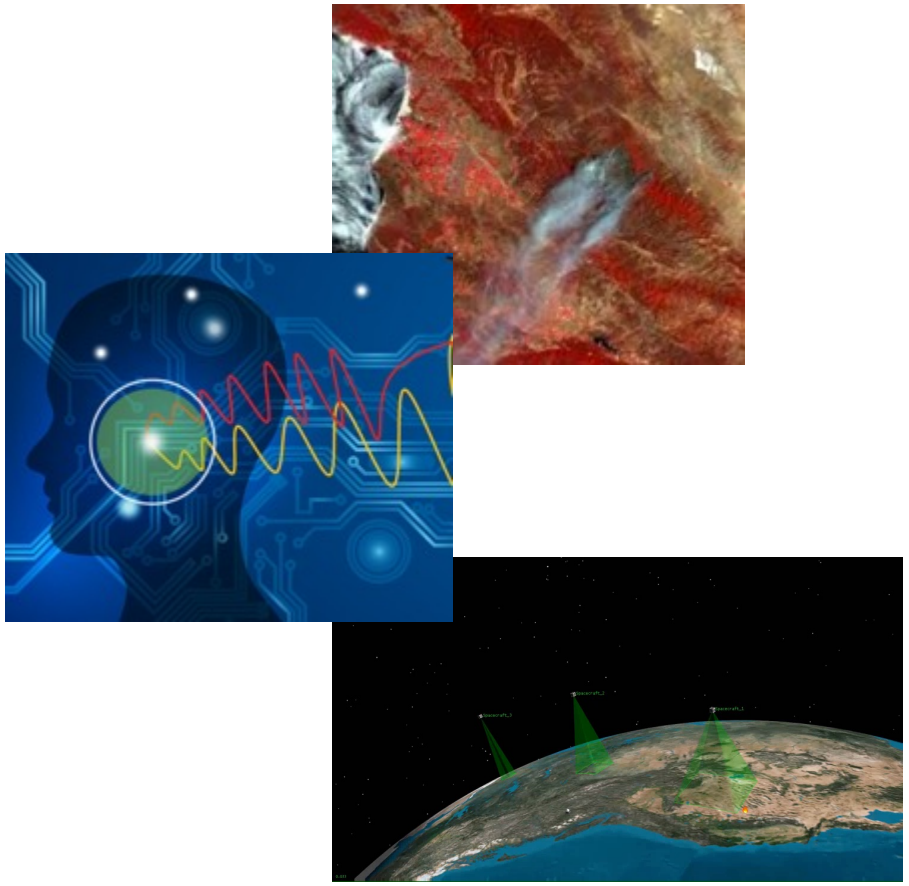


NASA Earth Science Technology Office (ESTO)

NASA's Advanced Information Systems Technology (AIST) –

Combining New Observing Strategies and Analytics Frameworks to Build Earth System Digital Twins

Jacqueline Le Moigne

July 2022

Earth Science Technology Office

ESTO leads technology development activities for NASA 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

Advanced Information Systems Technology

Innovate in technologies that enable:

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

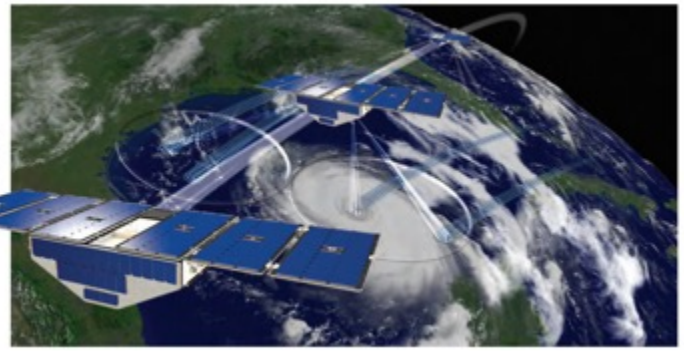
O2. Agile science investigations that fully utilize the large amount of diverse observations using advanced analytic tools, visualizations, and computing environments, and that interact seamlessly with relevant observing systems
=> Analytic Collaborative Frameworks (ACF)

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.

NOS for *Optimizing Measurements Design & Dynamically Capturing full Science Events*

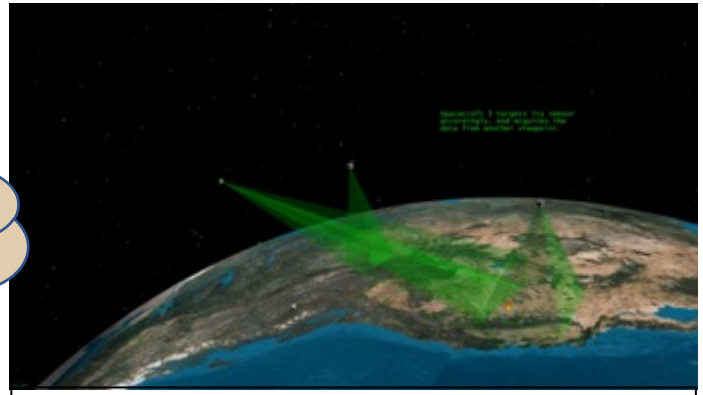


CYGNSS microsatellite observatories in orbit. Image credit: Southwest Research Institute

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

Provide complete picture of physical processes or natural phenomena

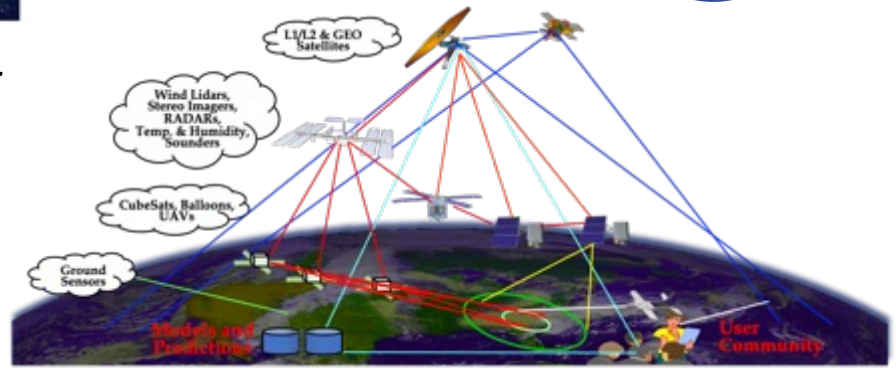
Increased understanding and predictability of dynamic events on Earth.



