discharge, spatial position within watershed, size and distribution of wildland fires and population density within a watershed.*
- *Optimized event-driven architecture based on NOS-testbed => automated message and information flow between on-premise and cloud resources, commercial satellite observations and tasking application.*

The system was run continuously in automated fashion for several months from August to December 2022. Based on the targets identified by the model forecasts, commercial imagery was tasked and ordered from Planet and Capella and incorporated into the model estimates.

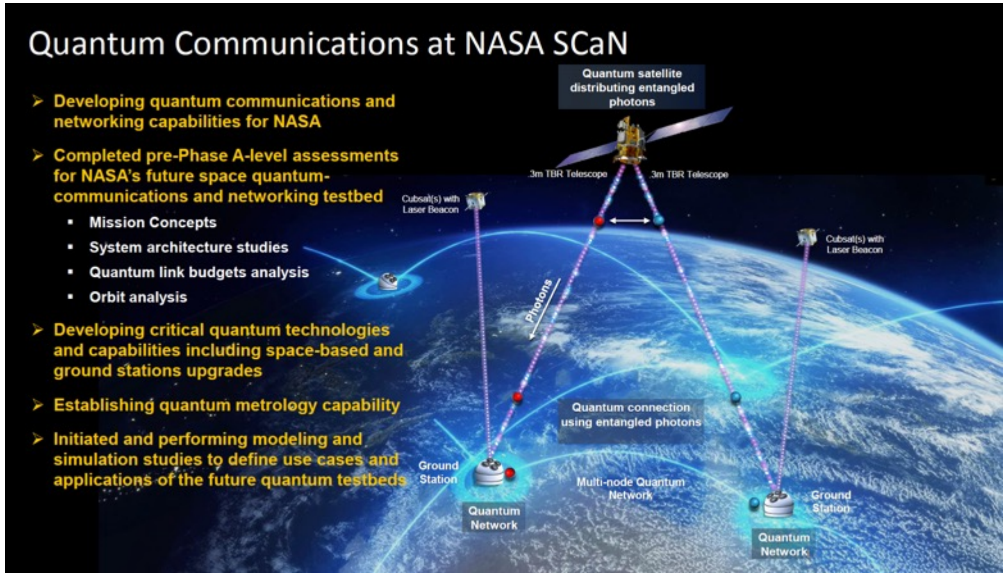
Other Capability for NOS-like Systems

NASA SCaN Communications (Angela Hodge, Babak Saif, Nasser Barghouty)

NASA has more than a decade of experience in technology development for both optical and quantum communications

Laser Communications Relay Demonstration (LCRD)

