EXPLORE EARTH

National Aeronautics and Space Administration

NASA

New and Innovative Sensors and Instruments Development at NASA Earth Science Technology Office for Future missions

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The Annual Conference of the IEEE Photonics Society

IPC


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YOUR HOME, OUR MISSION

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ESTO

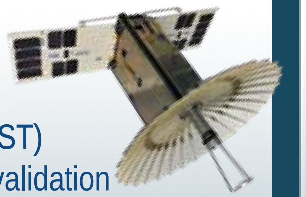
Earth Science Technology Program Elements

ESTO manages, on average, 120 active technology development projects. Most are funded through the primary program lines below. Over 800 projects have completed since 1998.

Advanced Technology Initiatives: ACT and InVEST

Advanced Component Technologies (ACT)
Critical components and subsystems for advanced instruments and observing systems

12 projects awarded in 2018
Solicitations planned in FY20, and FY23
Average selection rate: 16.4%



In-Space Validation of Earth Science Technologies (InVEST)
On-orbit technology validation and risk reduction for small instruments and instrument systems.

Four projects selected in FY18
Solicitations planned in FY21 and FY24
Average selection rate: 18.3%

Instrument Incubator Program (IIP)

Earth remote sensing instrument development from concept through breadboard and demonstration

17 projects awarded in FY17
Solicitation open in FY19
Solicitations planned in FY22 and FY25
Average selection rate: 23.2%

Advanced Information Systems Technology (AIST)

Innovative on-orbit and ground capabilities for communication, processing, and management of remotely sensed data and the efficient generation of data products

22 projects awarded in FY17
Solicitation open in FY19
Solicitations planned in FY21, FY23, and FY25
Average selection rate: 19.3%

Decadal Incubation

Maturation of observing systems, instrument technology, and measurement concepts for Planetary Boundary Layer and Surface Topography and Vegetation observables through technology development, modeling/system design, analysis activities, and small-scale pilot demonstrations

Solicitations planned in FY19 and FY21

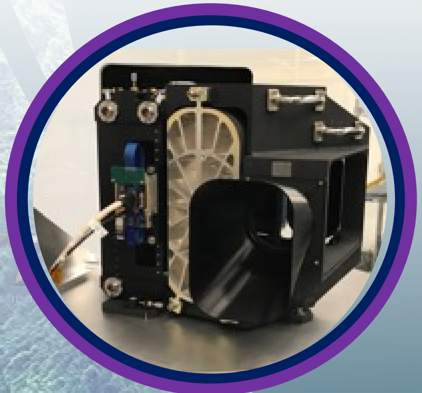
Other ESD Technology Activities Managed by ESTO

ESTO also manages specific sets of technology development and integration projects on behalf of the ESD Research and Flight programs.

Sustainable Land Imaging – Technology

Funded by the Flight Program, the **Sustainable Land Imaging-Technology (SLI-T)** program develops innovative technologies to achieve future land imaging (Landsat) measurements with more efficient instruments, sensors, components and methodologies.

First solicitation released in FY16
Solicitations planned in FY20
Average selection rate: 20.0%



Earth Venture Instruments – Technology

With funding from the Flight Program's Earth Systems Science Pathfinder (ESSP) program, the **Earth Venture Instruments – Technology (EVI-T)** program develops promising, highly-rated Earth Venture proposals that require additional technology risk reductions (average award: $5 - 8M)

First solicitation released in FY19;

Airborne Instrument Technology Transition

The **Airborne Instrument Technology Transition (AITT)** program provides campaign ready airborne instrumentation to support the objectives of the R&A Program. AITT converts mature instruments into operational suborbital assets that can participate in field experiments, evaluate new satellite instrument concepts, and/or provide calibration and validation of satellite instruments.

Ocean Biology and Biogeochemistry

With funding through the R&A Program, the **Ocean Color Remote Sensing Vicarious Calibration Instruments** program
develops in situ vicarious calibration instrument systems to maintain global climate-quality ocean color remote sensing of radiances and reflectances

A Flexible, Science-driven Strategy

- Competitive, peer-reviewed proposals enable selection of best-of-class technology investments
- Risks are retired before major dollars are invested: a cost-effective approach to technology development and validation
- Successful partnering establishes leveraging opportunities
- This approach has resulted in:

    a portfolio of emerging technologies that will enhance and/or enable future science measurements

    a growing number of infusion successes into science campaigns, instruments, applications, ground systems, and missions

ESTO Enables – Science Selects

ESTO BY THE NUMBERS

FY18 Project Stats

136 Projects Active in FY18

37 Projects Added

455 Co-Investigators

29 Projects Completed

60 Unique PI Organizations

139 Unique Co-I Organizations

107 Students Involved

4 CubeSats Launched

21 States

7 Projects Airborne-Tested

31 Universities

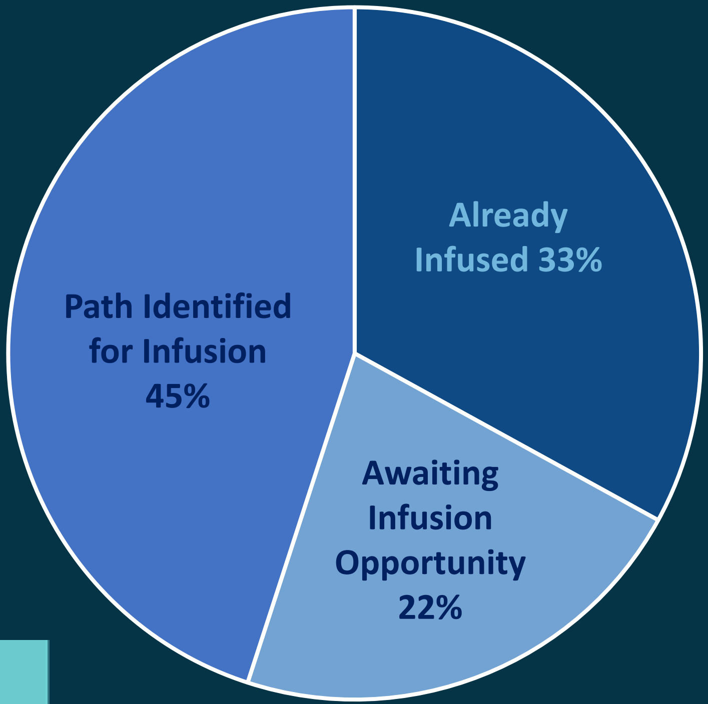
28 States

ESTO

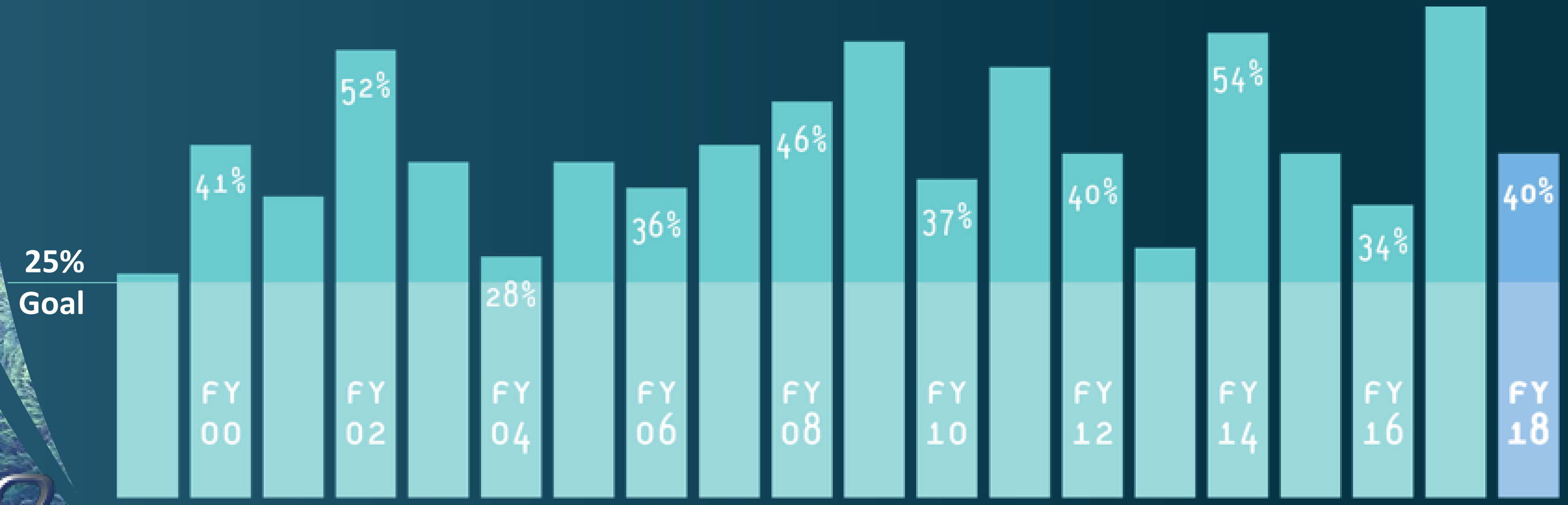
FY18 Program Metrics

Infusions

ESTO's all-time infusion success, drawn from 804 completed projects through the end of FY18. In this fiscal year, at least 6 ESTO projects achieved infusion into science measurements, airborne campaigns, data systems, or follow-on development activities.



TRL Advancement

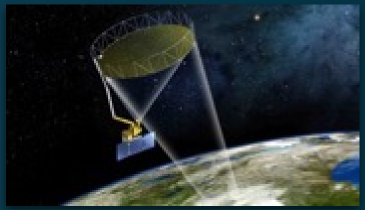


40% of ESTO technology projects funded during FY18 advanced one or more TRLs over the course of the fiscal year (9 advanced more than one TRL). The average TRL advancement for all years is 41%.

Science Driven : Enabling Earth Science Missions

Satellite Missions

Aquarius – Launched 2011
- Ultra-Stable Radiometers (B. Wilson, IIP-01)
- Lightweight Feed (S. Yueh, ACT-02)
- Calibration Subsystem (J. Peipmeier, ACT-99)



SMAP – Launched 2015
- Digital RFI Detector (C. Ruf, IIP-04)
- SoilScape Cal/Val sensor web (M. Moghaddam, AIST-08)

SWOT – Launch NET 2020
- Deployable Ka-band Antennas (M. Thompson, ACT-08)
- Precision Deployable Mast(G. Agnes, ACT-10)
- 3-frequency Microwave Radiometer (S. Reising, ACT-08)

CYGNSS – NET 2016
- GPS Reflection Wind Speed System (S. Katzberg, ATI-03)

TEMPO – NLT 2021
- GeoSpec Spectrograph (S. Janz, IIP-02)
- GEO-TASO UV-Vis spectrometer (J. Leitch, IIP-10)

Airborne Campaigns

Hurricane and Severe Storm Sentinel (HS3) – 2011-14
- HAMSR Sounding Radiometer (B. Lambrigsten, IIP-98)
- HIWRAP Ku- and Ka-band Radar (G. Heymsfield, IIP-04)
- Tropospheric Wind Lidar (B. Gentry, IIP-04)
- EPOS Operational Assessment Tools (S. Kolitz, AIST-11)

DISCOVER-AQ – 2011-15
- GEO-TASO UV-Vis spectrometer (J. Leitch, IIP-10)

AirMOSS – 2010-15
- Microwave Observatory of Subcanopy and Subsurface (M. Moghaddam, IIP-01)
- Land Information System for AirMOSS (Moghaddam, AIST-11)
- UAVSAR (S. Hensley, IIP-04)

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10-Year ESTO Infusions Snapshot (2008-2018)

Earth Science Flight Mission Infusions: 35
NASA: *AIRS, ASCENDS (pre-formulation work), CATS, CLARREO-PF, CSIM-FD, DESDyni/NISAR, EO-1, GEOCAPE, GPM, GRACE-2, GRACE-FO, MISR, MODIS, NISAR, SMAP, SWOT;* **Other Government Agencies:** *COSMIC-2, COSMO-SkyMed, MicroMAS, NOAA/EUMETSAT Sentinel-6*

Other (non-ESD) Flight Mission Infusions: 13
NASA: *ARRM, CubeSat Hydrometric Atmospheric Radiometer Mission-CHARM, NASA DSN / NSF Green Bank Telescope, Interplanetary NanoSat Pathfinder In Relevant Environment (INSPIRE) mission, ISS Raven, Restore-L, RRM3, SDO;* **Other Government Agencies:** *AFRL Mid-Star, Air Force Enterprise Ground System*

Earth Venture Infusions: 37 ***(20 out of 26, or 77%, of Earth Venture selections include ESTO heritage)***
EV-Suborbital: *ABOVE, ACT-America, ACTIVATE, AirMOSS, ATTREX, CARVE, Delta-X, DISCOVER-AQ, HS3, IMPACTS, NAAMES, OMG, ORACLES, S-MODE;* ***EV-Instrument:*** *ECOSTRESS, GEDI, MAIA, TEMPO, TROPICS;* ***EV-Mission:*** *GeoCarb;* ***EV-ITechnology:*** *TEMPEST-D*

Airborne Campaign Infusions: 21
NASA: *Cloud Radar System, CORAL, Deep Convective Cloud & Chemistry (DC3) Field Campaign, GCPEX, GRIP, IceBridge, IceSat Gap Filler, MB08, Mid Latitude Continental Convective Clouds Experiment (MC3E), MIZOPEX, Polar Winds, SMAPVEX08, UAVSAR;* **Other Government Agencies:** *NSF-ORCAS, State of California-Great Southern CA Shakout, DoE-TCAP, Virginia Coastal Energy Research Consortium - Offshore Wind Turbine Study;* **Industry:** *Chevron – Airborne Methane Campaign*

Data Centers/Data Access: 10
NASA: *Giovanni, NASA Unified Weather Research & Forecasting (NU-WRF), NCCS DASS, TCIS, TOPS-NEX;* **Other Government Agencies:** *CEOS/GEOSS, Various In-situ Sensor Webs, NOAA ESRL, NSF Semantic eScience Framework, USGS Hawaiian Volcano Observatory;* **Other:** Various In-situ Sensor Webs

Commercial Application: 2
Boeing Next-gen ComSat, Navy Anti-Submarine Warfare Continuous Trail Unmanned Vessel (ACTUV)

