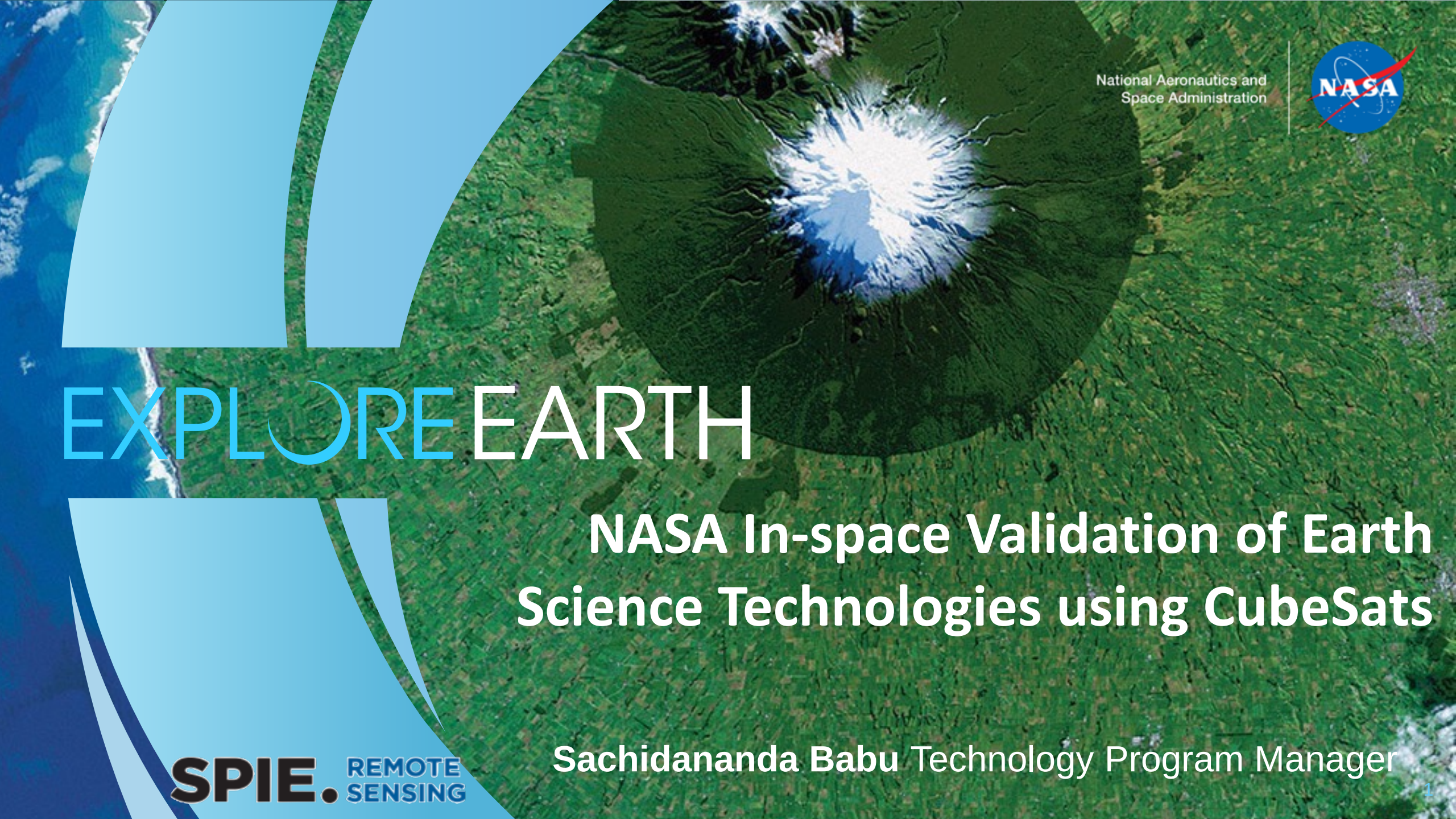

NASA In-space Validation of Earth Science Technologies using CubeSats

Sachidananda Babu Technology Program Manager

SPIE. REMOTE SENSING

ESTO Org Chart

EARTH SCIENCE TECHNOLOGY OFFICE (ESTO)

PROGRAM DIRECTOR : **Pamela Millar**

DEPUTY PROGRAM DIRECTOR : **Robert Bauer**

OFFICE ADMINISTRATOR : **Deborah Compere**

- ADVANCED OBSERVATIONS : **Parminder Ghuman**
- ADVANCED INFO SYSTEMS : **Michael Little**
- SPACE FLIGHT VALIDATION : **Sachidananda Babu**
- ADVANCED PLANNING : **Philip Larkin**
- ESTO CENTER ASSOCIATES : **GSFC // ARC LaRC // JPL**
- PROGRAM SUPPORT