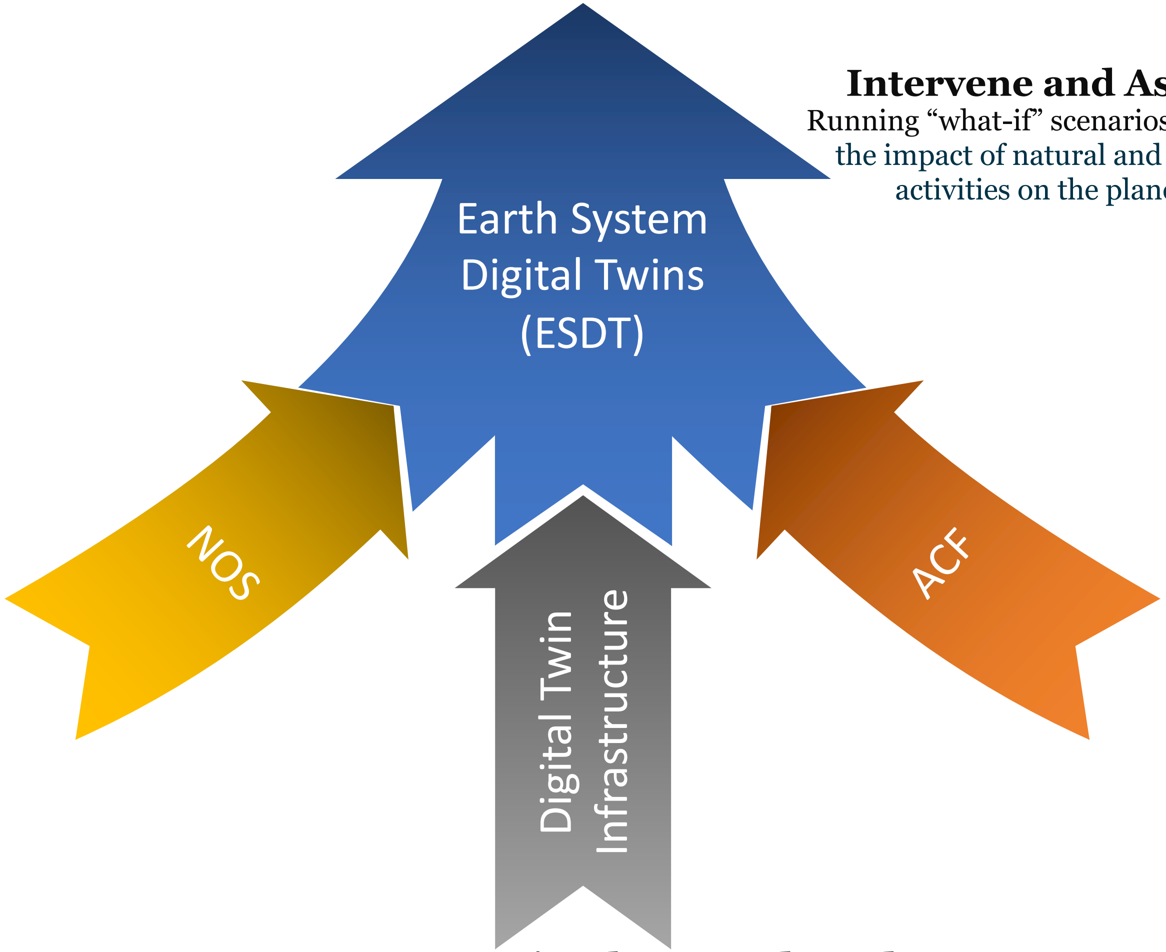
- LCRD showcasesthe unique capabilities of optical communications
- Provides benefits for missions, including bandwidth increases of 10 to 100 times more than radio frequency systems.
- Compared to RF, Optical Comms offer decreased size, weight, and power requirements.
- Optical communications will supplement radio frequency (RF), giving missions unparalleled communications capabilities.



- Experiments and performance assessments via:
  - Modeling & Simulation
  - Testbeds and laboratories on the ground and in space
- Projects include:
  - Quantum Physics in Microgravity
  - Communications and Networks
  - Computing and Algorithms
  - Development of Use Cases
  - Metrology

SCaN = Space Communications and Navigation

Using NOS for Digital Twins



Intervene and Assess

Running "what-if" scenarios to assess the impact of natural and human activities on the planet.

Observe, Target and Coordinate

Edge and on-the-ground intelligent planning, evaluating, coordinating and operating collections of diverse and distributed observing assets

Fuse, Analyze, Share and Collaborate

Simplify access to diverse and large amounts of data, analytics & modeling tools and advanced computational resources for collaborative science

Interrogate, Simulate, Trade and Visualize

Robust tools for interrogating, assessing uncertainties & causality, and for visualization, leveraging diverse data, models and products

NOS = Novel Observing Strategies

ACF = Analytic Collaborative Frameworks

Earth System Digital Twins Components

Digital Replica . . . What now?

An integrated picture of the past and current states of Earth systems.

Forecasting . . . What next?

An integrated picture of how Earth systems will evolve in the future from the current state.

Impact Assessment . . . What if?

An integrated picture of how Earth systems could evolve under different hypothetical what-if scenarios.