AO Proposal Infusions: 2
Athena-OAWL, Discovery-Lunar Volatiles Orbiter

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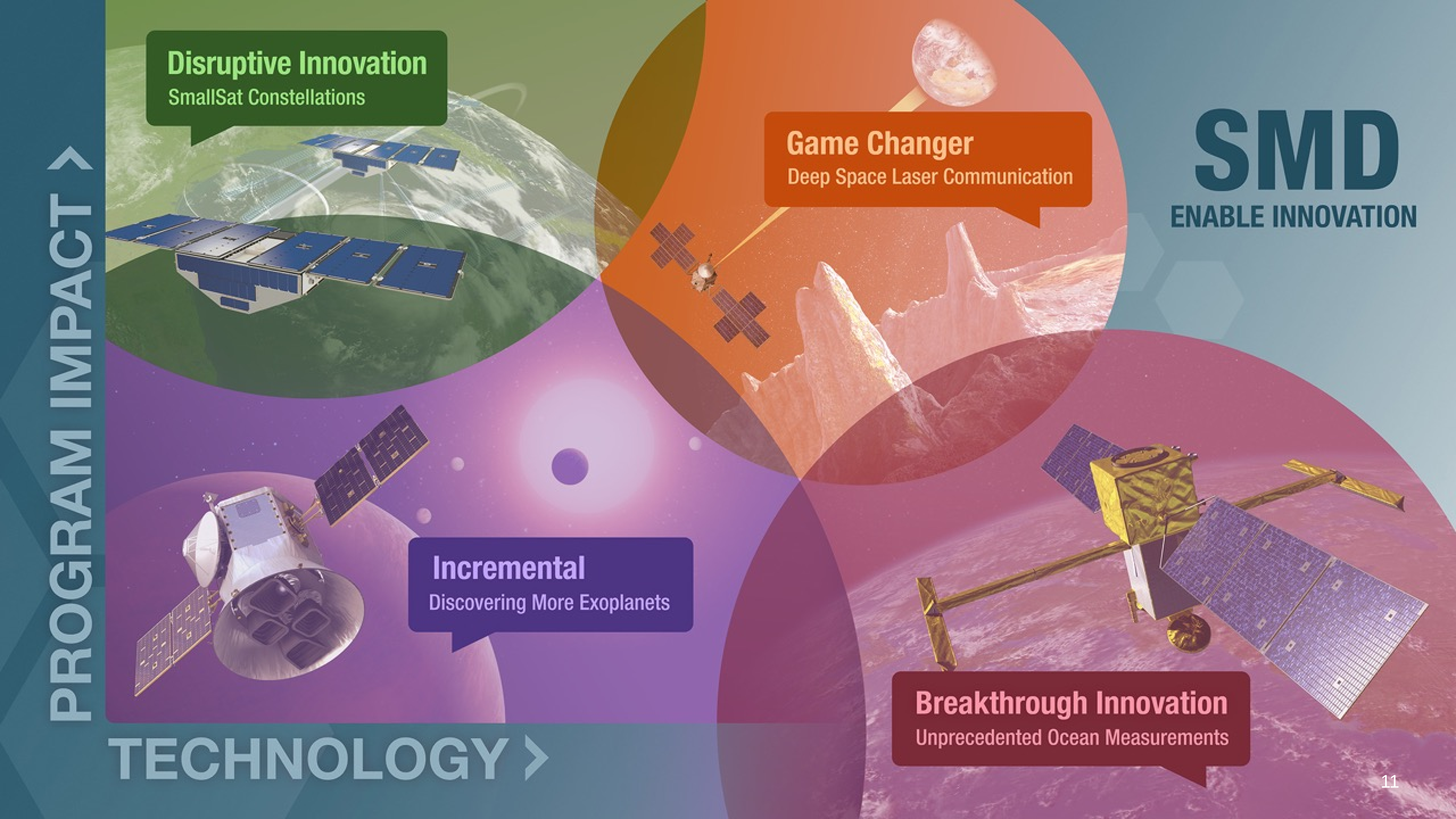
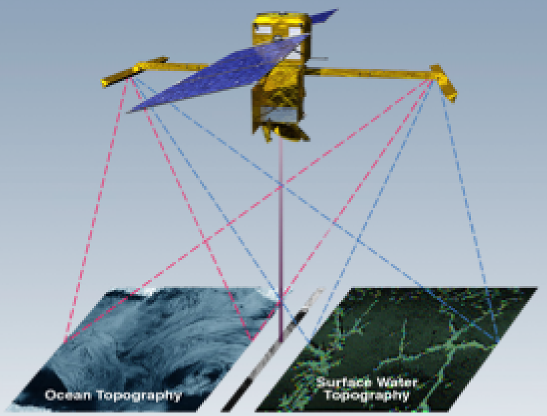
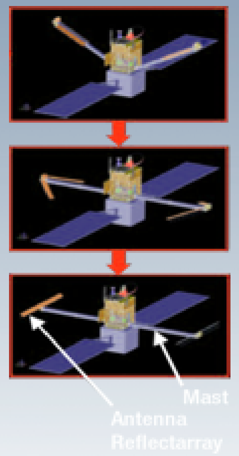

SMD
ENABLE INNOVATION
Disruptive Innovation
SmallSat Constellations
Game Changer
Deep Space Laser Communication
Incremental
Discovering More Exoplanets
Breakthrough Innovation
Unprecedented Ocean Measurements
PROGRAM IMPACT ›
TECHNOLOGY ›

Breakthrough Innovation

Surface Water and Ocean Topography (SWOT) Mission

CONCEPT	TECHNOLOGY	IMPLEMENTATION



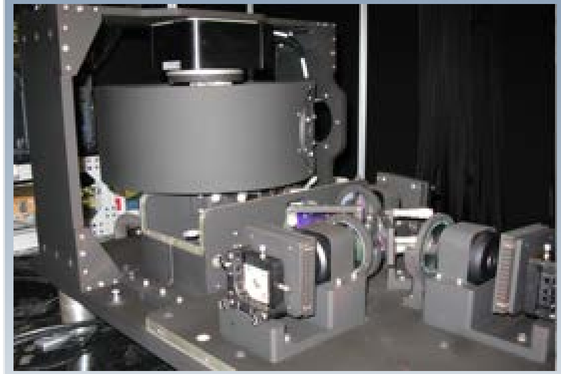
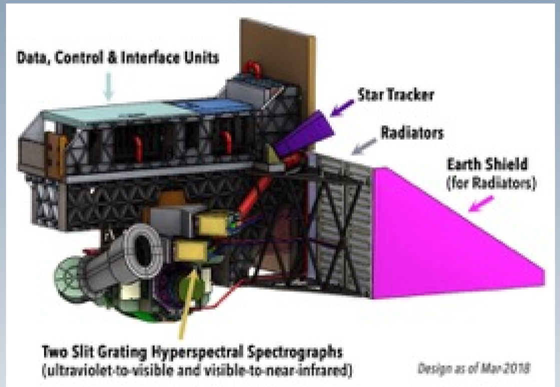


Enabling Technology *Investments in Ka-band interferometer and precision antenna mast*

Result *Unprecedented swath measurements of terrestrial water heights and sea surface heights (SWOT to launch in 2020)*

Breakthrough Innovation

PACE Ocean Color Imager (OCI)

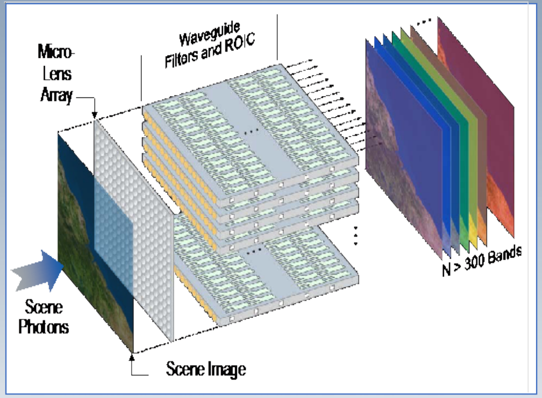
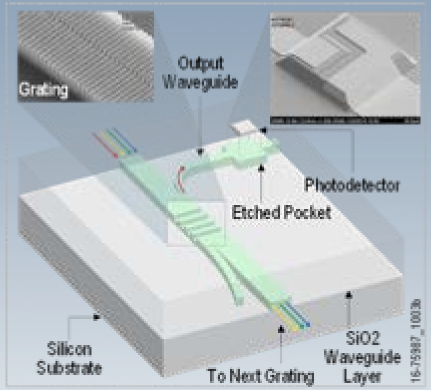
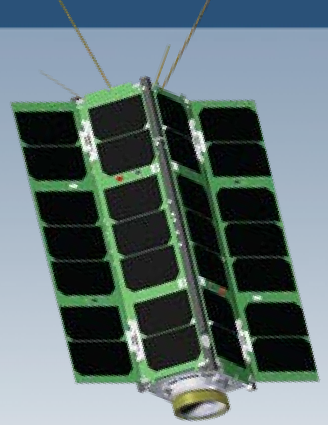
CONCEPT	TECHNOLOGY	IMPLEMENTATION
 Ocean Radiometer for Carbon Assessment (ORCA)	 Ocean Color Instrument (OCI)	

Enabling Technology *ESTO investments in multiple IIP awards for ORCA instrument*

Result *When PACE program was initiated, ORCA instrument was baseline Ocean Color Instrument. IIP investments were vital in quick start of the program.*

Breakthrough Innovation

Photonic Integrated Circuit based Photonic Spectrometer

CONCEPT	TECHNOLOGY	IMPLEMENTATION
		

Photonic Integrated Circuit

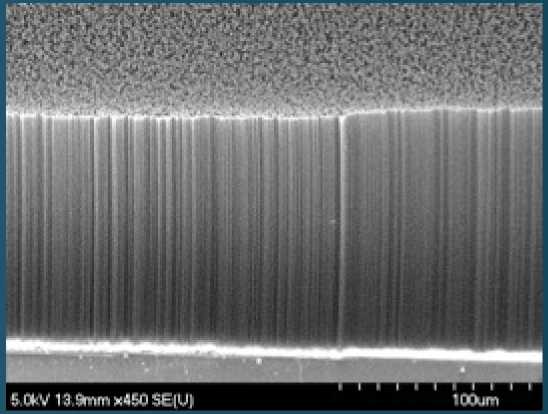
Hyperspectral Imaging CubeSat

Enabling Technology *Recent technology advances in Silicon based Photonic Integrated Circuits (PIC) taking advantage of developments in CMOS IC's development*

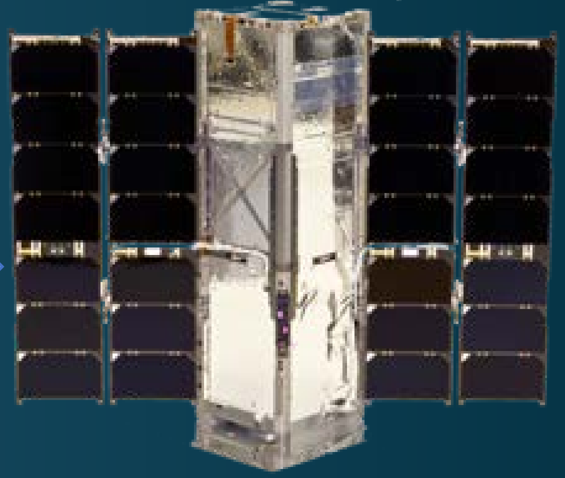
Result *Development of technology that will lead to PIC based ultra compact hyperspectral imagers*

Technology Advancement Example

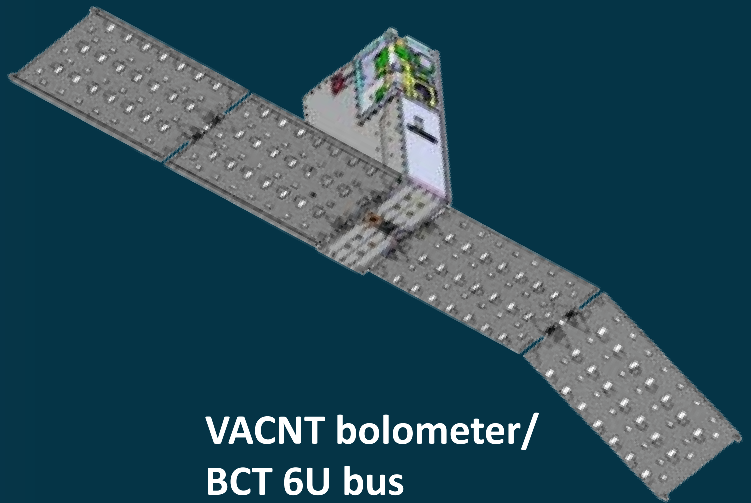
VACNT technology evolution



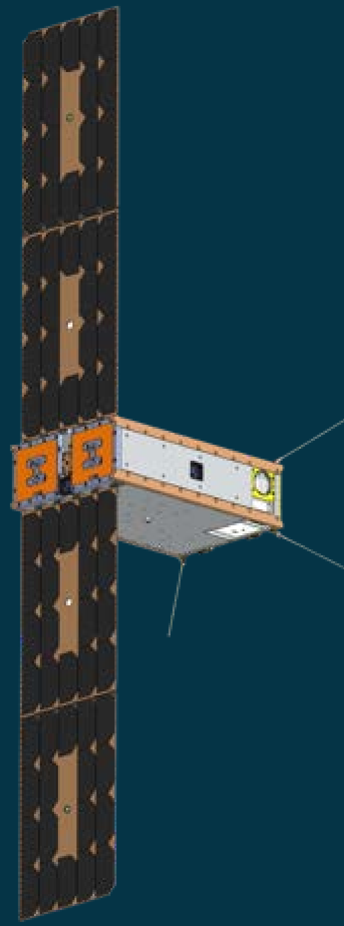
VACNT low-TRL development (2003–2012)
APL IRAD; NASA



VACNT, Ga BB demonstration
BCT 3U bus
RAVAN (2016)
NASA ESTO InVEST



VACNT bolometer/
BCT 6U bus
LASP CSIM-FD (2018)
NASA ESTO ACT, IIP, FD



VACNT bolometer/
BCT 6U bus
LASP CTIM (2020)
NASA ESTO InVEST

VACNT emitter; Ga BB
LaRC/APL Trutinor next-gen “CERES”
LaRC IRAD, NASA ESTO IIP proposal

Technology Advancement Example

TEMPEST-D Technology Advancement

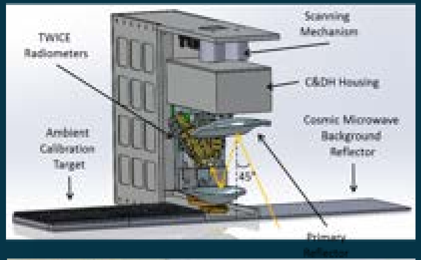
NASA ACT
CSU/JPL

2009-2012

NASA IIP
CSU/JPL/UCLA

2011-2015

NASA IIP
CSU/JPL/NGC



2014-2019

NASA Earth
Venture Tech
CSU/JPL/BCT

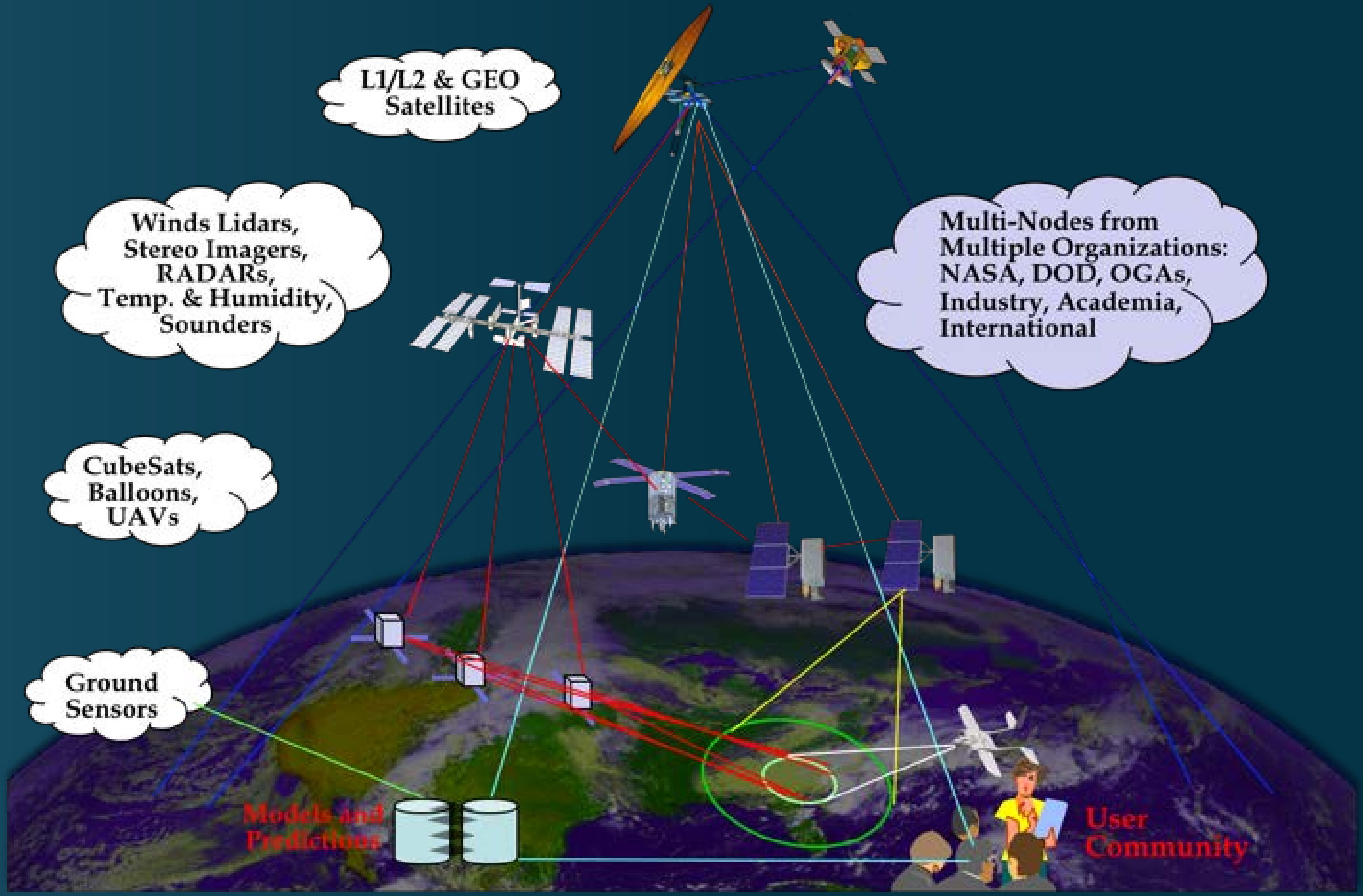
2015-present

Advanced Information Systems Technology (AIST)