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

NOS OBJECTIVES:

1. **Design and develop Novel Observing Strategies (NOS) 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

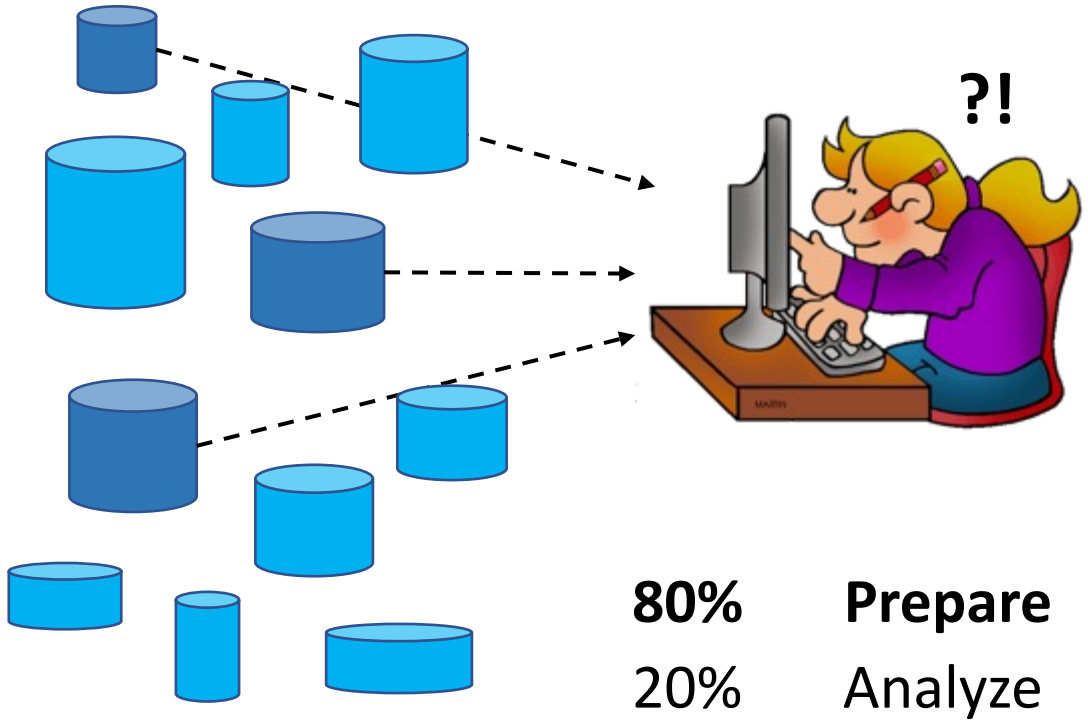
System-of-Systems NOS-Testbed for technologies & concepts validation, demonstration, comparison and socialization

From Archives to Analytic Frameworks: *Focus on the Science User*

Data Archives

Focus on data capture, storage, and management

Each user has to find, download, integrate, and analyze



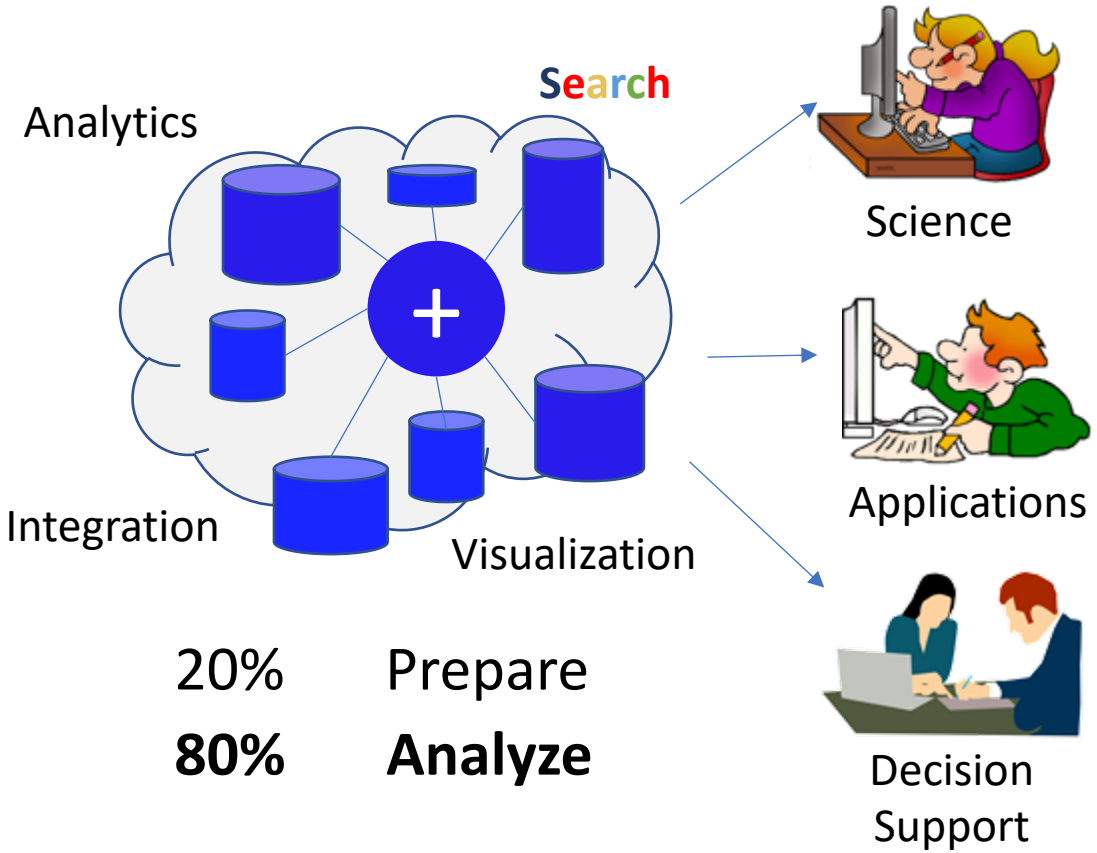
80% **Prepare**

20% Analyze

Analytic Collaborative Frameworks (ACF)