- **Continuous observations** of interacting Earth systems and human systems
- From many **disparate sources**
- Driving **inter-connected models**
- At many **physical and temporal scales**
- With fast, powerful and integrated **prediction, analysis** and **visualization** capabilities
- Using **Machine Learning, causality and uncertainty quantification**
- Running at **scale** in order to improve our **science** understanding of those systems, their **interactions and** their **applications**

NOS Demonstrations Roadmap

NOS-T Historical Flood Demonstration	NOS-T Live Flood Demonstration (If/When Live Event Happens)	NOS + NOS-T Live (NOS-L) Live Science Demonstration	Future Potential NOS Science Demonstration, e.g., Ocean Science

Early Spring 2021:
- NOS-T Node Coordination
- Simulated Trigger Generation
- Integration of *Historical* Data **On Demand**
- GSaaS *Simulation* Demonstration

Late Spring 2021:
- NOS-T Node Coordination
- **Live** Trigger Generation *(not necessarily autonomous)*
- Integration of **Live** Data **On Demand**
- GSaaS **Live** Demonstration

2022:
- NOS-T Node Coordination for **Science Application**
- **Actual** Autonomous Trigger Generation
- Integration of **Live** Data **On Demand**
- GSaaS **Live** Demonstration

TBD:
- NOS **Science Scenario** in coordination with upcoming PACE mission
- "Virtual Field Campaign"
- Potential coordination with prototype ESDT

Conclusions

- **Future Earth Science missions are going to be "revolutionized" if designed as NOS:**
  - NOS improves science by optimizing the observation of diverse science events and by minimizing model uncertainties
  - NOS enables observing systems and models to be "truly intelligent systems" and make autonomous decisions
  - NOS may reduce the cost of future missions through autonomy and by re-using "existing" nodes
  - Some of the nodes may be contributed by small businesses, e.g., Planet, Capella, Spire

- **The NOS-Testbed:**
  - Will enable :
    - Test new technologies as well as new NOS concepts/missions
    - Reduce the risk and the time of integrating new technologies into future observing systems
  - Architecture will evolve iteratively, and will include a Concept of Operations and a Governance Model

- **AIST is developing technologies** beyond State-Of-The-Art to enable those future NOS systems and their design

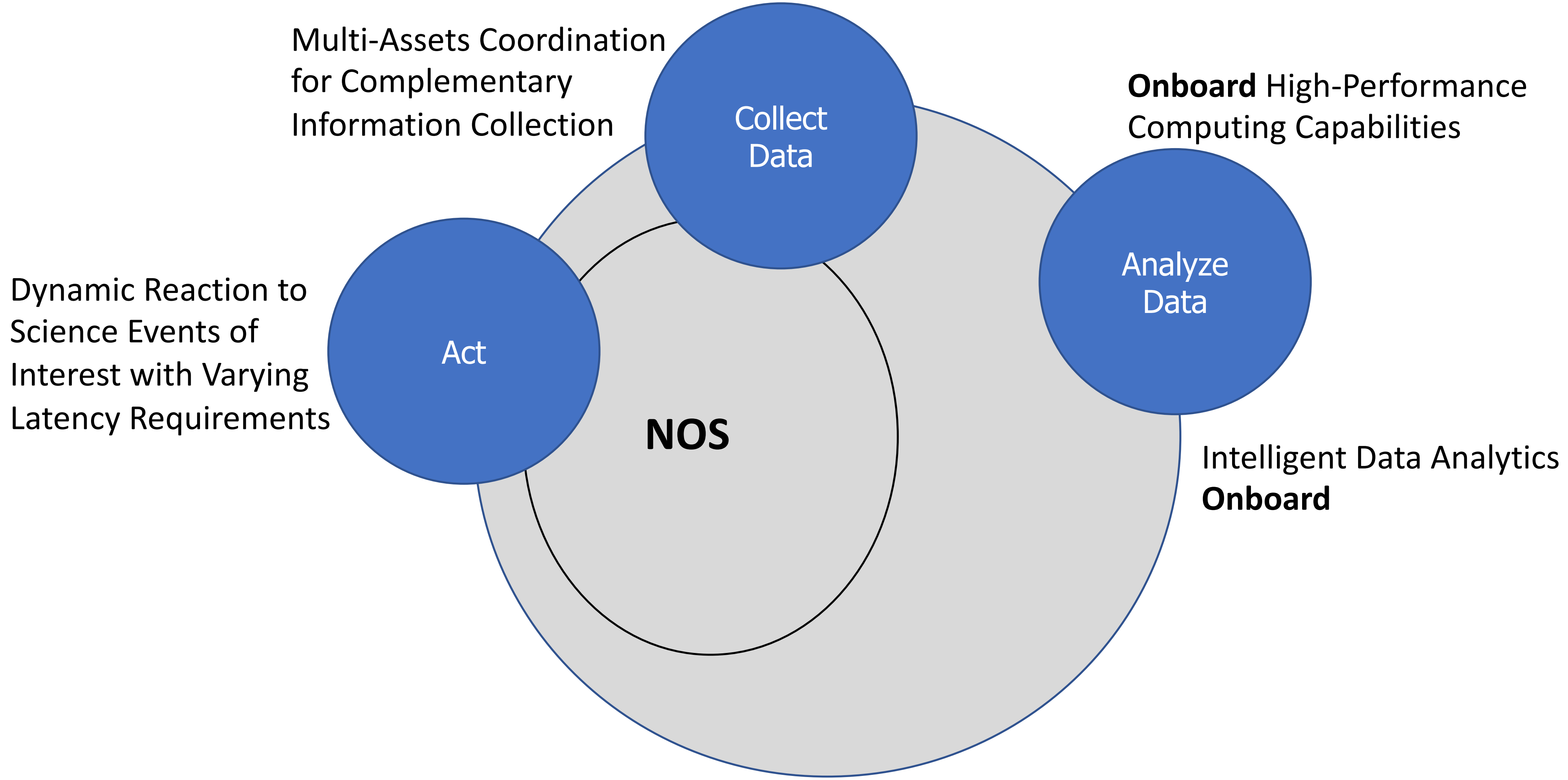
- **Concept** can be **applied to many future Earth Science missions**, eventually to Planetary and Helio too