New Observing Strategies (NOS)

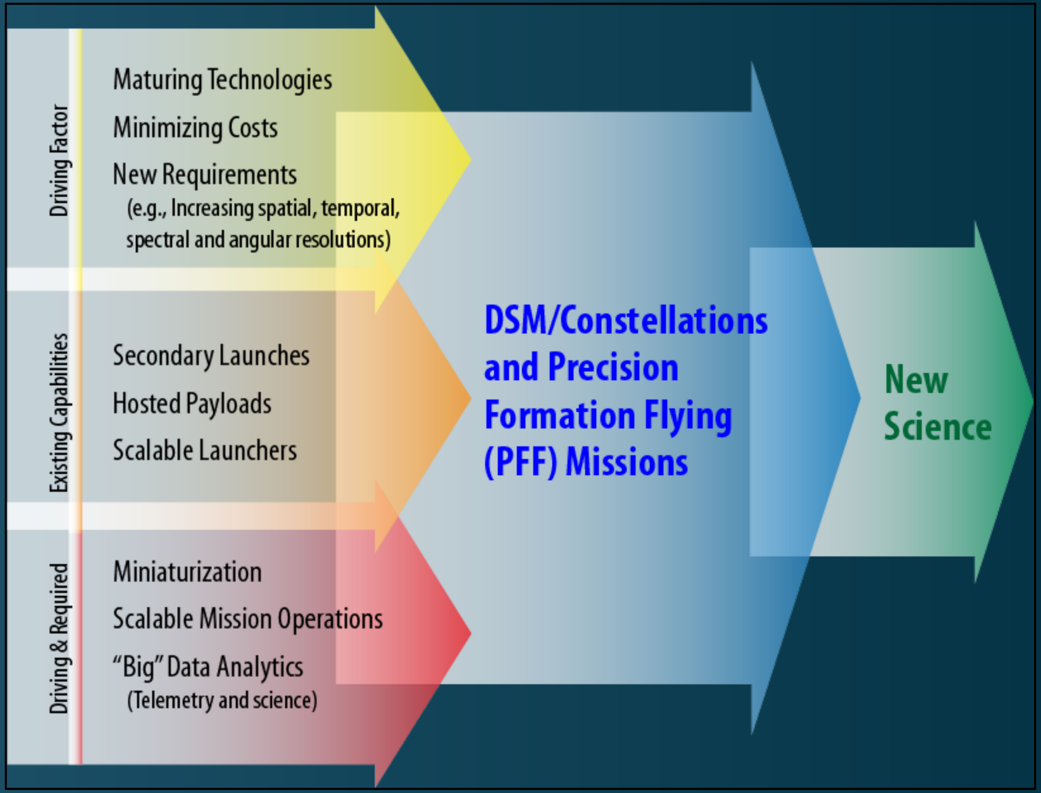
New Observing Strategies:

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



NOS Environment

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



NOS will:

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

NOS Goals:

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

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DSM/ICC and Sensor Webs

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

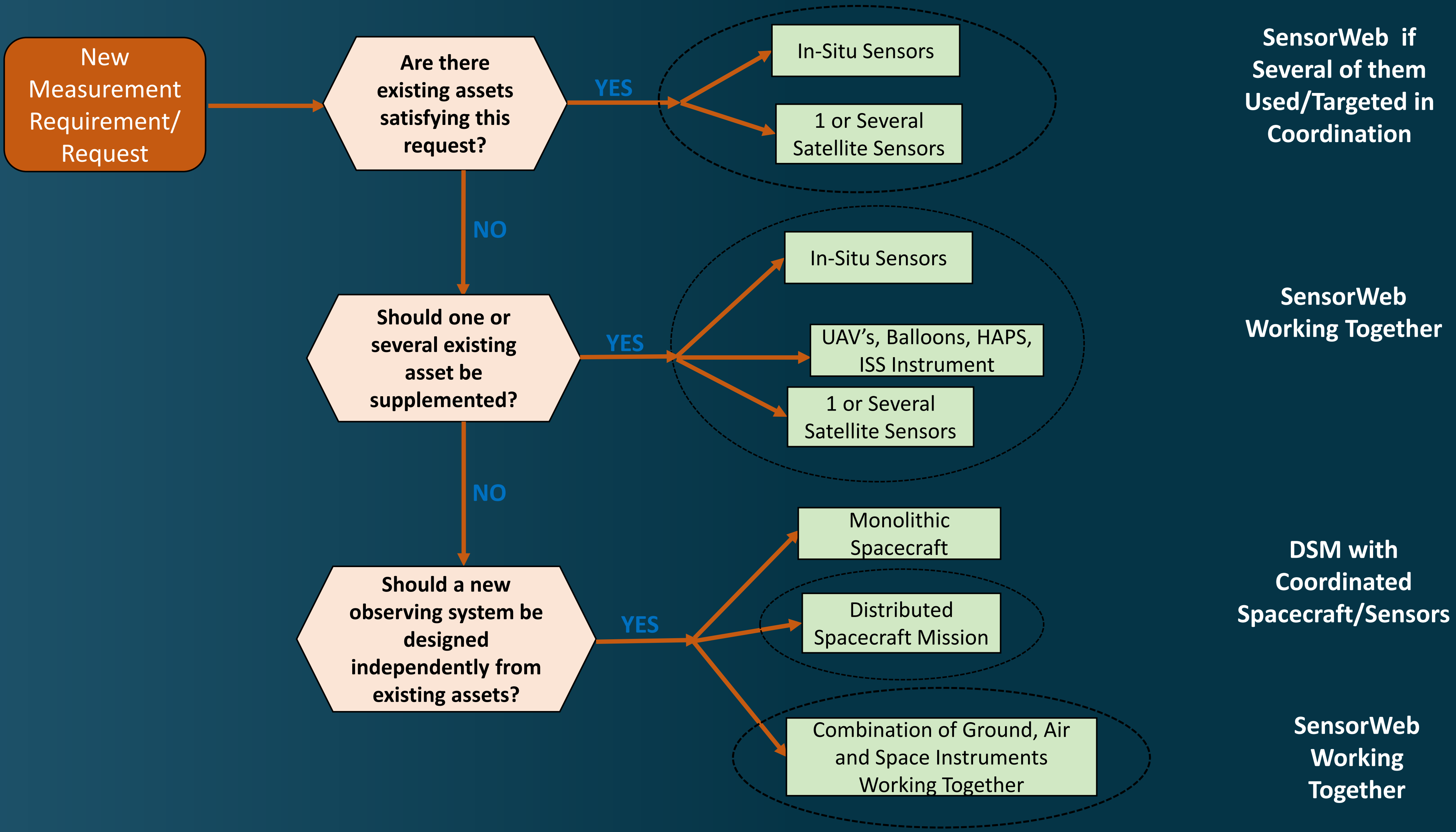
- Real-time data understanding
- Situational awareness
- Problem solving
- Planning and learning from experience
- Communications and cooperation between multiple S/C.

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

NOS Drivers

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

New Observing Strategies (NOS) – Measurement Acquisition (“Mission” Design or Model-Driven)



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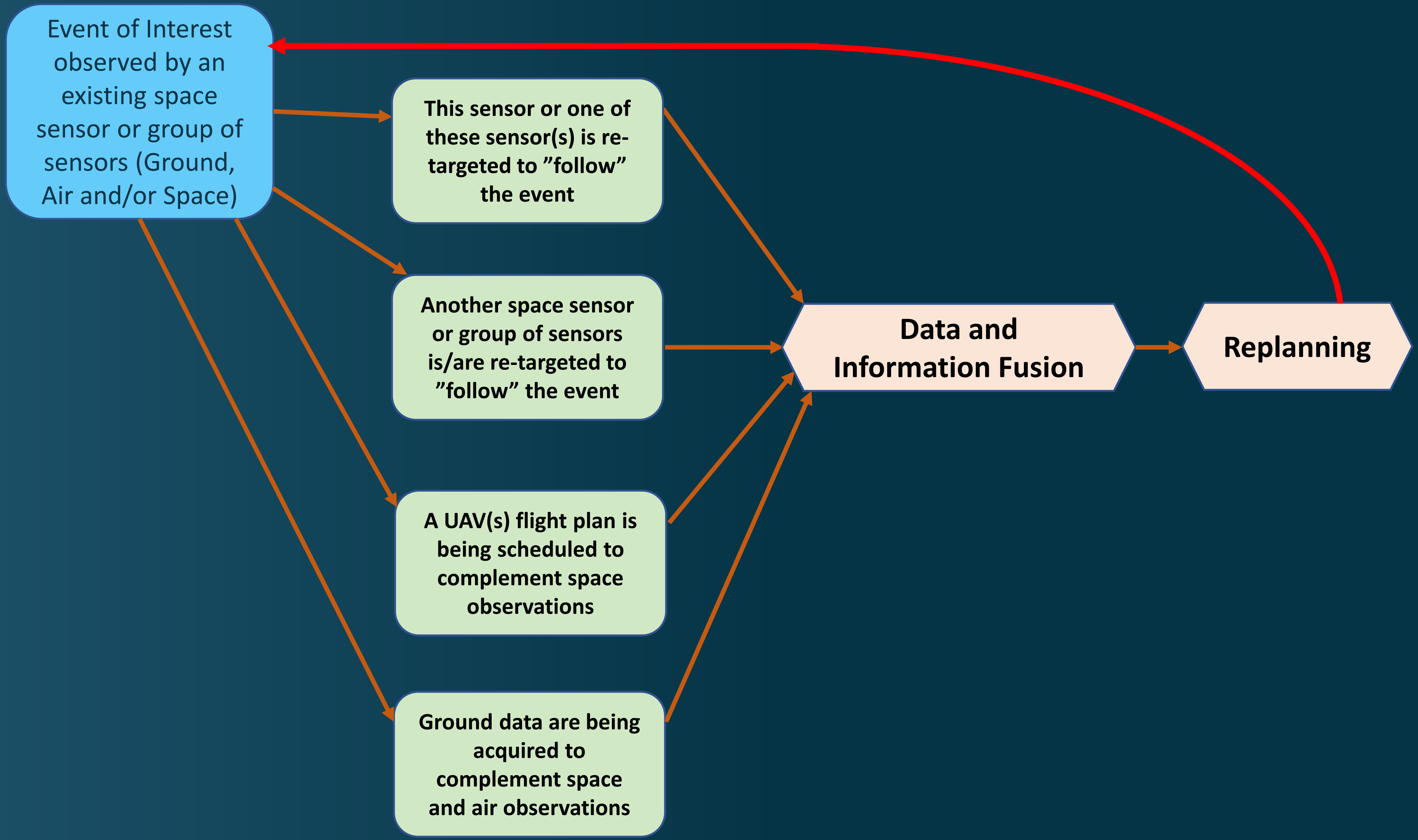
NOS Enables Earth Science

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

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

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

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



NOS for Candidate Science Needs

- **Hydrology**
  - River flow and Flooding
  - Snow fall in 3D
  - Aquifer degradation
- **Precipitation**
  - Extreme precipitation events
- **Cryosphere**
  - Glaciers changes
  - Sea Ice changes

Urban Air Quality Events

- At a resolution (vertical and horizontal)

- **Biodiversity**
  - Migrations
  - Invasive species
  - Transient spring phenomena
- **Solid Earth and Interior**
  - Landslides
  - Plate movement
  - Volcanic activity
  - Interior magma movement

Disaster Management

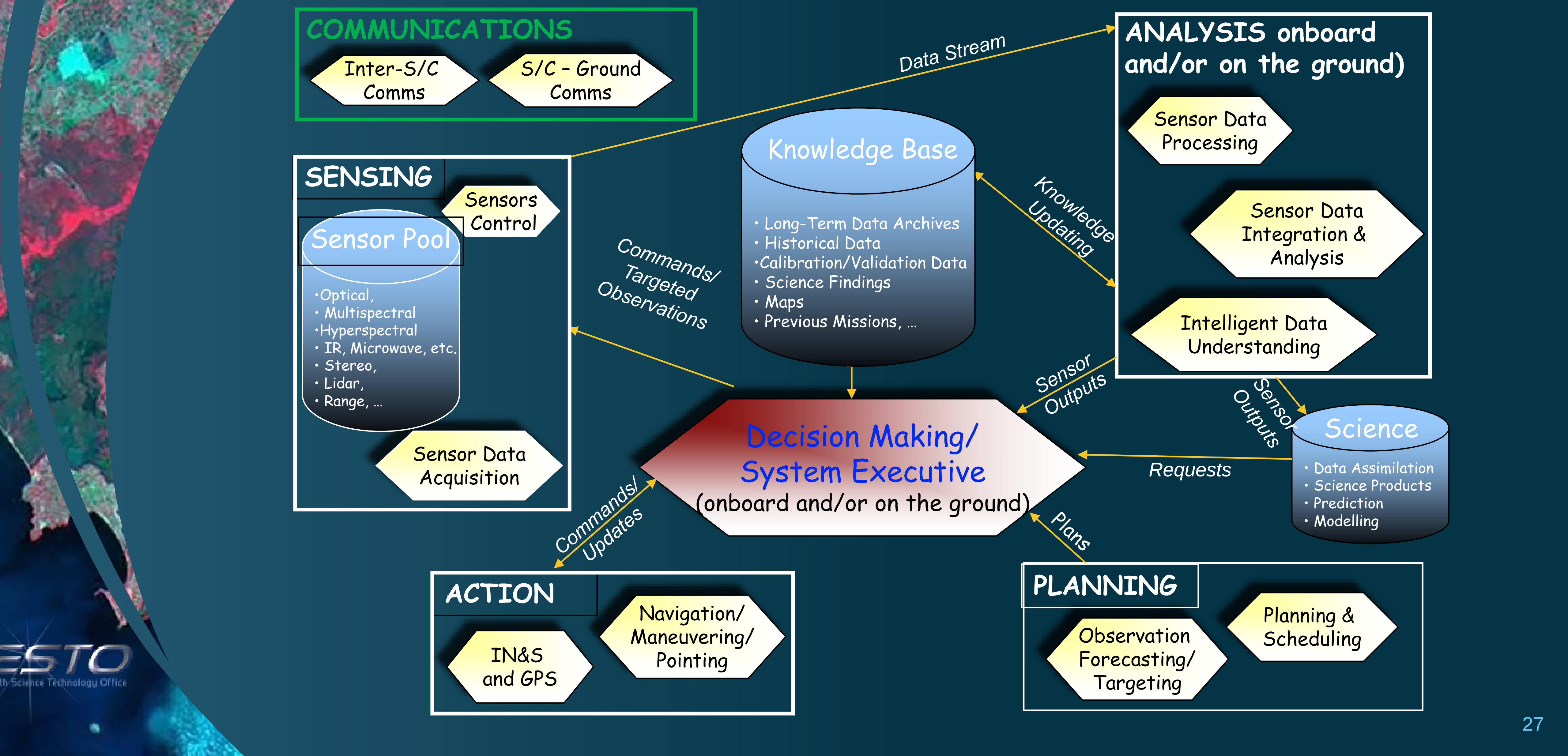
- Floods
- Earthquakes
- Volcanic Eruptions

Example of an Hydrology Use Case

Flood Monitoring with Space and Ground Sensors

1. A weather forecast or radar image indicates the potential for flood-inducing precipitation.
2. This triggers a network of ground-based sensors measuring changes in overland flow to begin telemetering data at high frequency.
3. When the ground sensors detect change in overland flow, they trigger a series of additional measurements:
    a. Space-based measurements, e.g., combination of space-based optical and radar, to determine surface water extent.
    b. In-situ measurements taken by either USGS technicians or future in-situ or UAS-mounted sensors, to measure high water level.
    c. A constellation of radar CubeSats is tasked to take targeted multi-angle measurements