Contributors

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Deputy Dir	Robert Bauer

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	Pamela Harris
	Jacqueline Ferguson
	Teresa Kauffmann
	Jeff Sealover
	Debbie Compere
	Tana Bowling

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

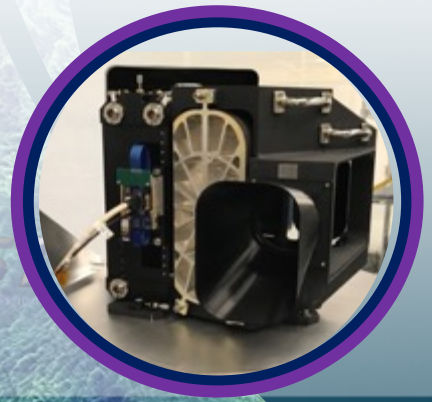
Other ESD Technology Activities Managed by ESTO

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 FY16;

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

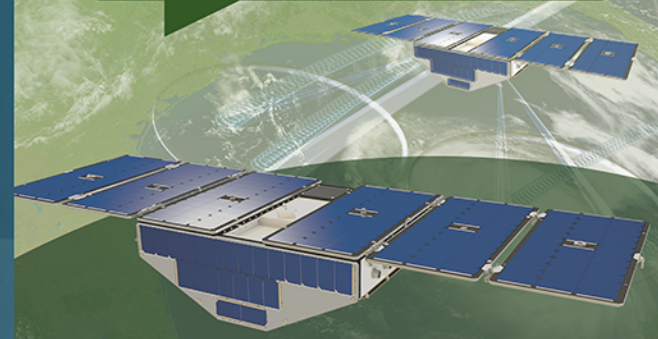
- Competitive, peer-reviewed proposals enable selection of best-of-class technology investments
- Risks are retired before major dollars are invested: a cost-effective approach to technology development and validation
- Successful partnering establishes leveraging opportunities
- This approach has resulted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