- **NOS** (as well as the other AIST thrust) main building block towards the development of future **Earth Systems Digital Twins**

Backup

AIST Technologies

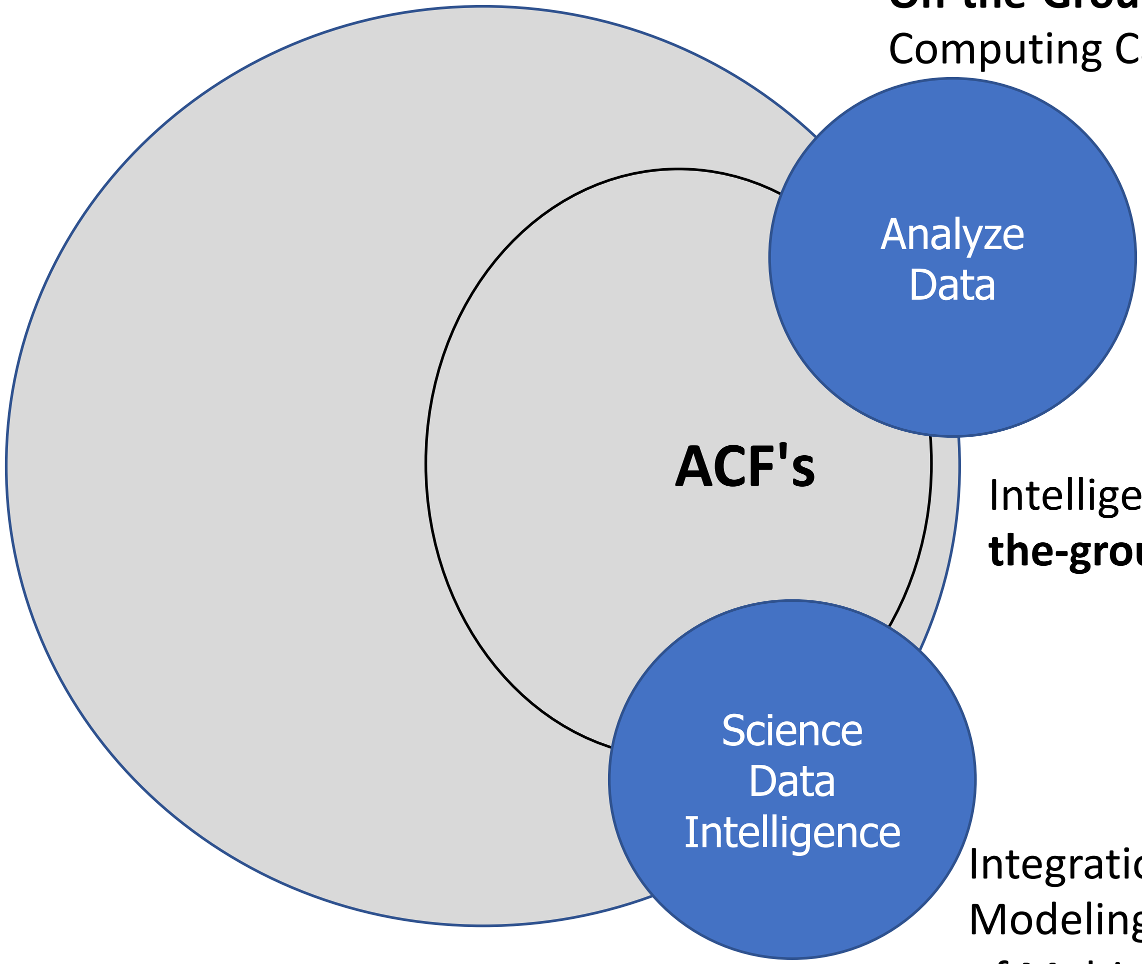
NOS Technologies



AIST Technologies

ACF Technologies