NOS Testbed – System Architecture



Cultural Change is Needed

Technology Community Resistance

- Lack of familiarity and a new direction
- Leisurely pace of technology development in Government environments

Science Community Resistance

- Perceived risk of new measurement techniques and unproven technologies
- Lack of confidence

Flight Community Resistance

- Consider a mission to be an entire suite of observations of a phenomenon
- New Mission Ops Model with autonomy and management

Confidence must be built within the Science and Flight Communities

- Conduct well designed experiments early and get a science team buy-in
- Demonstrate components at earliest possible date and keep using them
- Communications plan to reduce the lack of familiarity
- InVEST experiments and demonstrations
- Open conversation, not isolated experiments

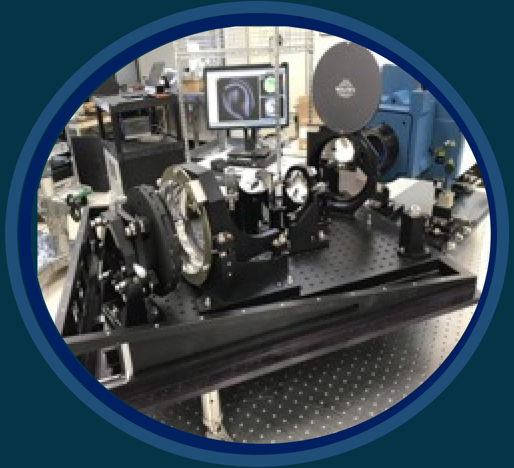
Sustainable Land Imaging Technology

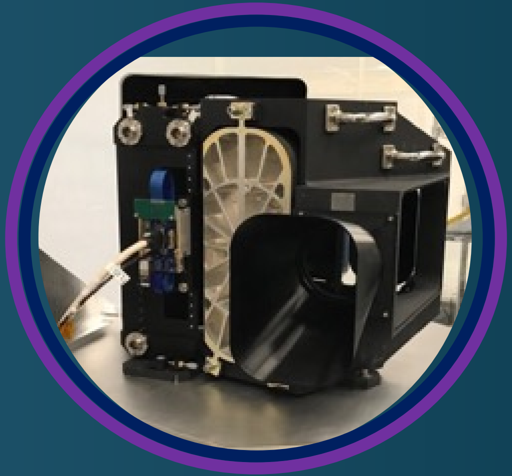
SLI-T 15 Advanced Technology Demonstrations

Thomas Kampe,

Ball Aerospace & Technology Corporation

Mature Ball Compact Hyperspectral Prism Spectrometer(CHPS) small form factor VSWIR imaging spectrometer for SLI Demo mission. Advance TRL through airborne demonstration validating instrument low stray light performance





Jeff Puschell, Raytheon

Demonstrate compact low mass Advanced Technology Land Imaging Spectrometer (ATLIS) design approach with wide field of view (WFOV, freeform fast optics, large format small detector digital FPS and on-chip Time delay Integration (TDI) to SLI-T VSWIR requirements

Dennis Nicks,

Ball Aerospace & Technology Corporation

Develop a compact multispectral instrument for SLI and perform an airborne demonstration. Key technologies include: scan mechanism to perform step-stare motion, jitter removal, and image motion correction.

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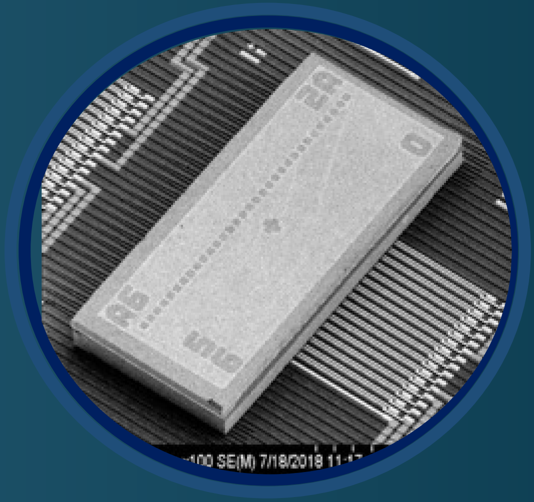
SLI-T 15 Technology Investments

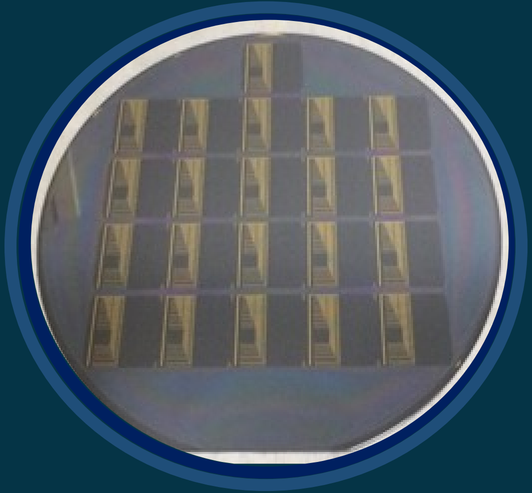
David Ting, NASA Jet Propulsion Laboratory

Demonstrate a high-performance long-wavelength infrared (LWIR) focal plane array (FPA) technology with the flexibility to meet a variety of possible future land imaging needs.



Stephanie Sandor-Leahy, Northrop Grumman

Develop next-generation compact SLI instrument based on NGAS photonic waveguides. Reduce instrument volume by x25, mass by x7 compared to current multispectral approach

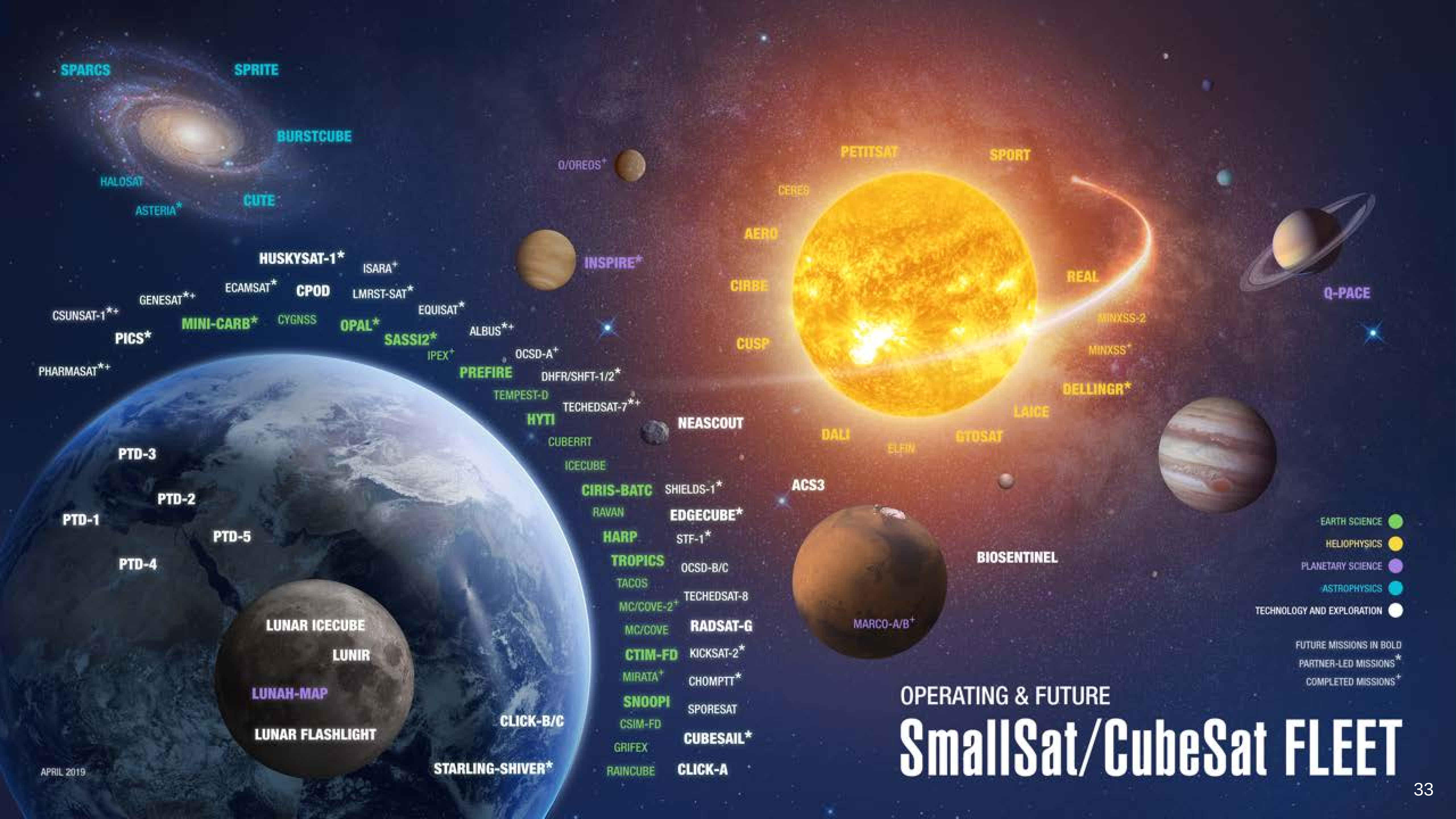


S J Ben Yoo, UC Davis

Design, fabrication and testing of an electro-optical (EO) imaging sensor concept that provides a low mass, low volume alternative to the traditional bulky optical telescope and focal plane detector array

In-Space Validation of Earth Science Technology (InVEST)

InVEST is on-orbit technology validation and risk reduction for small instruments and instrument systems.



SPARCS
SPRITE
BURSTCUBE
HALOSAT
ASTERIA*
CUTE
O/OREOS+
INSPIRE*
HUSKYSAT-1*
ISARA+
ECAMSAT*
CPOD
LMRST-SAT*
GENESAT*+
CSUNSAT-1*+
MINI-CARB*
CYGNSS
OPAL*
EQUISAT*
SASSI2*
ALBUS*+
PICS*
IPEX+
OCSD-A+
PHARMASAT*+
PREFIRE
DHFR/SHFT-1/2*
TEMPEST-D
TECHEDSAT-7*+
HYTI
NEASCOUT
CUBERRT
ICECUBE
CIRIS-BATC
SHIELDS-1*
RAVAN
EDGECUBE*
HARP
STF-1*
TROPICS
OCSD-B/C
TACOS
MC/COVE-2+
TECHEDSAT-8
MC/COVE
RADSAT-G
CTIM-FD
KICKSAT-2*
MIRATA+
CHOMPTT*
SNOOPI
SPORESAT
CSIM-FD
CUBESAIL*
GRIFEX
RAINCUBE
CLICK-A
PTD-3
PTD-2
PTD-1
PTD-5
PTD-4
LUNAR ICECUBE
LUNIR
LUNAH-MAP
LUNAR FLASHLIGHT
CLICK-B/C
STARLING-SHIVER*
APRIL 2019
PETITSAT
SPORT
CERES
AERO
CIRBE
CUSP
REAL
MINXSS-2
MINXSS+
DELLINGR*
LAICE
GTOSAT
DALI
ELFIN
ACS3
Q-PACE
BIOSENTINEL
MARCO-A/B+
EARTH SCIENCE
HELIOPHYSICS
PLANETARY SCIENCE
ASTROPHYSICS
TECHNOLOGY AND EXPLORATION
FUTURE MISSIONS IN BOLD
PARTNER-LED MISSIONS*
COMPLETED MISSIONS+
OPERATING & FUTURE
SmallSat/CubeSat FLEET


NASA EARTH FLEET
OPERATING & FUTURE THROUGH 2023
LANDSAT-9
NISAR
TROPICS (6)
SENTINEL-6A/B
SWOT
MAIA
PACE
TEMPO
ICESAT-2
GRACE-FO (2)
CYGNSS (8)
NISTAR, EPIC (DSCOVR/NOAA)
SORCE
CLOUDSAT
TERRA
AQUA
AURA
CALIPSO
GPM
LANDSAT 7 (USGS)
LANDSAT 8 (USGS)
OCO-2
OSTM/JASON 2 (NOAA)
SMAP
SUOMI NPP (NOAA)
TSIS-2
PREFIRE (2)
GEOCARB
GLIMR
ISS INSTRUMENTS
EMIT
CLARREO-PF
GEDI
SAGE III
OCO-3
TSIS-1
ECOSTRESS
LIS
JPSS-2, 3 & 4 INSTRUMENTS
OMPS-Limb
09.10.19
INVEST/CUBESATS
RAVAN
RainCube
CSIM
CubeRRT
TEMPEST-D
CIRiS
HARP
CTIM
HyTI
SNoOPI
NACHOS
(PRE) FORMULATION
IMPLEMENTATON
PRIMARY OPS
EXTENDED OPS

NASA Earth Science

Missions: Present through 2023

- (Pre)Formulation
- Implementation
- Primary Ops
- Extended Ops

ISS Instruments

LIS (2020), SAGE III (2020)
TSIS-1 (2018), OCO-3 (2019),
ECOSTRESS (2019), GEDI (2020)
CLARREO-PF (2020), EMIT (TBD)

JPSS-2 Instruments

OMPS-Limb (2018)

PREFIRE (2) (TBD)
PACE (2022)
TSIS-2 (2020)
GeoCARB (~2021)
TROPICS (12) (~2021)
MAIA (2020)
Landsat 9 (2020)
Sentinel-6A/B (2020, 2025)
NISAR (2021)
SWOT (2021)
TEMPO (2018)
ICESat-2 (2021)
GRACE-FO (2) (2023)
CYGNSS (8) (2019)
SMAP (>2022)
Landsat 7 (USGS) (~2022)
SORCE, TCTE (NOAA) (2019)
NISTAR, EPIC (DSCOVR / NOAA) (2019)
Suomi NPP (NOAA) (>2022)
Terra (>2021)
Landsat 8 (USGS) (>2022)
Aqua (>2022)
CloudSat (2021)
GPM (>2022)
CALIPSO (>2022)
Aura (>2022)
OCO-2 (>2022)
OSTM/Jason-2 (NOAA) (>2022)

InVEST/CubeSats

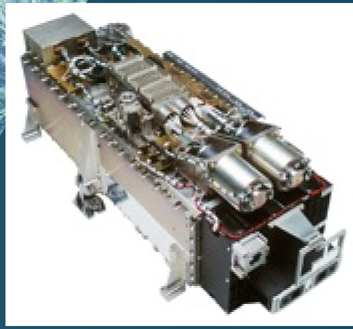
RAVAN (2016)
RainCube (2018)
TEMPEST-D (2018)
CubeRRT (2018)
CSIM (2018)
CIRiS (2019)
HARP (2019)
SNoOPI*
HyTI*
CTIM*
NACHOS*

** Launch date TBD*

05.09.19

Mission Evolution: From a Large Satellite to CubeSat

Compact Spectral Irradiance Monitor (CSIM) Flight Follow-On



SORCE SIM (launched 15 Jan 2003)

- Two channel instrument (duty-cycled for stability corrections)
- Absolute ESR detector (NiP bolometer)
  - First generation (Noise 3 nW @ 40 sec.)
  - Diamond substrate
  - NiP black absorber
  - Kapton™ thermal link
- Abs. accuracy: 2-10% wavelength dependent (no-SI validation)