Focus on the science user

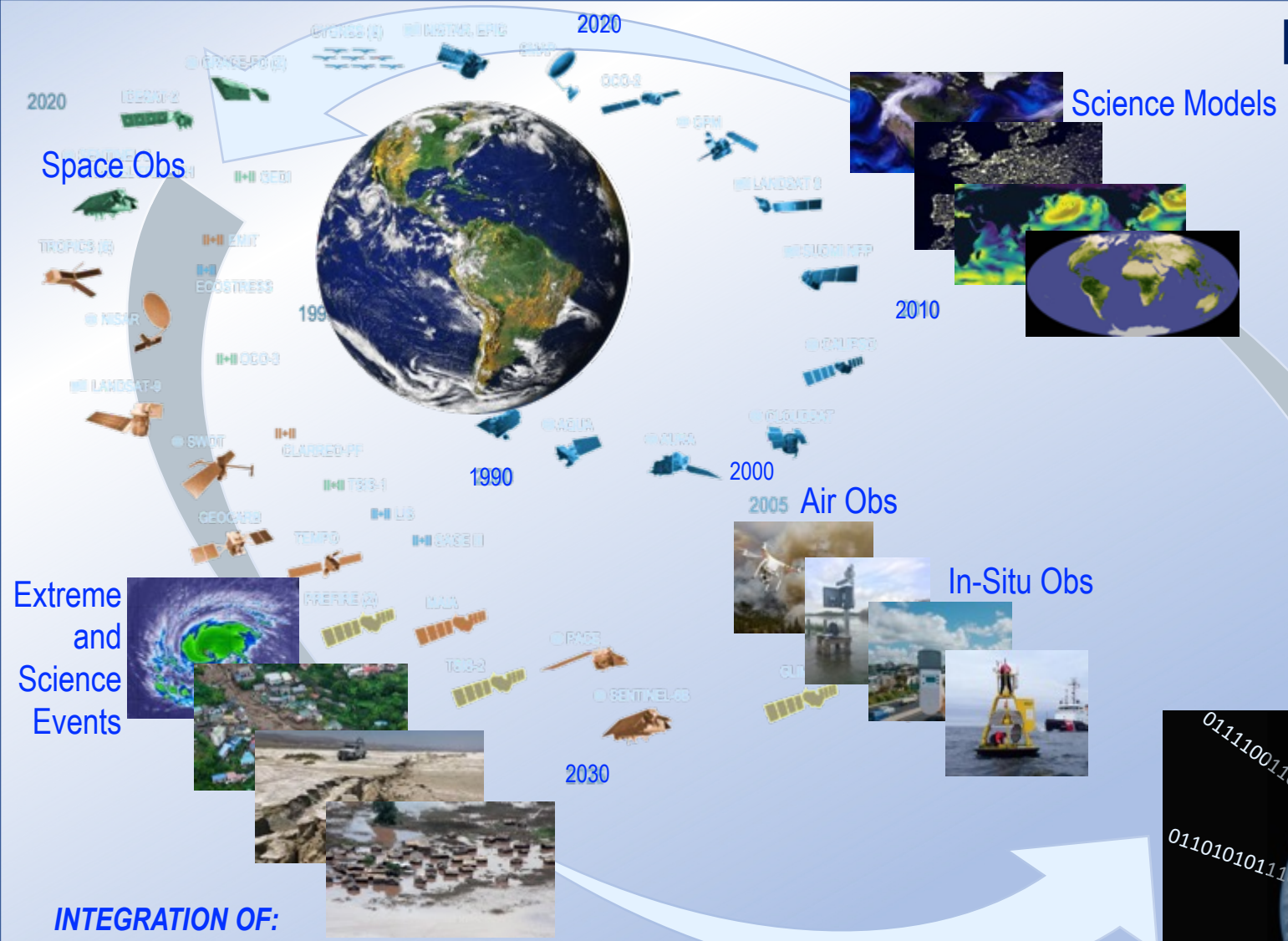
Integrated data analytics & tools tailored for a science discipline



20% Prepare

80% **Analyze**

Earth System Digital Twins (ESDT) Technology



INTEGRATION OF:

- \+ ***Continuous Observation and Data Stream Optimization***
- \+ ***Asset Identification, Access & Management (IAM)***
- \+ ***Interconnected Modeling***
- \+ ***Machine Learning***
- \+ ***High-End Computing Environments***
- \+ ***Investigative Capabilities (incl. Uncertainty Quantification)***
- \+ ***Advanced Visualization & AR/VR/MR***

Dynamic Interactive Replica of State and Temporal Evolution of the Earth or a Subcomponent of the Earth