On-the-Ground High-Performance Computing Capabilities

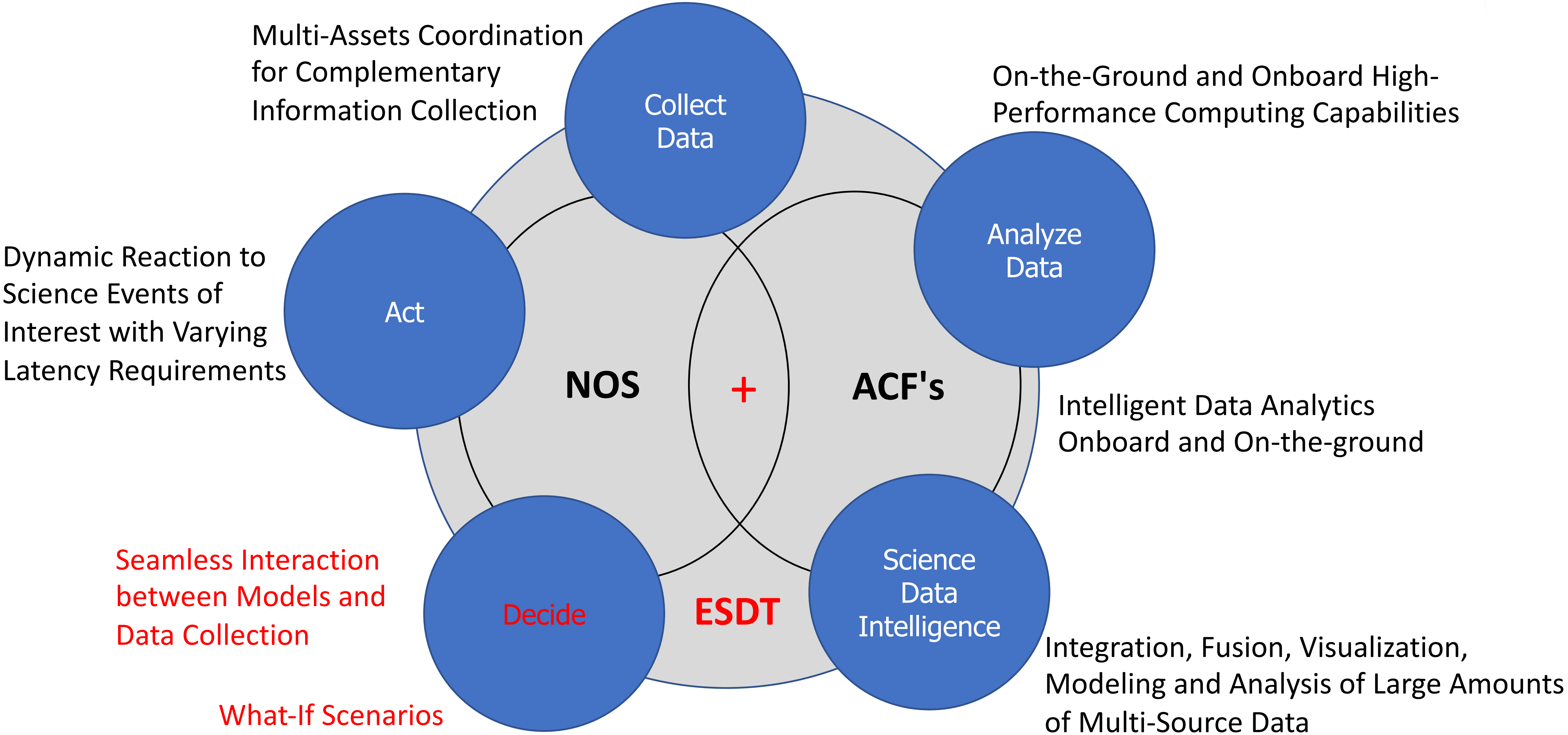


Intelligent Data Analytics **On-the-ground**

Integration, Fusion, Visualization, Modeling and Analysis of Large Amounts of Multi-Source Data