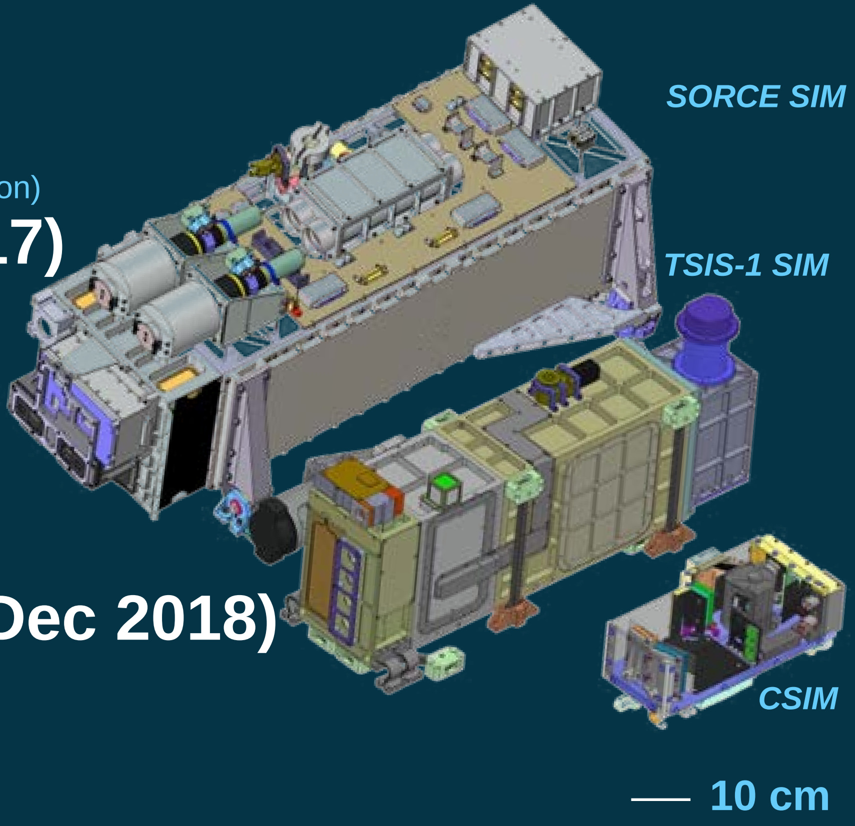
TSIS SIM (launched 15 Dec 2017)

- Three channel instrument
  - For long-term stability validation of duty-cycling
- Absolute ESR detector (NiP bolometer)
  - Second gen. (Noise 1.6 nW @ 40 sec.)
  - Diamond substrate
  - NiP black absorber
  - Kapton™ thermal link
- Abs. accuracy – 0.2 % (SI-traceable validation)

CSIM 6U CubeSat (launched 3 Dec 2018)

- ✓ Two channel instrument (duty-cycled)
- ✓ Absolute ESR detector (VACNT bolometer)
  - Third gen. (Noise 0.2 nW @ 40 sec.)
  - Silicon substrate
  - VACNT black absorber
  - SiNx thermal link
- ✓ 200-2400 nm (continuous)
- ✓ Abs. accuracy – 0.2 % (SI-traceable validation)

Relative instrument size comparison



CSIM represents a significant reduction in mass (1/10th), volume (1/20th), and flight ready costs and maintains maximum performance to meet SSI measurement requirements

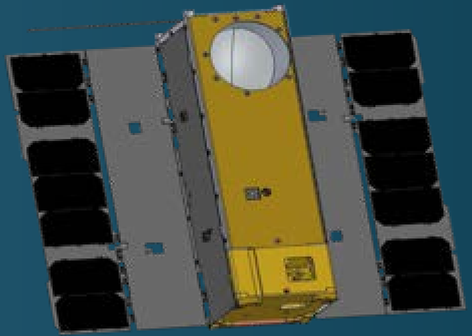
ESTO InVEST 2012 Program

U-Class Satellites Advancing TRLs for Future Earth Science Measurements

MiRaTA

MIT / MIT-LL

Launched: July 2017



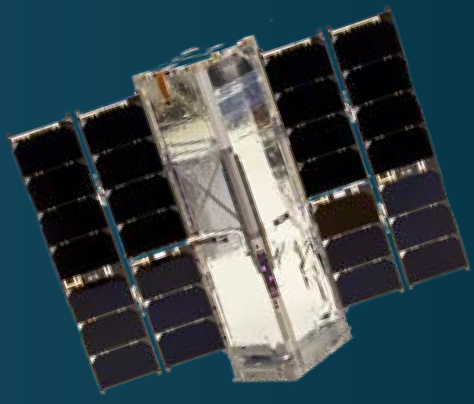
3 Frequency Radiometer and GPSRO

Validate new microwave radiometer and GPSRO technology for all-weather sounding

RAVAN

APL

Launched: Nov 2016



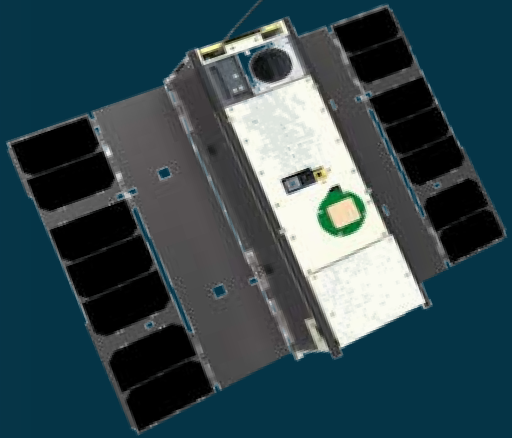
Vertically Aligned Carbon Nanotubes (VACNTs)

Demonstrate VACNTs as radiometer absorbing material and calibration standard for total outgoing radiation

IceCube

GSFC

Launched: March 2017



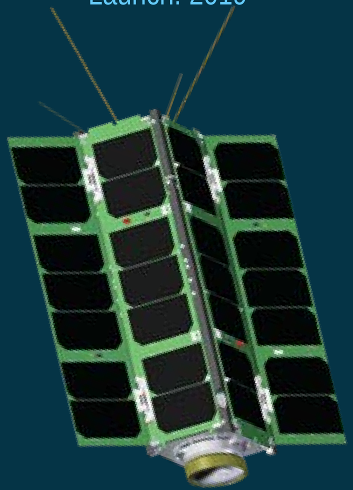
883 GHz submm-Wave radiometer

Validate sub-mm radiometer for space borne cloud ice remote sensing

HARP

UMBC

Launch: 2019



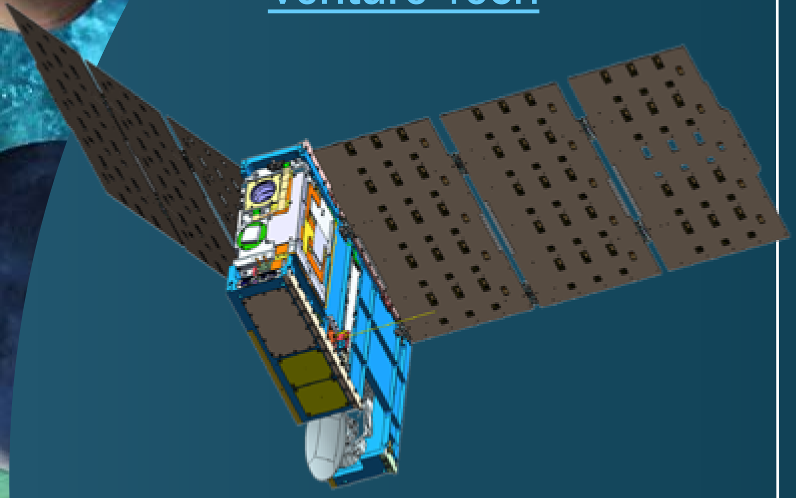
Wide FOV Rainbow Polarimeter

Demonstrate 2-4 km wide FOV hyperangular polarimeter for cloud & aerosol characterization

ESTO InVEST 2015 Program / Venture Tech

U-Class Satellites Advancing TRLs for Future Earth Science Measurements

<u>Venture Tech</u>



TEMPEST-D

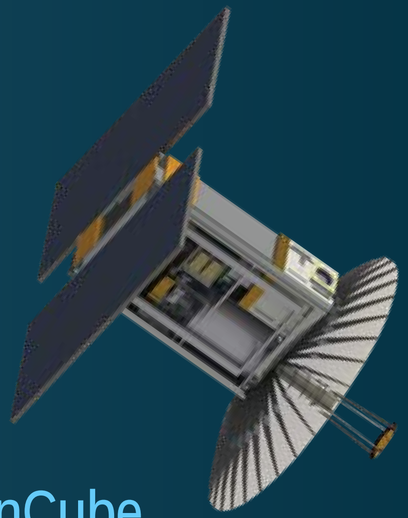
Colorado State University

Launched June 2018

5 Frequency mm-Wave Radiometer

Technology demonstrator measuring the transition of clouds to precipitation

<u>ESTO InVEST 2015 Program</u>



RainCube

Jet Propulsion Lab

Launched June 2018

Precipitation Radar

Validate a new architecture for Ka-band radars on CubeSat platform and an ultra-compact deployable Ka-band antenna

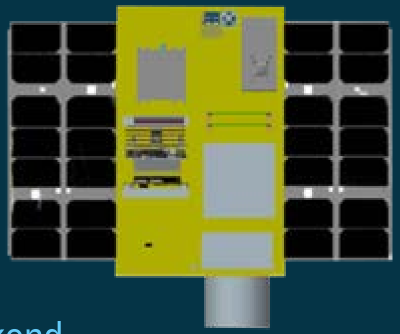
CubeRRT

The *Ohio State University*

Launched: June 2018

Radiometer RFI

Demonstrate wideband RFI mitigating backend technologies vital for future space-borne microwave radiometers



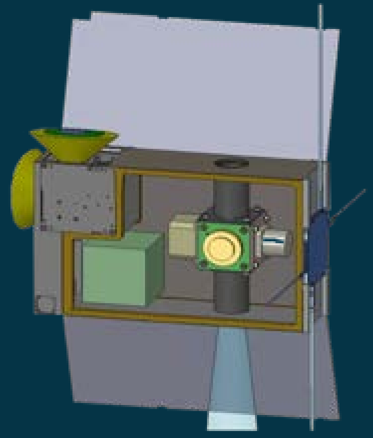
CIRiS

Ball Aerospace

Launch: 2019

Infrared Radiometer

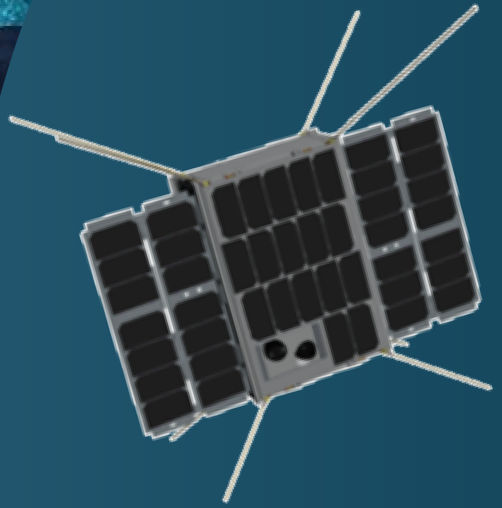
Validate an uncooled imaging infrared (7.5 um to 13 um) radiometer designed for high radiometric performance from LEO



ESTO InVEST 2017 Program

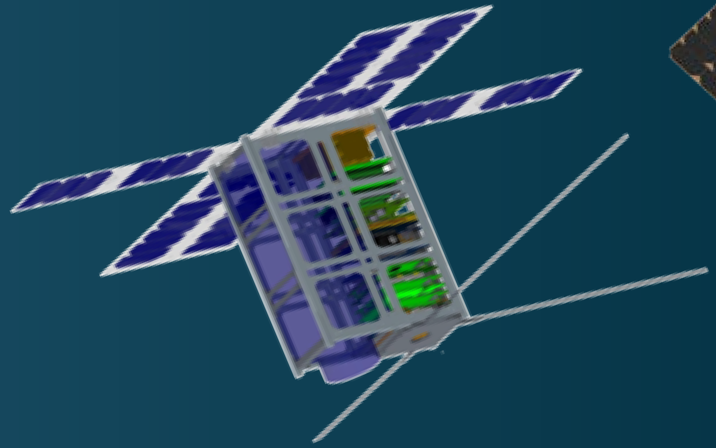
U-Class Satellites Advancing TRLs for Future Earth Science Measurements

SNoOPI
Purdue University



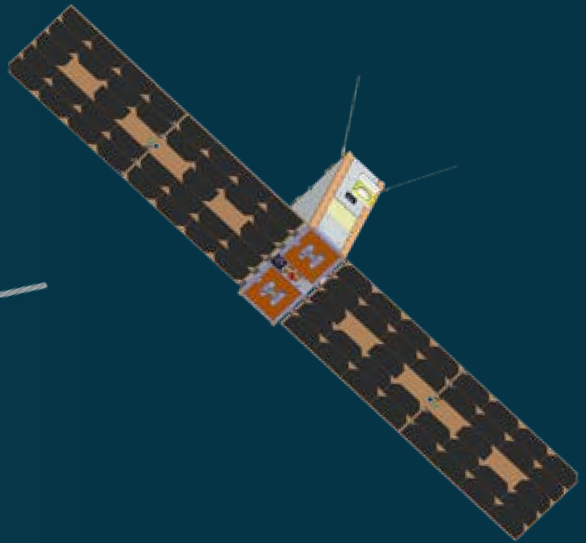
SigNals of Opportunity: P-band Investigation
Demonstrate measurement of the reflection coefficient and phase of land surface reflections from P-band communication satellite signals of opportunity

HyTI
University Of Hawaii



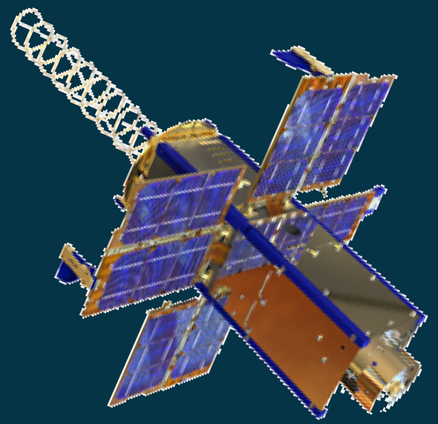
Hyperspectral Thermal Imager
Demonstrate a 6U CubeSat based LEO thermal infrared ITIR) hyperspectral imager with agile on-bard processing

C-TIM FD
LASP-Univ of Colorado



Infrared Radiometer
Validate and demonstrate science performance validate 6U CubeSat system against existing TSIS instrument

NACHOS
Los Alamos National Laboratory



NanoSat Atmospheric Chemistry Hyperspectral Observation System
Compact high-resolution trace-gas hyperspectral imagers, with agile on-board processing

And Now…..
some
InVEST Program Highlights

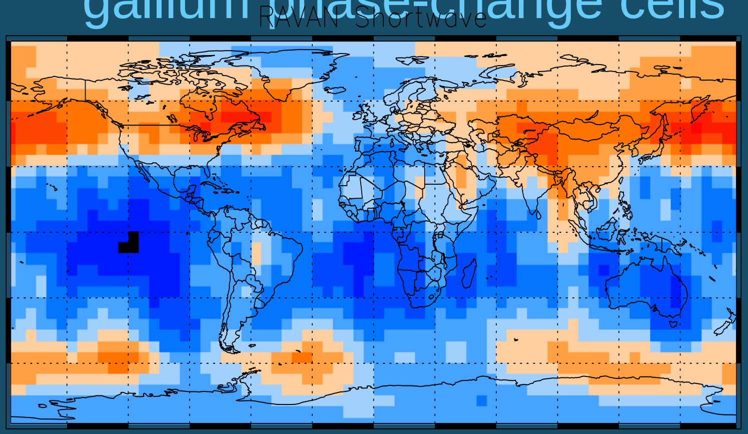
RAVAN demonstrates a novel way of making calibrated Earth outgoing radiation (climate) measurements during its 20-month orbital mission

New technologies demonstrated:

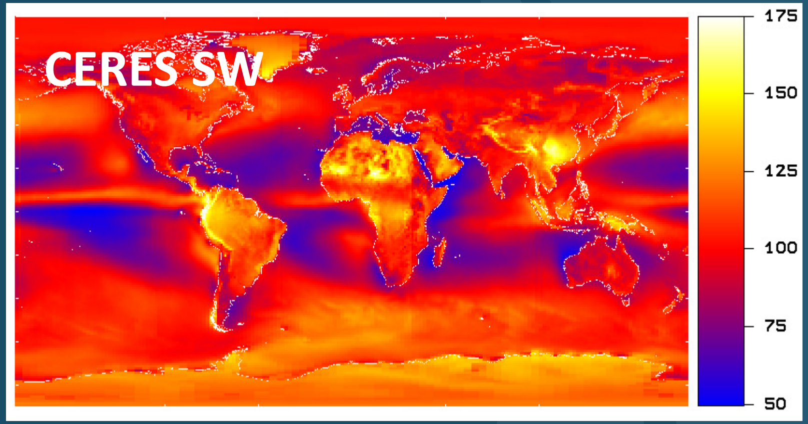
- carbon nanotube–based radiometers
- gallium phase-change cells