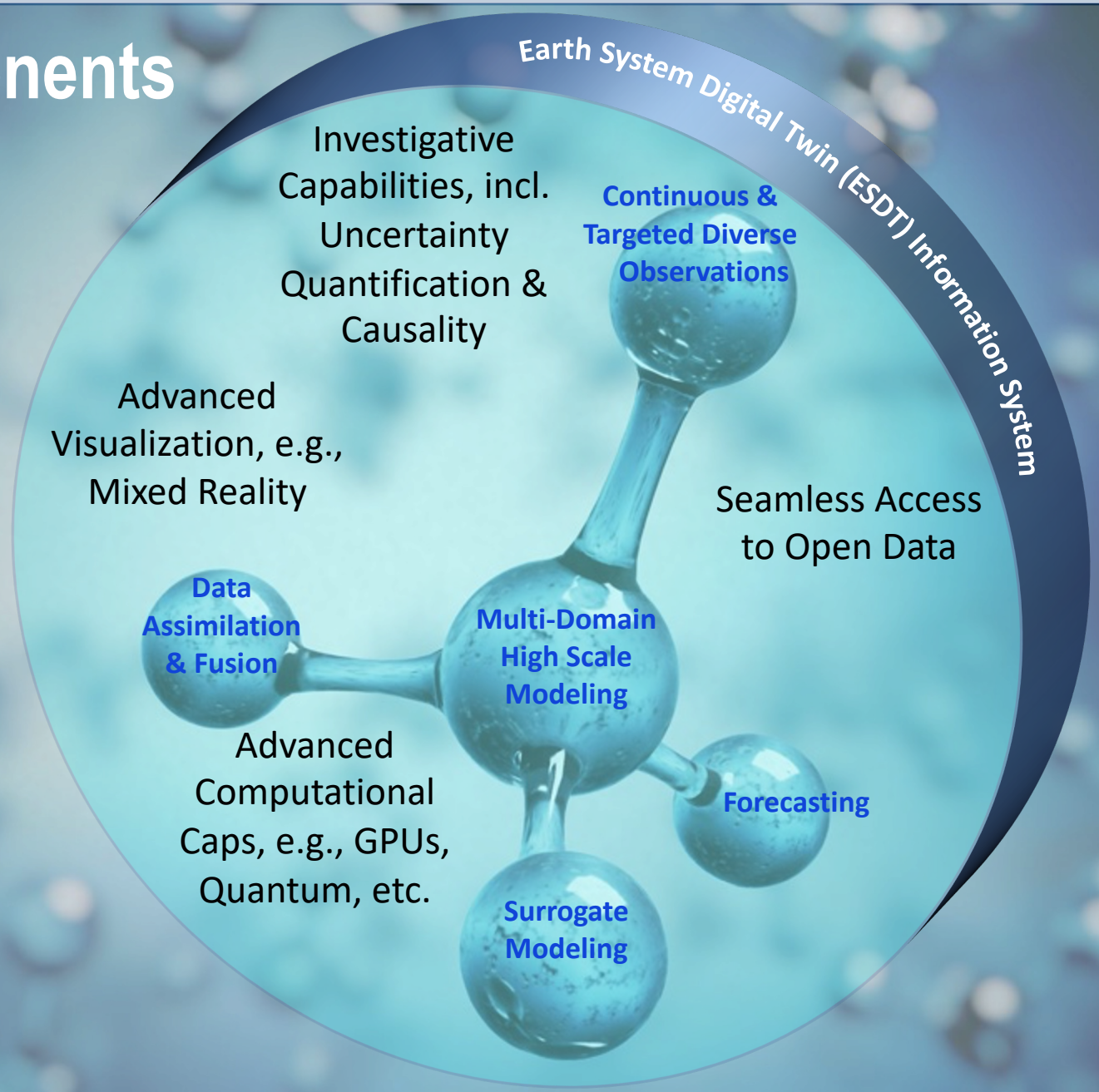
Enable "Constant Finger on the Pulse of the Planet"