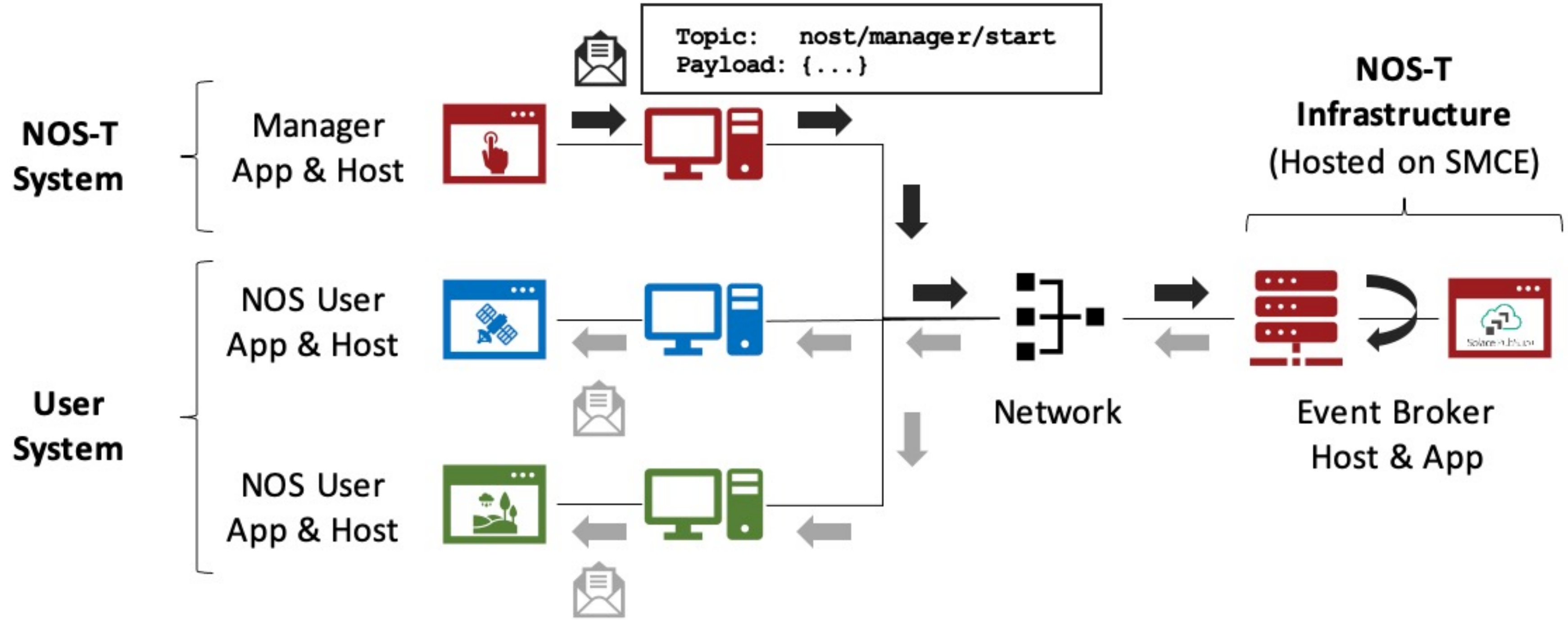
AIST Technologies

Continuous Integration of NOS and ACF Technologies for ESDT



NOS-T System Architecture

Developed by System Engineering Research Center (SERC)



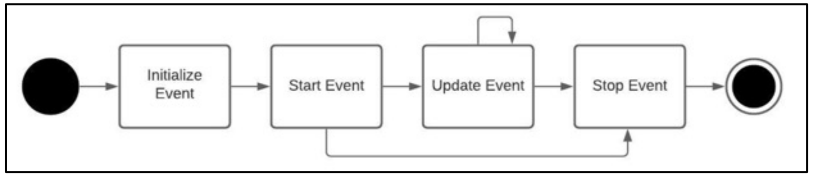
- Loosely-coupled event-drive architecture. Events = Notification Messages => **Scalability & Modularity**
- Centralized infrastructure component = **Event Broker** to exchange event notifications between applications. here implemented with **Solace PubSub+** hosted on **Science Managed Cloud Environment (SMCE)**, supports up to 1000 concurrent connections and 10,000 messages per second
- 2-level NOS-T Components: ***NOS-T System*** (fixed) & ***User System*** (tailored to each use case)
    - NOS-T System: NOS-T Operator + Event Broker Infrastructure + Manager Application
    - Test Run: Browser-based GUI to issue control commands and control progression

NOS-T System Architecture
Interface Protocol and Event Manager

- Message Protocol
  - Solace PubSub+ event broker supports and interoperates among several protocols including its own Solace Message Format (SMF) and several open protocols, e.g., Message Queuing Telemetry Transport (MQTT), Advanced Message Queuing Protocol (AMQP), and Representational State Transfer (REST)