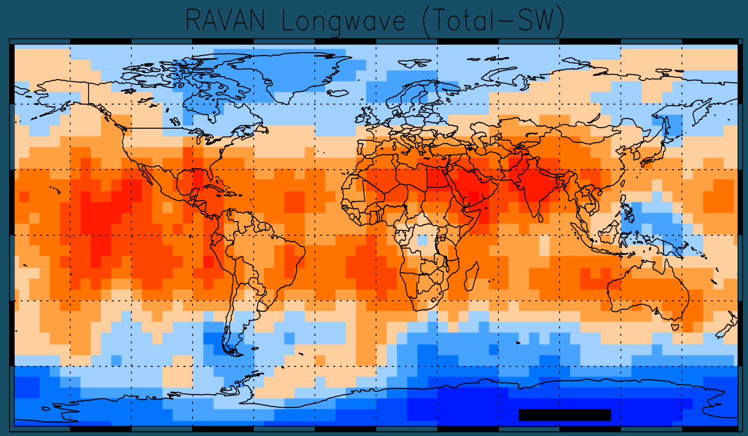
RAVAN

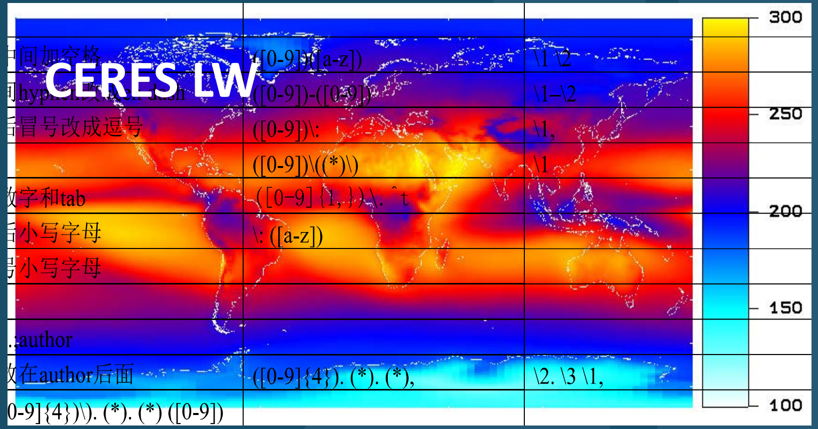
Measuring Earth Radiation



10-year mean CERES EBAF Flux, *Dewitte et al.* [2017]



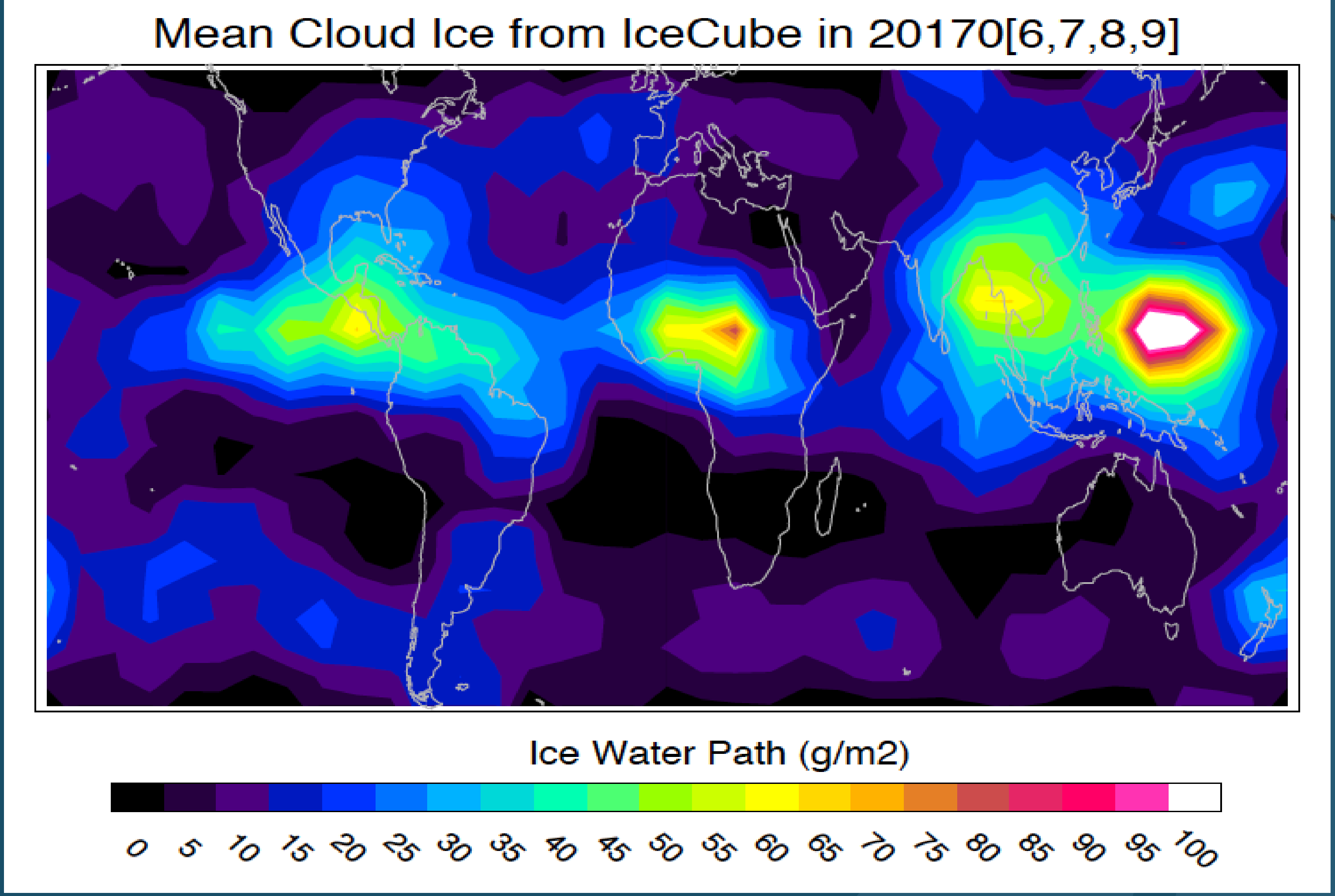




RAVAN demonstrates new technologies that enable future Earth radiation budget (ERB) measurements and establishes a benchmark for an ERB small satellite constellation.

W. H. Swartz et al. (2019) *Remote Sensing*

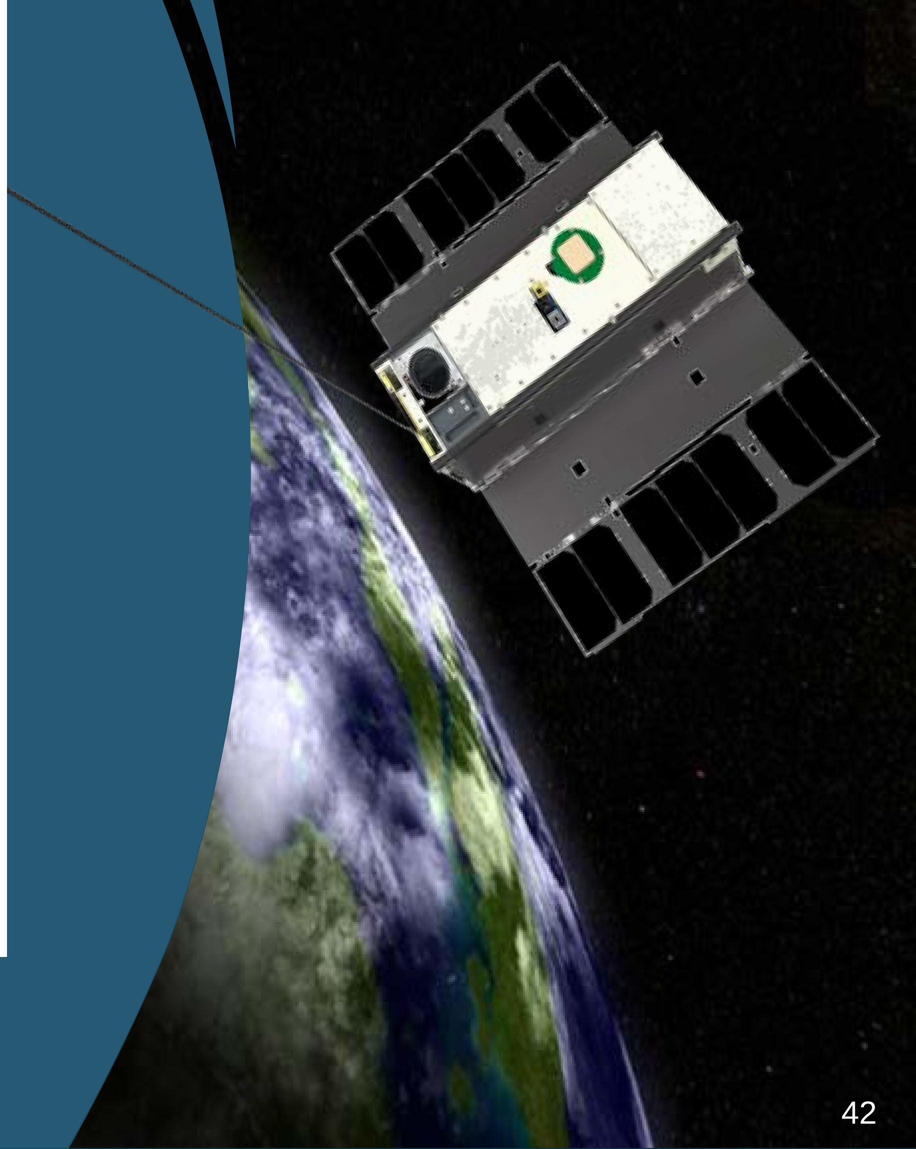
First 883-GHz Earth Cloud Ice Map



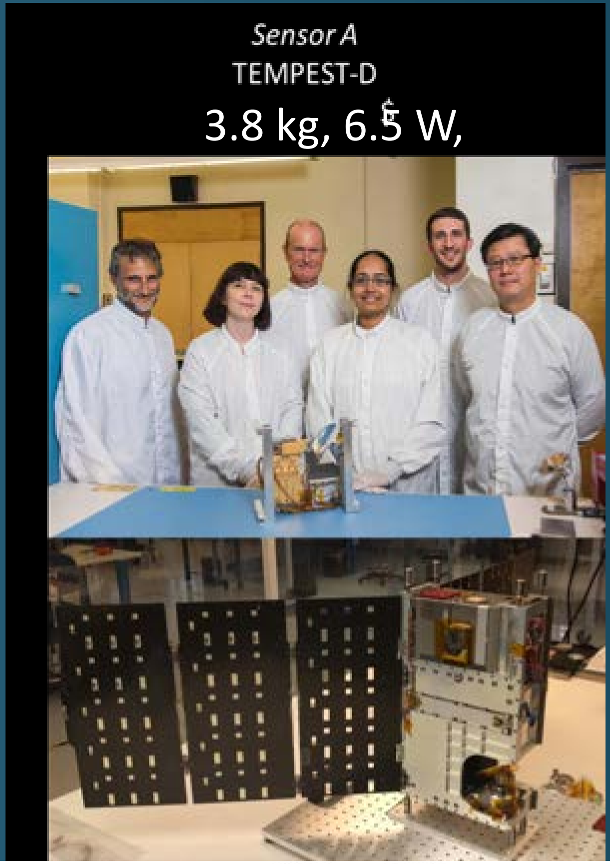
IceCube was the first ever global 883-GHz Cloud Ice Map.

IceCube

883 GHz submm-Wave radiometer

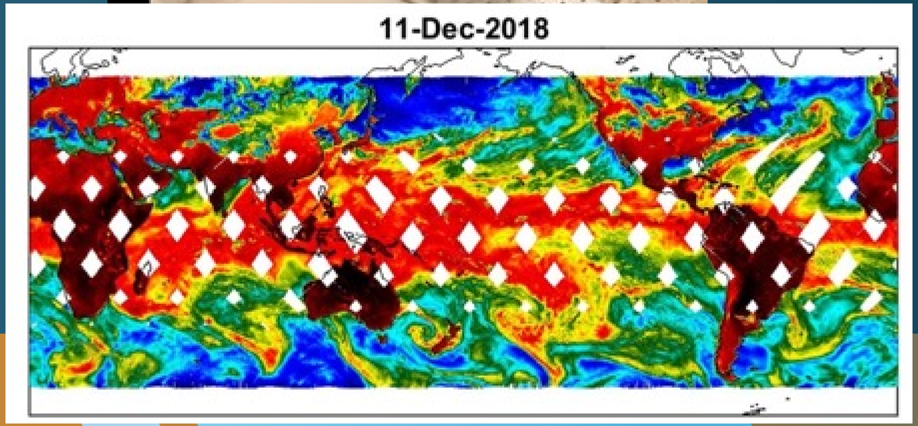


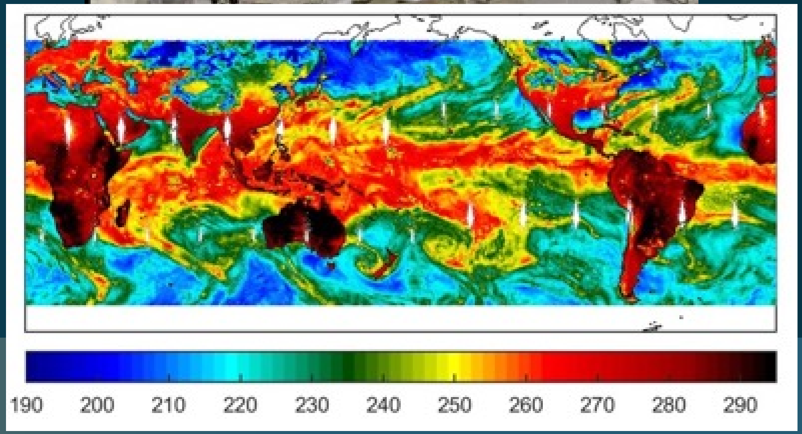
Comparison Between On-orbit Passive Microwave Sensors