Actionable Predictions

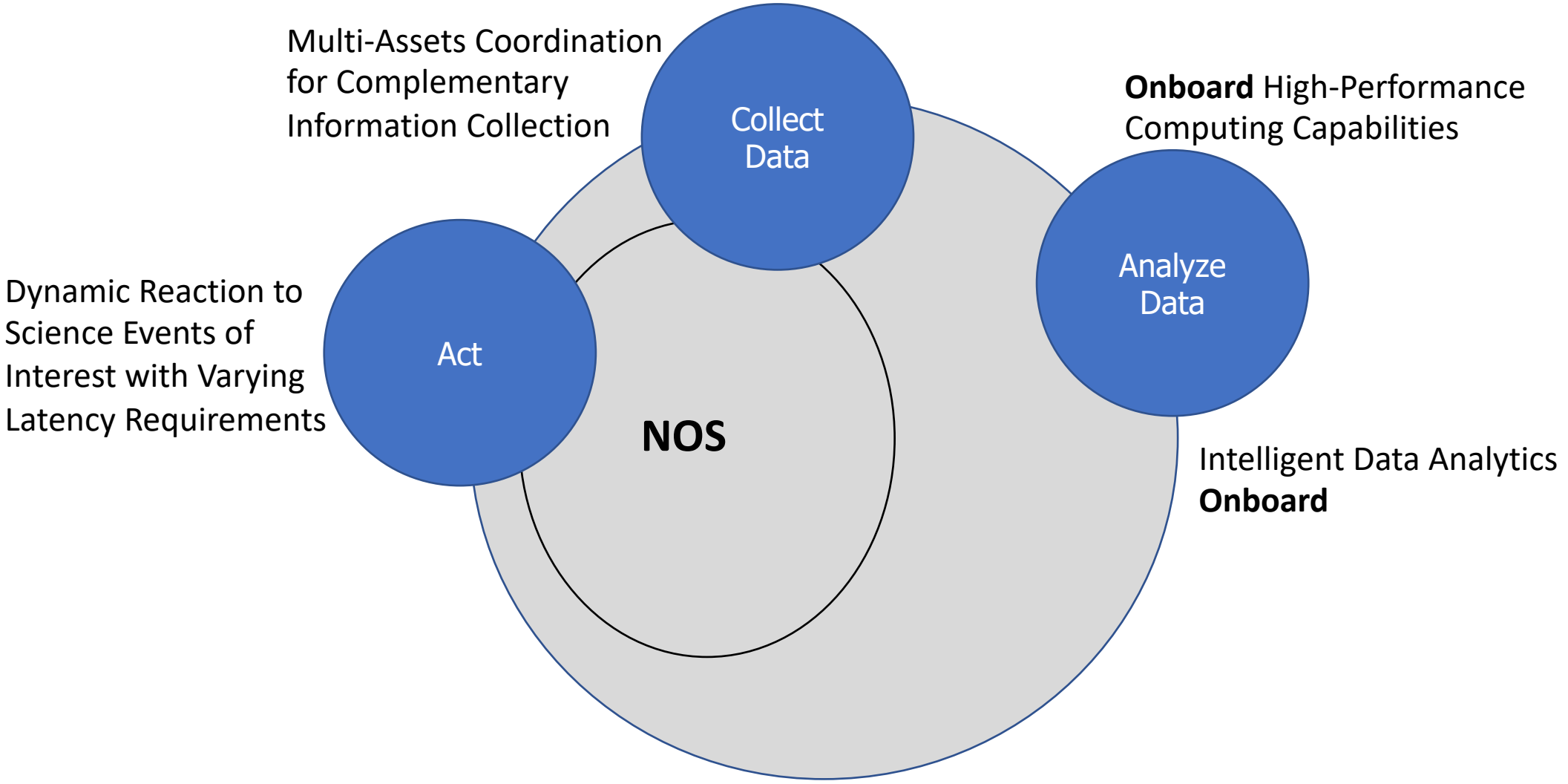
What-If Scenarios

ESDT Components

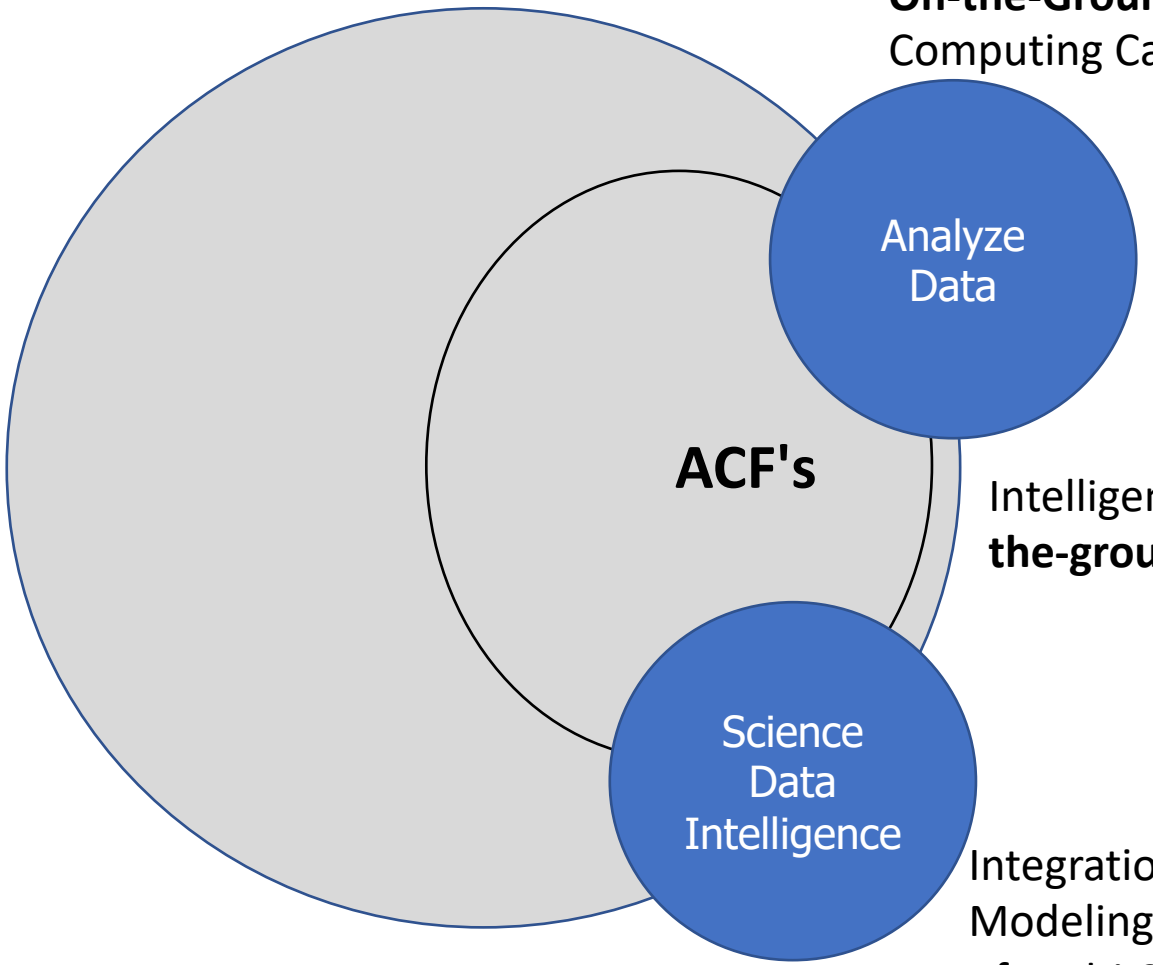
ESDT Components



AIST New Observing Strategies (NOS)



AIST Analytic Collaborative Frameworks (ACF)