- Message Format:

```
{
  "taskingParameters": {
    "startTime": "2021-04-15T12:00:00+00:00",
    "simStartTime": "2019-03-15T00:00:00+00:00",
    "simStopTime": "2019-03-19T00:00:00+00:00",
    "timeScalingFactor": 60
  }
}
```

- Typical Test Run Execution Lifecycle



List of NOS-T Manager Control Events

Event	Message Topic	Example Message Payload (JSON)
Initialize	`$PREFIX/manager/init`	`{ "taskingParameters": { "simStartTime": "2019-03-15T00:00:00+00:00", "simStopTime": "2019-03-21T00:00:00+00:00" } }`
Start	`$PREFIX/manager/start`	`{ "taskingParameters": { "startTime": "2021-04-15T12:00:00+00:00", "simStartTime": "2019-03-15T00:00:00+00:00", "simStopTime": "2019-03-21T00:00:00+00:00", "timeScalingFactor": 60 } }`
Update	`$PREFIX/manager/update`	`{ "taskingParameters": { "simUpdateTime": "2019-03-17T00:00:00+00:00", "timeScalingFactor": 100 } }`
Stop	`$PREFIX/manager/stop`	`{ "taskingParameters": { "simStopTime": "2019-03-21T00:00:00+00:00" } }`

P.T. Grogan et al, "New Observing Strategies Testbed (NOS-T). Technical Interface Brief; Version 1.0-alpha, April 2021", to be released soon on the ESTO AIST website

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