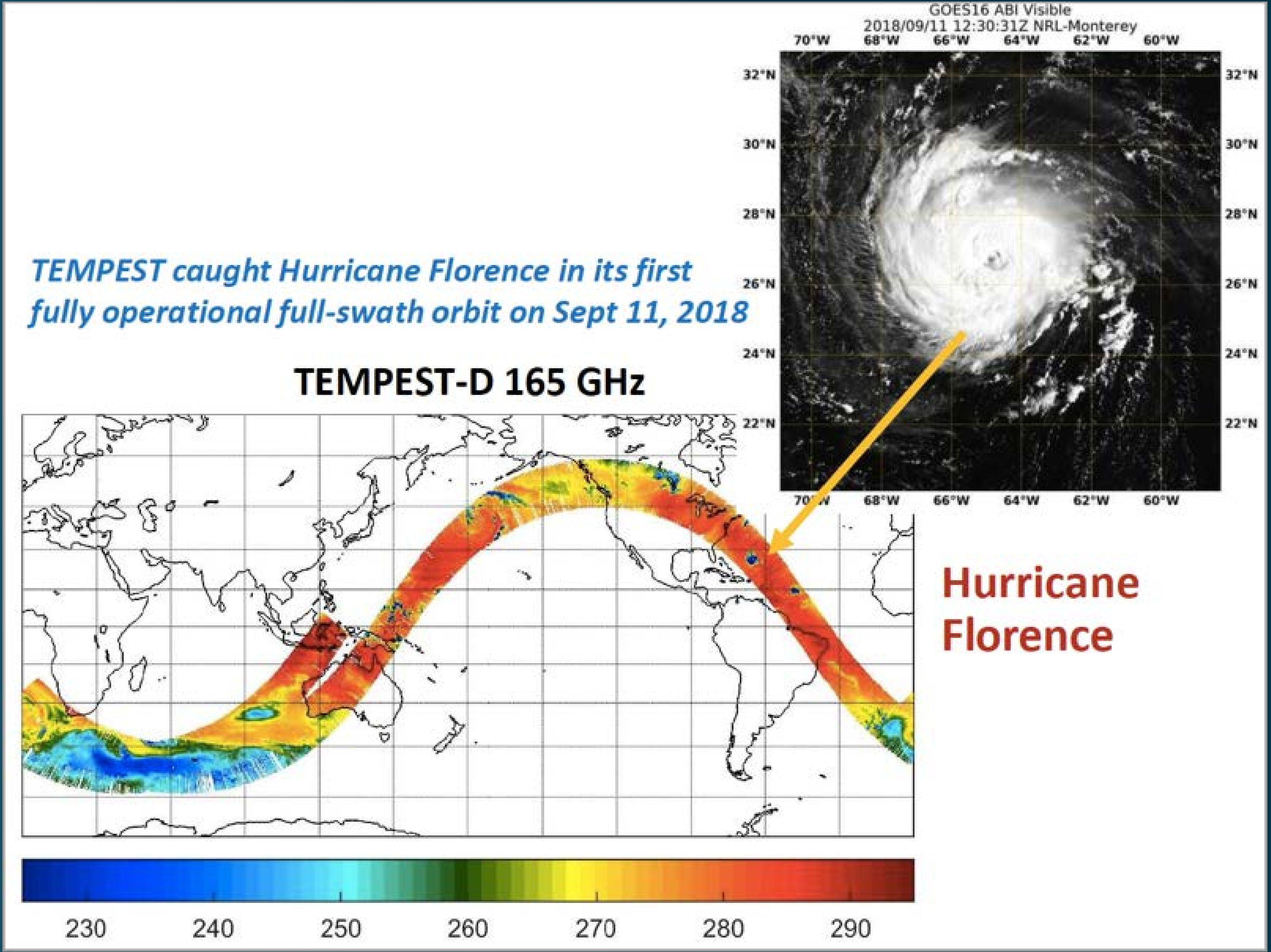
TEMPEST-D

87 GHz Brightness Temperature (K)

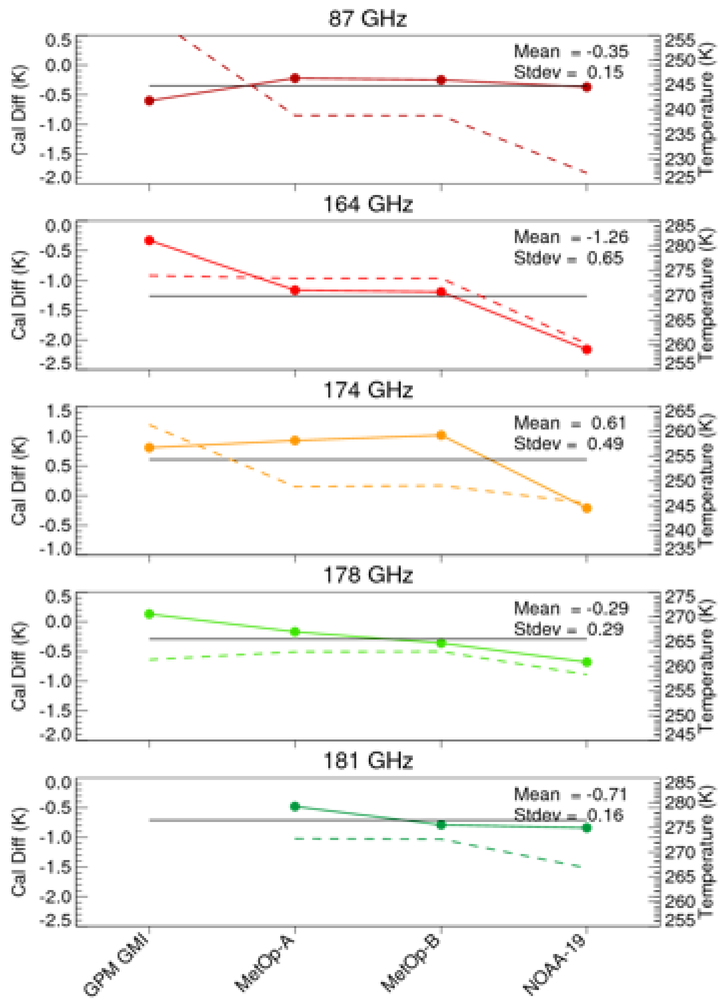




TEMPEST-D First Fully Operational Full-swath Orbit



Validation of TEMPEST-D Data using NASA, NOAA & EUMETSAT Sensors



Mean calibration differences between TEMPEST-D and four reference sensors based on 18 days of data. Dashed lines indicate corresponding mean scene brightness temperature.

- Double difference technique developed for GPM used to evaluate TEMPEST-D calibration compared to reference sensors; maps other sensors' observations to TEMPEST frequencies and view angles
- TEMPEST calibration within 1.3 K of reference sensors, meeting accuracy requirement of 4 K.
- TEMPEST stability within 0.7 K of reference sensors, meeting precision requirement of 2 K.
- Model uncertainty contributing to larger differences for 164 GHz channel
- **Results indicate TEMPEST-D is a very well-calibrated radiometer, indistinguishable from operational-class imaging radiometers.**

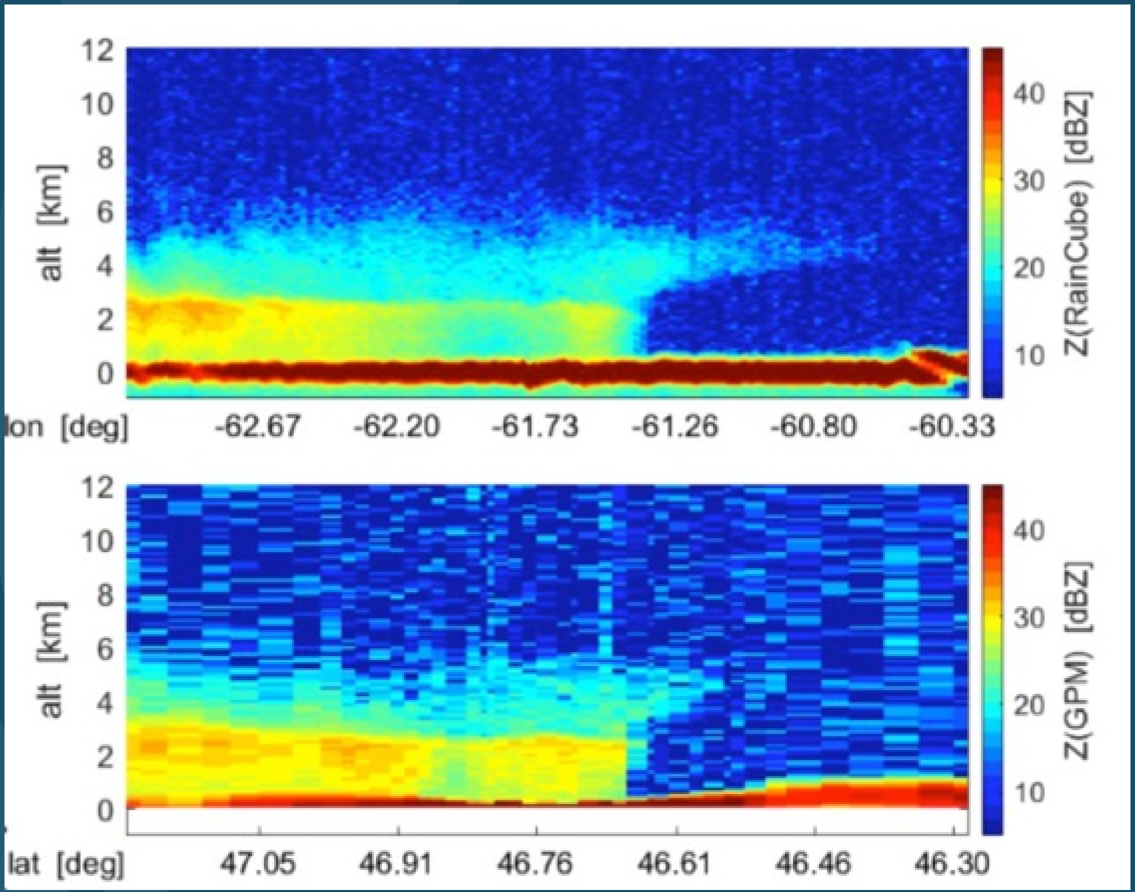
Calibration Differences in Kelvin (Reference – TEMPEST-D)

Reference Sensor	87 GHz	164 GHz	174 GHz	178 GHz	181 GHz
GPM GMI	-0.60	-0.33	0.81	0.13	N/A
MetOp-A MHS	-0.22	-1.16	0.93	-0.17	-0.48
MetOp-B MHS	-0.25	-1.19	1.02	-0.36	-0.79
NOAA-19 MHS	-0.37	-2.16	-0.21	-0.68	-0.84
Mean Difference Requirement: 4 K	**-0.35**	**-1.26**	**0.61**	**-0.29**	**-0.71**
Standard Deviation Requirement: 2 K	**0.15**	**0.65**	**0.49**	**0.29**	**0.16**

RainCube

First Ka-Band CubeSat Radar

RainCube / GPM Observations



Jan. 2019 – Near-collocated measurements of vertical rain reflectivity profiles from RainCube (top) and GPM's Ka-band radar (bottom)

RainCube points Nadir while GPM scans along-track

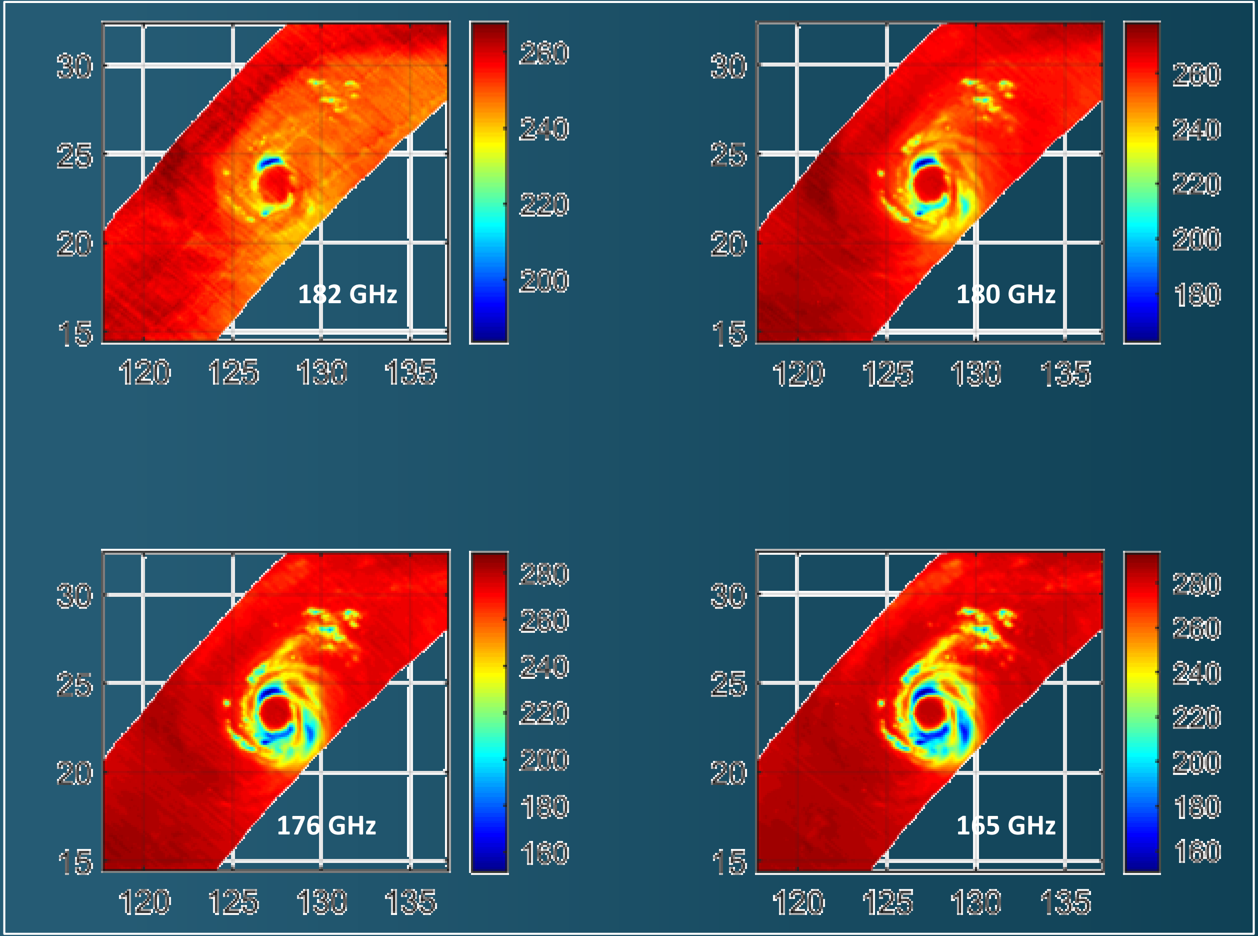
RainCube Status

- The mission L1 requirements have been met
  - L1-1: The RainCube mission shall launch a Ka-band radar payload to LEO in a 6U CubeSat.
  - L1-2: The RainCube mission shall operate a Ka-band radar payload on-orbit for a minimum of two days and acquire (collect and downlink) nadir-pointed measurements of precipitation.
- The mission radar performance L2 requirements have been met based on preliminary calibration:
  - L2-17: The payload shall vertically profile precipitation (as defined by L2-18, -19, -20) between 0 km and 18 km altitude above the WGS84 ellipsoid.
    - By design, confirmed in flight.
  - L2-11: The payload shall demonstrate a calibration stability of ±2.0 dB during the payload demonstration phase.
    - Estimated better than +/-2dB (although more data is needed to refine this result)
  - L2-18: The payload shall demonstrate a maximum 10 km horizontal resolution.
    - Estimated ~ 8km
  - L2-19: The payload shall demonstrate a maximum vertical resolution of 250 m for all altitudes in the required window.
    - Measured ~120m

The project has produced the following payload data products:
- Level 0: Radar payload telemetry/science data & bus telemetry
- Level 1: Uncalibrated radar telemetry/science & bus telemetry
- Level 2: L2-GEOPROF Geolocated, calibrated, measured radar reflectivity factor

RainCube/TEMPEST-D Observing Typhoon Trami

Spacecraft constellation separated by 5 minutes revealing 3D storm structure



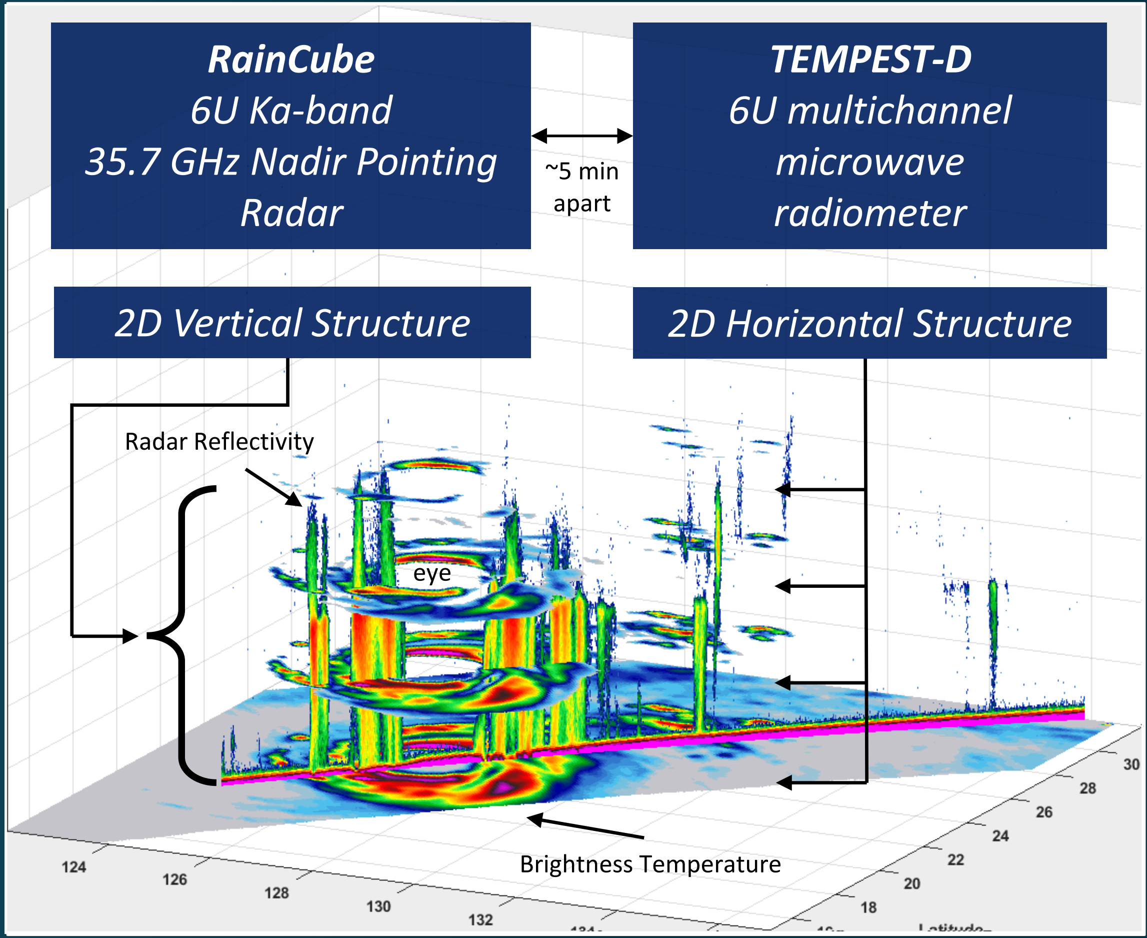


Illustration of complementary nature of these sensors flown in constellation for observing precipitation