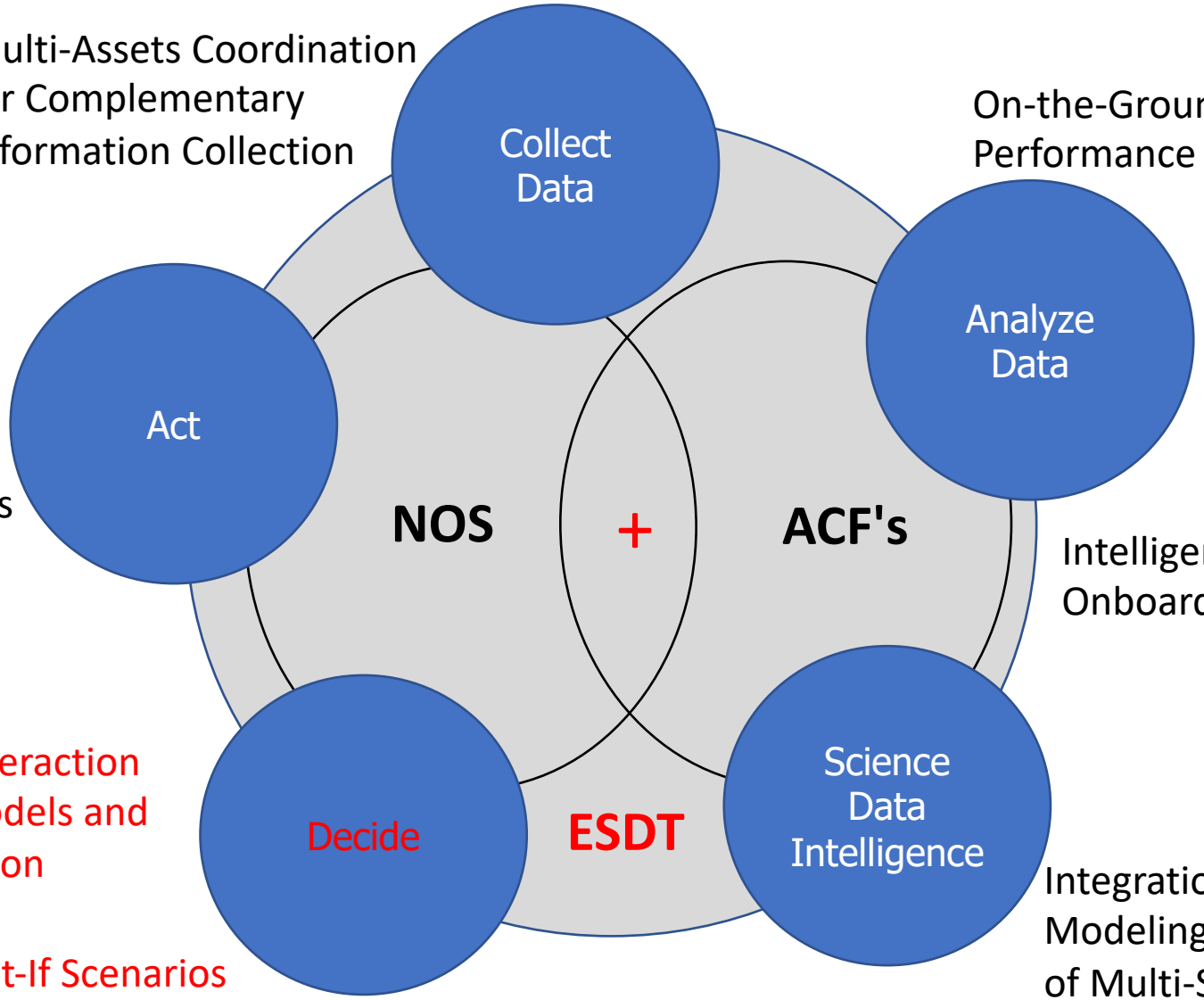


On-the-Ground High-Performance Computing Capabilities

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

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

Earth System Digital Twins (ESDT): New AIST-21 Thrust – *Continuous Integration of NOS and ACF Techs*



Multi-Assets Coordination for Complementary Information Collection

On-the-Ground and Onboard High-Performance Computing Capabilities

Dynamic Reaction to Science Events of Interest with Varying Latency Requirements

Intelligent Data Analytics Onboard and On-the-ground

Seamless Interaction between Models and Data Collection

What-If Scenarios

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

ESDT Technologies Requested in AIST-21

- Technologies for agile interaction and interoperability between measurement acquisition (NOS or NOS-like) and science investigations (ACF or ACF-like)
- Frameworks that enable data ingest from multiple, integrated models, and/or moving from mono-discipline to multi-discipline inter-related systems
- Leveraging of Model-Based System Engineering (MBSE) frameworks for the development and sustainment of Earth Systems Digital Twins, especially based on the integration and coordination of NOS and ACF systems
- Digital Thread developments to link all digital twin capabilities (design, performance data, product data, operational status data, event status data), to enable design requirements, records, provenance, and system reorientations to be easily reviewed and address issues within the digital twin system
- Concepts and technologies for developing "federated ESDTs" in which multiple individual ESDTs interact and can be integrated as the layers of broader ESDTs
- Novel AI (not limited to ML) techniques enabling systems to quickly request, integrate, and fuse diverse and timely Earth observations into ESDTs
- Investigative technologies to facilitate "what-if" investigations inherent to ESDT systems, including but not limited to:
  - Multi-scale simulations, statistics, uncertainty quantification, and causality methodologies
  - Computational algorithms and methodologies involving high-end computing, such as GPUs or other hardware systems that will enable running large permutations of what-if scenarios using large amounts of data and high-resolution and high-fidelity models
  - Statistical methodologies that optimize the computational efficiency of such "what-if" investigations
  - Innovative and simple user interfaces and visualization methods based on Augmented Reality (AR) and Mixed Reality (MR) techniques and capable of visualizing complex systems of systems

AIST-21 ESTD Awards

https://esto.nasa.gov/project-selections-for-aist-21

- **ESDT Infrastructure**

PI's Name	Organization	Title	Synopsis
Tanu Malik	De Paul University	Reproducible Containers for Advancing Process-oriented Collaborative Analytics	Aims to establish reproducible scientific containers that are easy-to-use and are lightweight. Reproducible containers will transparently encapsulate complex, data-intensive, process-oriented model analytics, will be easy and efficient to share between collaborators, and will enable reproducibility in heterogeneous environments.
Thomas Grubb	NASA Goddard Space Flight Center (GSFC)	Goddard Earth Observing System (GEOS) Visualization And Lagrangian dynamics Immersive eXtended Reality Tool (VALIXR) for Scientific Discovery	Proposes to develop a scientific exploration and analysis mixed augmented and virtual reality tool with integrated Lagrangian Dynamics (LD) to help scientists identify, track, and understand the evolution of Earth Science phenomena in the NASA GEOS model. It will provide both a scientific discovery tool and a model analysis and improvement tool.
Matthias Katzfuss	Texas A&M University (TAMU)	A scalable probabilistic emulation and uncertainty quantification tool for Earth-system models	Proposes to develop a fully automated toolbox for uncertainty quantification in Earth-system models, to provide insight into the largest and most critical information gaps and identify where potential future observations would be most valuable. It would allow interpolation between observed covariate values and running extensive what-if scenarios.
Thomas Clune	NASA Goddard Space Flight Center (GSFC)	A Framework for Global Cloud Resolving OSSEs	Will enable global, cloud-resolving Observing System Simulation Experiments (OSSEs) by addressing key computational challenges to enable existing technologies to scale to the spatial resolutions needed by the end of decade, e.g., extending parallel I/O capabilities, adopting a 2-phase Nature Run approach and a flexible API for customization.

AIST-21 ESTD Awards

https://esto.nasa.gov/project-selections-for-aist-21

- **AI-Surrogate Modeling for ESDT**

PI's Name	Organization	Title	Synopsis
Allison Gray	Univ. of Washington, Seattle	A prototype Digital Twin of Air-Sea Interactions	Proposes to develop hybrid physics-informed AI model that ingests several existing flux estimates and observation data products and train against simultaneous ocean-atmosphere data from Saildrones. This will ascertain uncertainty of existing flux measurements and optimize combination of near-real-time existing flux data and observational data => This represents the first step towards a Digital Twin for the Planetary Boundary Layer.
Christopher Keller	Morgan State University (MSU)	Development of a next-generation ensemble prediction system for atmospheric composition	Proposes to develop a next-generation modeling framework for the real-time simulation of reactive gases and aerosols in the atmosphere. Will deploy computationally efficient parameterizations of atmospheric chemistry and transport and will develop generative models based on machine learning (ML) to predict model uncertainties.
Jouni Susiluoto	NASA Jet Propulsion Laboratory (JPL)	Kernel Flows: emulating complex models for massive data sets	Proposes a general-purpose, versatile emulation tool to provide fast, accurate emulation with little tuning, to scale up to very large training sets, and to provide uncertainties associated with outputs. This tool set will facilitate large-scale implementation of forward modeling and retrievals, and of UQ at production scales. To be applied to SBG radiative transfer emulation & convective storm nowcasting.

AIST-21 ESTD Awards (cont.)

https://esto.nasa.gov/project-selections-for-aist-21

- **ACF Towards ESDT**

PI's Name	Organization	Title	Synopsis
Arlindo Da Silva	NASA Goddard Space Flight Center (GSFC)	An Analytic Collaborative Framework for the Earth System Observatory (ESO) Designated Observables	Will develop an Analytic Collaborative Framework for the Earth System Observatory (ESO) missions, based on realistic, science-based observing system simulations and the Program of Record (PoR), tied together in a cloud-based cyberinfrastructure. Create a 3D, holistic view of Earth with all ESO unique satellites.
Thomas Allen	Old Dominion University	Pixels for Public Health: Analytic Collaborative Framework to Enhance Coastal Resiliency of Vulnerable Populations in Hampton Roads, Virginia (VA)	Proposes to design and operationally demonstrate a system linking the VA Open Data Cube, a socio-spatial-health information “Digital Neighborhood” (Hampton Roads Biomedical Research Cons.), hydrodynamic models, and in-situ flood sensor network. Will connect observational and physical environmental domains with human vulnerability.
Thomas Huang	NASA Jet Propulsion Laboratory (JPL)	Fire Alarm: Science Data Platform for Wildfire and Air Quality	Proposes to advance AIST's Air Quality Analytics Collaborative Framework (AQACF) to establish a wildfire and air quality ACF, Fire Alarm, focusing on the prediction and analysis of wildfire, burned area and the air quality as an integrated platform to guide decision-makers, science researchers, and first-responders.

AIST-21 ESTD Awards (cont.)

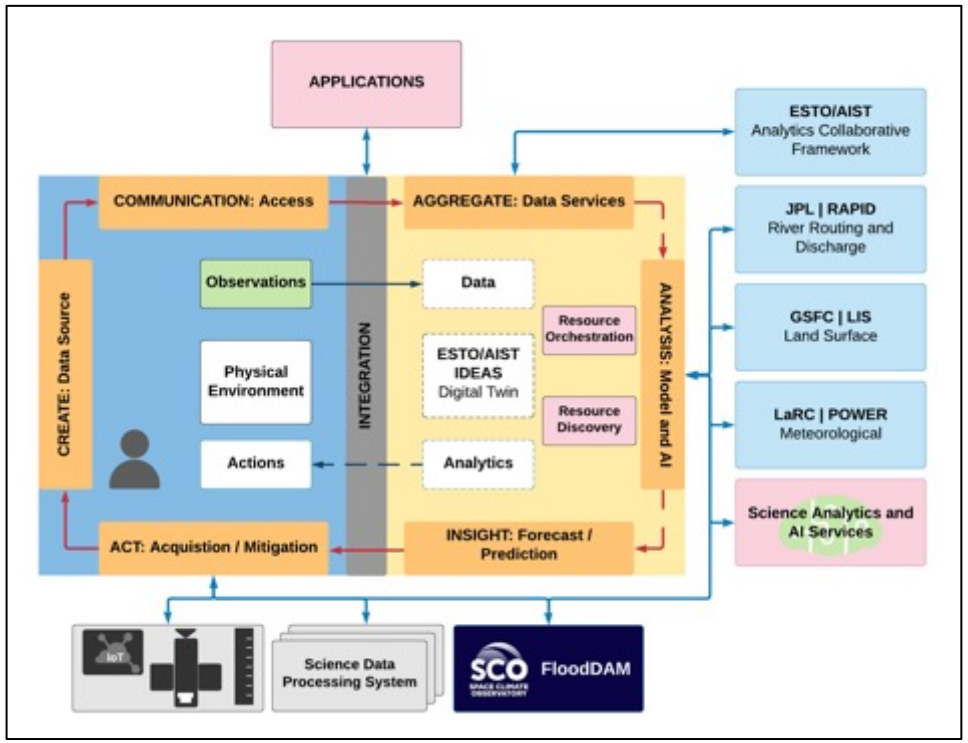
https://esto.nasa.gov/project-selections-for-aist-21

- **ESDT Prototypes**

PI's Name	Organization	Title	Synopsis
Milton Halem	University of Maryland, Baltimore County (UMBC)	Towards a NU-WRF based Mega Wildfire Digital Twin: Smoke Transport Impact Scenarios on Air Quality, Cardiopulmonary Disease and Regional Deforestation	Will develop and implement a Regional Wildfire Digital Twin (WDT) model with a sub-km resolution to enable the conduct of mega wildfire smoke impact scenarios at various spatial scales and arbitrary locations over N. America. WDT will provide a valuable planning tool for impact scenarios by season, location, intensity, and atmospheric state.
Rajat Bindlish	NASA Goddard Space Flight Center (GSFC)	Digital Twin Infrastructure Model for Agricultural Applications	Will develop an agriculture productivity modeling system over Continental United States as an example of incorporating representations of infrastructure-oriented process, for the understanding, prediction, and mitigation/response of Earth system process variability, with application to crop growth, yield, and agricultural production information, critical to commodity market, food security, economic stability, and government policy formulation.
Craig Pelissier	(SSAI)	Terrestrial Environmental Rapid-Replicating Assimilation Hydrometeorology (TERRAHydro) System: A machine-learning coupled water, energy, and vegetation terrestrial Earth System Digital Twin	Proposes to develop a terrestrial Earth System Digital Twin (TESDT) that couples state-of-the-art ML with NASA (and other) EO data. It will combine the best ML hydrology models with capabilities for uncertainty quantification and data assimilation to provide ensemble & probabilistic forecasting, sensitivity analyses, and counterfactual “what if'' experiments.