CSIM-FD

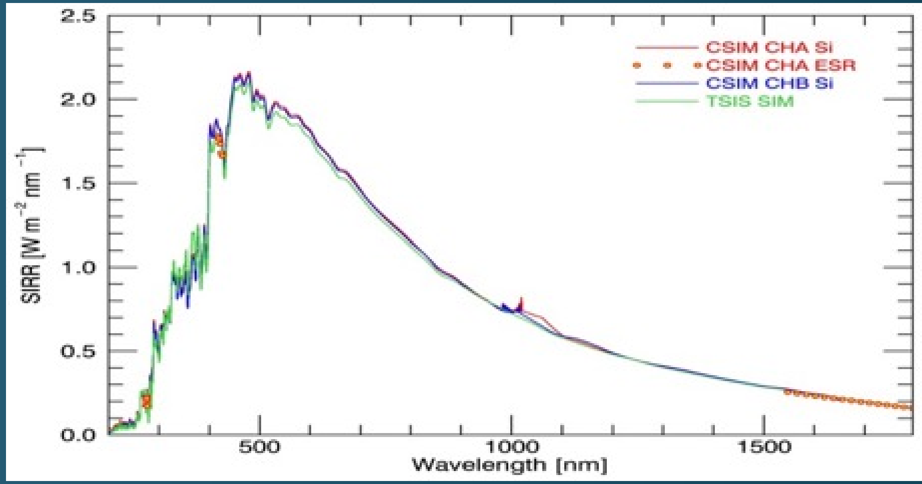
Compact Solar Irradiance Monitor Flight Demonstration

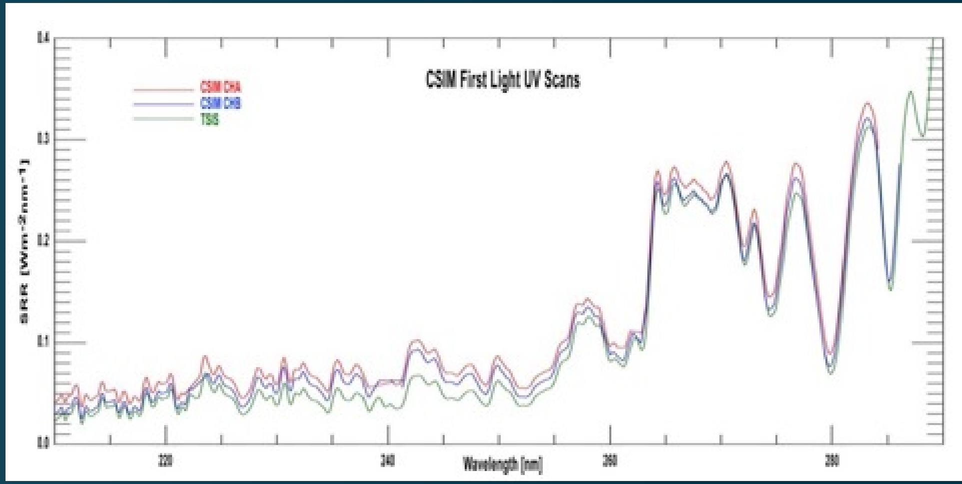
Measuring solar spectral irradiance (SSI), and how solar variability impacts the Earth's climate, contributing to long-term continuity measurements from SORCE SIM and TSIS SIM

CSIM is 11 kg based on a Blue Canyon Technologies bus

TSIS-1 is 363 kg built by LASP mounted to the ISS

SORCE is 290 kg based on an Orbital LEOStar-2 bus



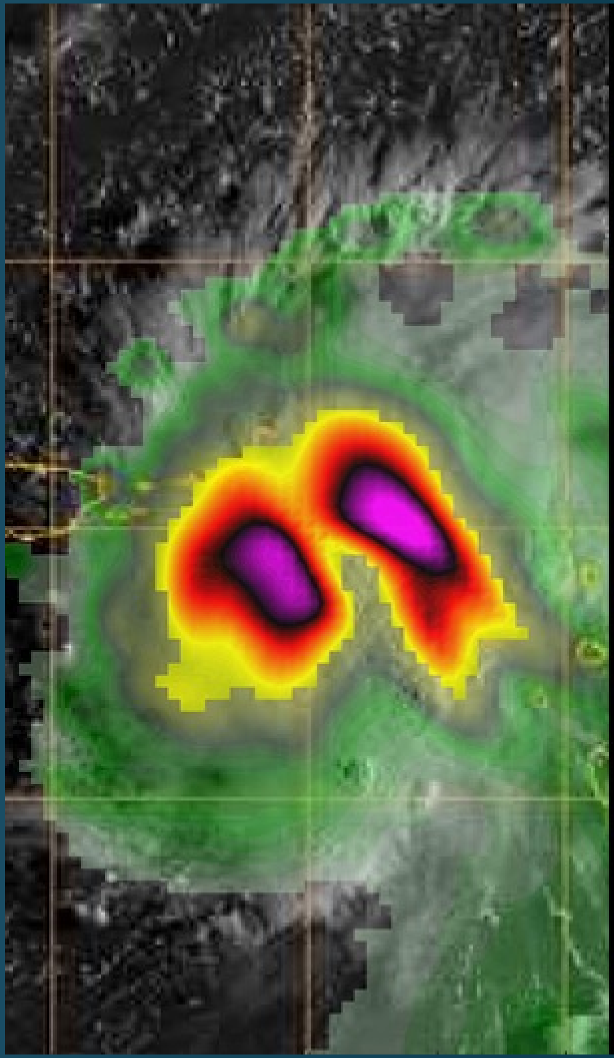


Latest full spectrum and First Light uncorrected CSIM data (channels A and B) compared to TSIS data in a portion of the UV spectrum

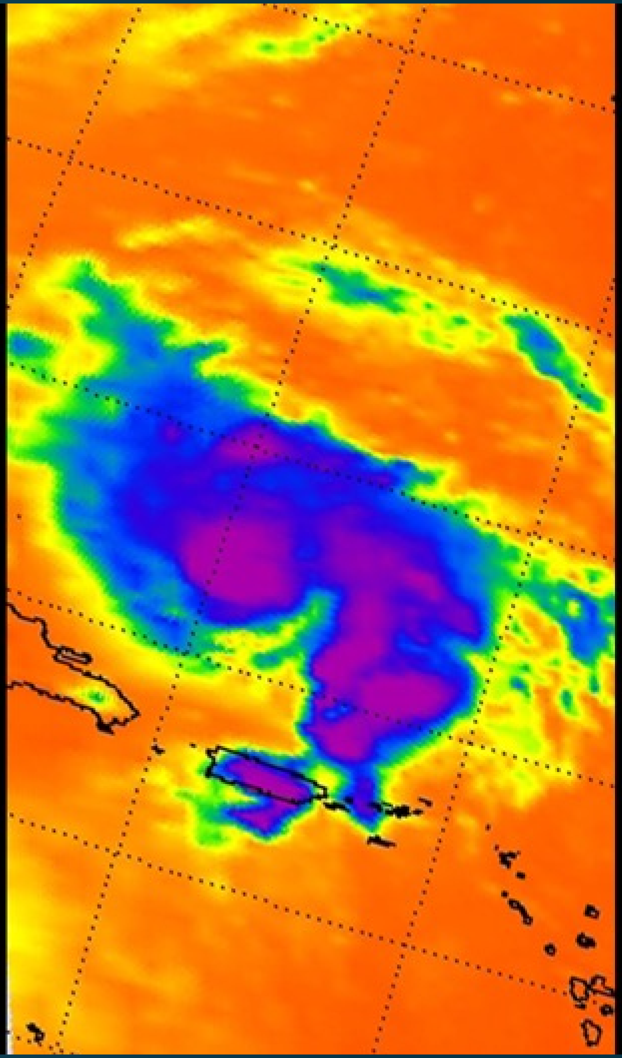
Latest from TEMPEST-D

NASA's Multiple Views of Hurricane Dorian from Space

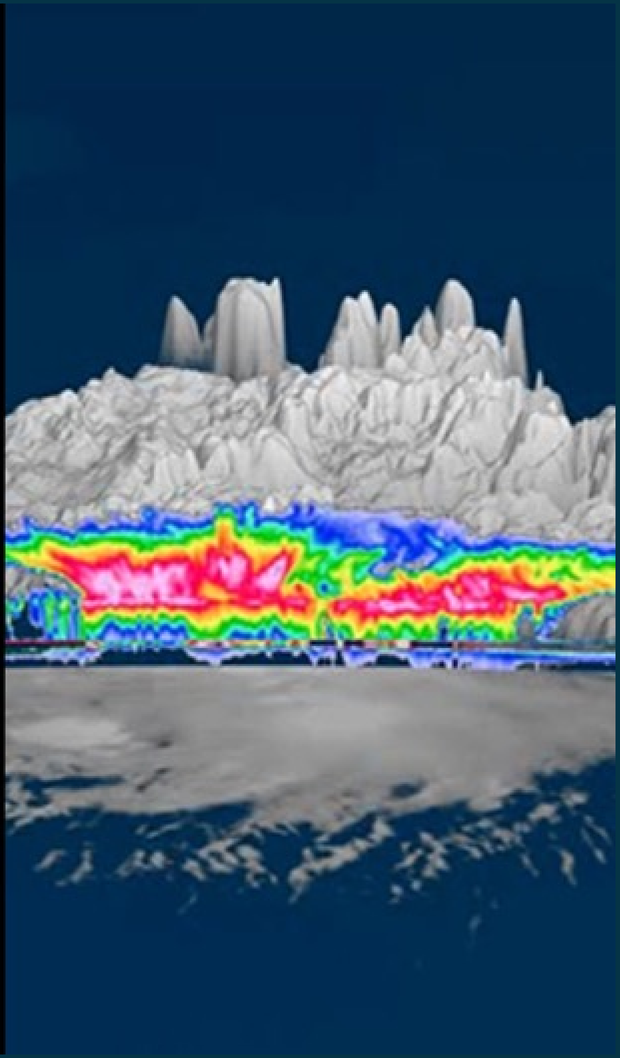
TEMPEST-D



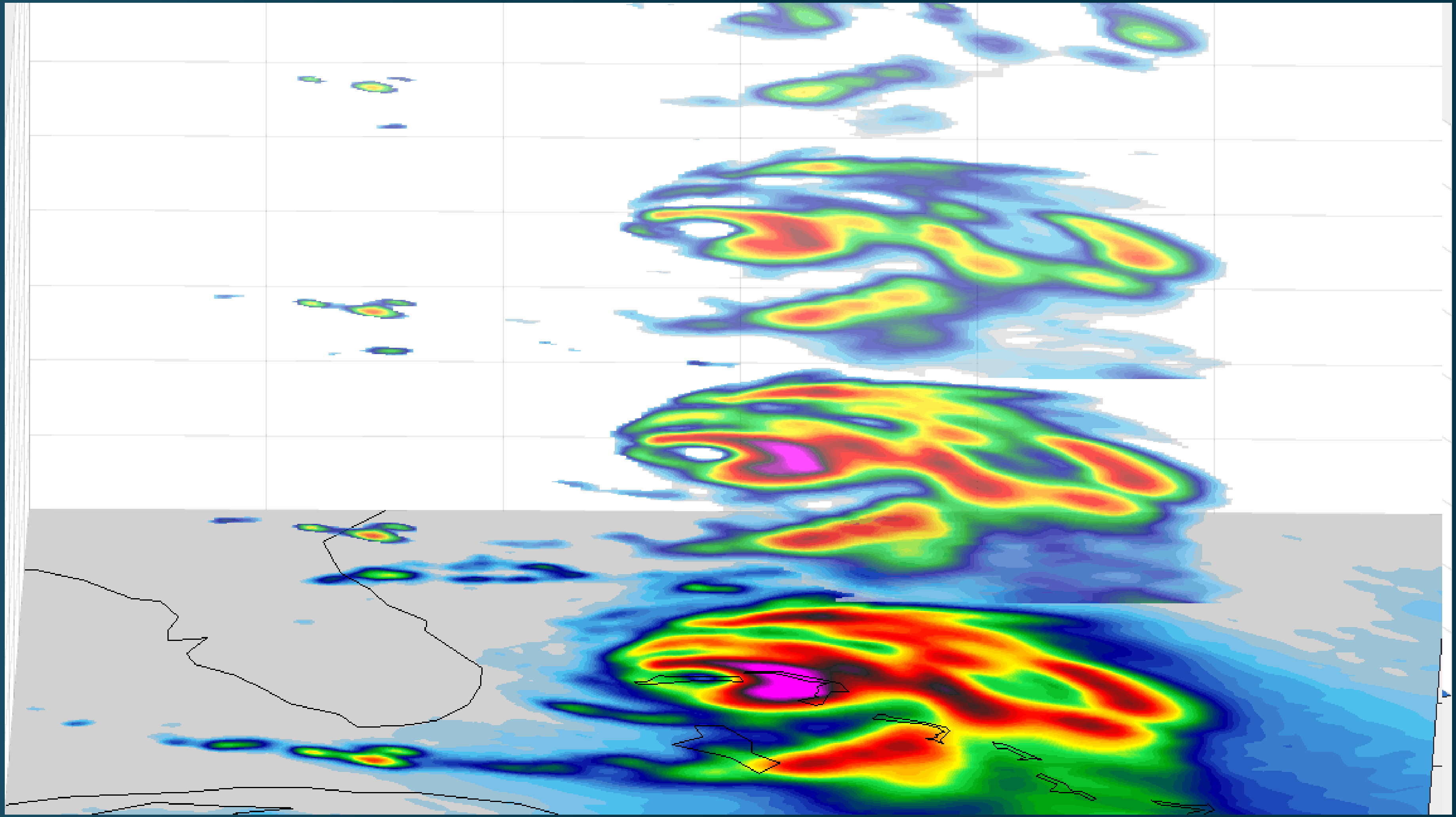
AIRS



CloudSat



An Inside Look at Hurricane Dorian from TEMPEST-D



Hurricane Dorian off the coast of Florida, as seen by the small satellite TEMPEST-D at 2 a.m. EDT on Sep. 3, 2019 (11 p.m PDT on Sept. 2, 2019). The vertical view of Dorian highlights where the storm is strongest in the atmosphere. The colors in the animation show the heavy rainfall and moisture inside the storm. The least-intense areas of rainfall are shown in green, while the most intense are yellow, red and pink.

Credits: NASA/JPL-Caltech/NRL-MRY

Summary

- ESTO Programs have been instrumental in development of breakthrough technology for past, present and future NASA missions.

- Investments to advance components, sensors and information technology will yield affordable observations

- Continuous pursuit of miniaturization and reducing SWaP translates to:
  - improving affordability and sometimes simplification
  - enabling implementation options, such as constellations, that can improve spatial coverage and temporal frequency

- The successful infusion of technologies into Earth Venture program line is expected to expand to the Venture Continuity strand

For more information visit

https://esto.nasa.gov