Integrated Digital Earth Analysis System (IDEAS) – *AIST Collaboration with CNES*

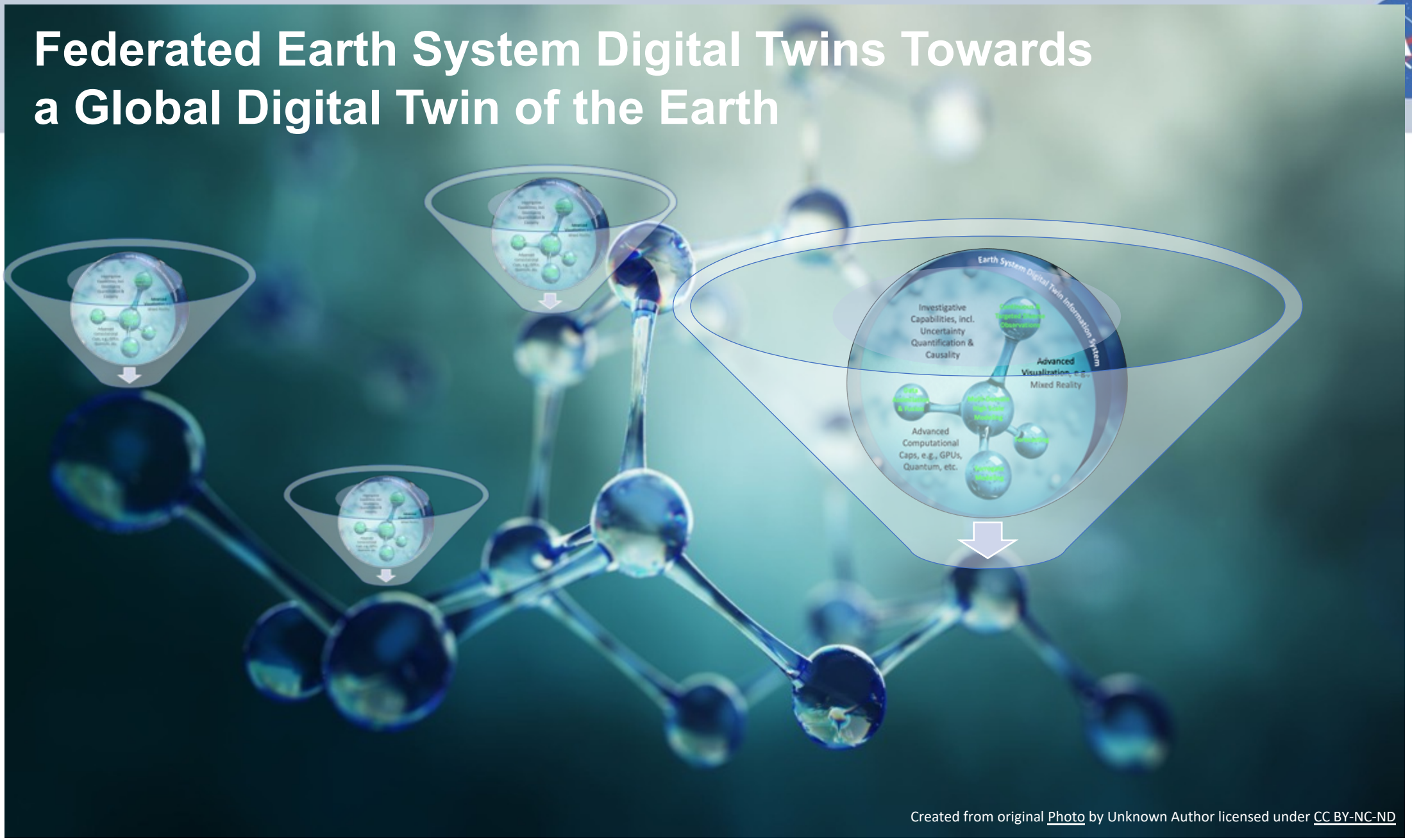
- **IDEAS is a NASA ESTO/AIST Earth System Digital Twin** project that bridges the physical environment and its virtual representation by continuously assimilating new observations to improve forecast and prediction for integrated science and decision support
- Using water cycle and flood analysis as the prototype application to integrate NASA, CNES, and Space Climate Observatory (SCO) data and science
- Multi-Agency and Multi-Center partnership
- Advanced numerical models and analysis
  - **JPL's RAPID**: Routing Application for Parallel computation of Discharge
  - **GSFC's LIS**: Land Information System
  - **LaRC's POWER**: Prediction of Worldwide Energy Resources
  - **CNES and SCO's FloodDAM:** Automated service to reliably detect, monitor and assess flood events globally
  - Integration with **NASA IPCC Sea Level Prediction** data for coastal flooding
  - Joint developed and trained flood detection and prediction machine learning algorithms
  - Promote and advance interoperable standards
- Improve the Machine Learning flood prediction model (Huang *et al.* 2020) from the JPL-CNES Joint Data Science pilot
- Scenario-based prediction for infrastructure and population impacts
- Ongoing formulation and planning with CNES and SCO's FloodDAM



IDEAS – Digital Twin for Water Cycle and Flood Detection and Monitoring

Jet Propulsion Laboratory, California Institute of Technology · Goddard Space Flight Center · Langley Research Center

Federated Earth System Digital Twins Towards a Global Digital Twin of the Earth




Questions?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