SMD
ENABLE INNOVATION

PROGRAM IMPACT >

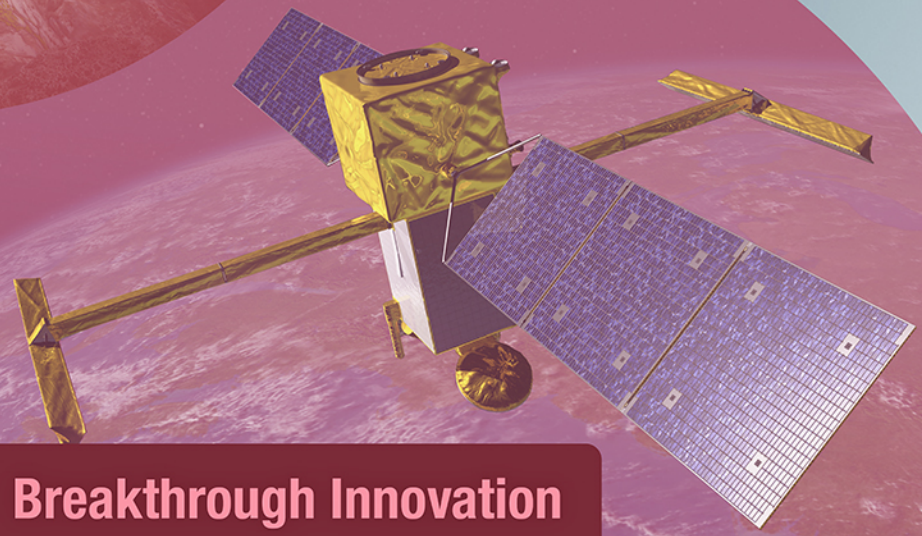
TECHNOLOGY >

Disruptive Innovation
SmallSat Constellations



Game Changer
Deep Space Laser Communication

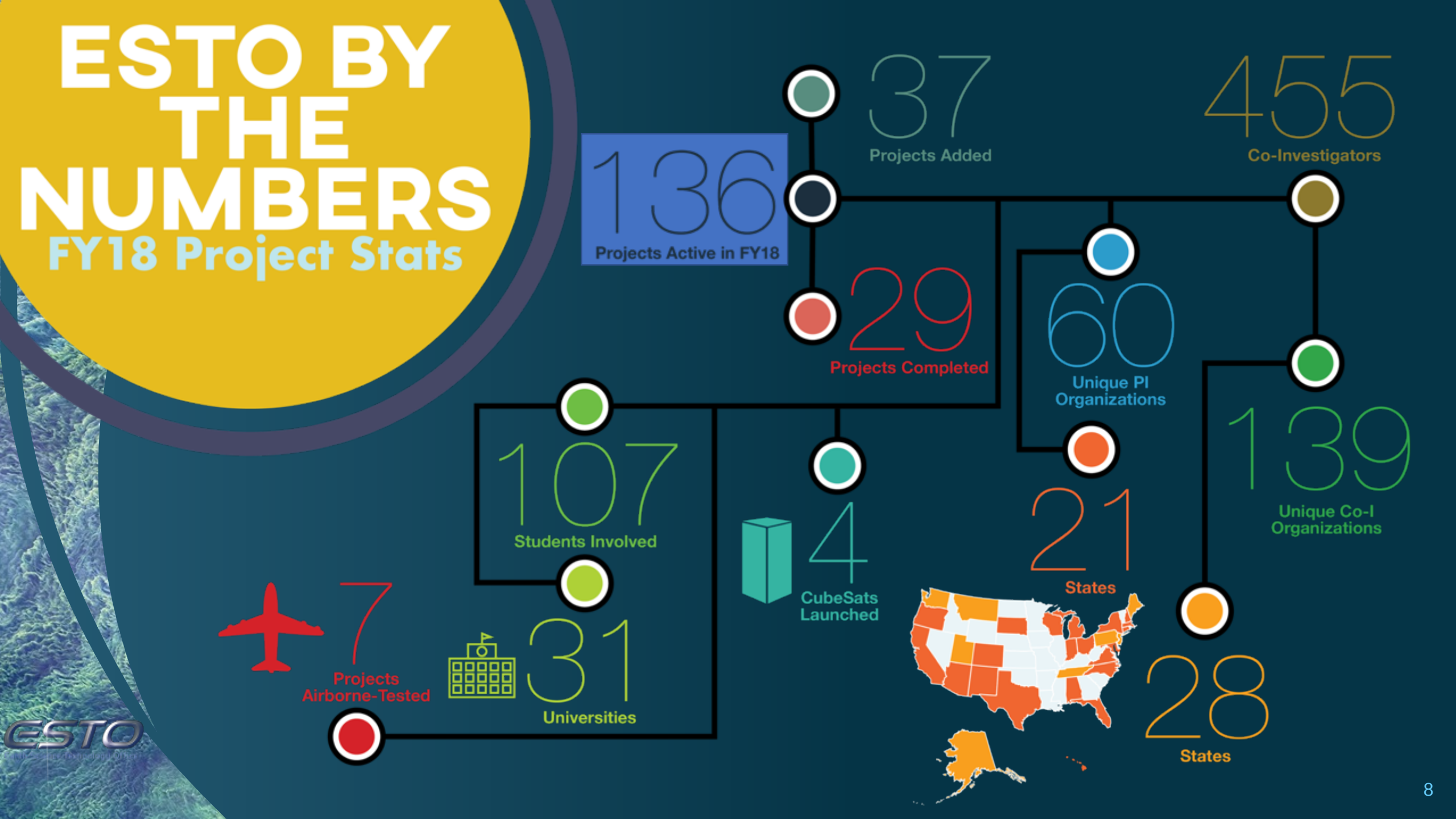
Incremental
Discovering More Exoplanets



Breakthrough Innovation
Unprecedented Ocean Measurements

ESTO BY THE NUMBERS

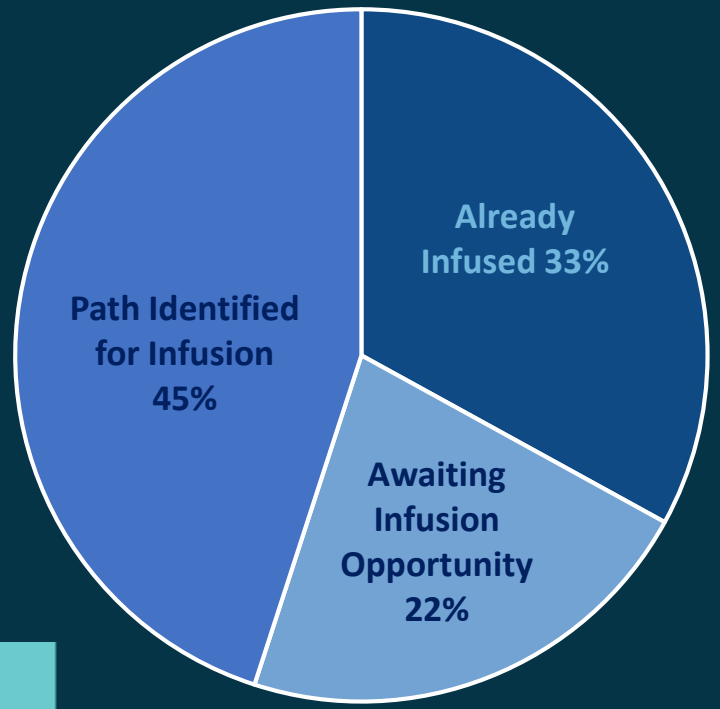
FY18 Project Stats



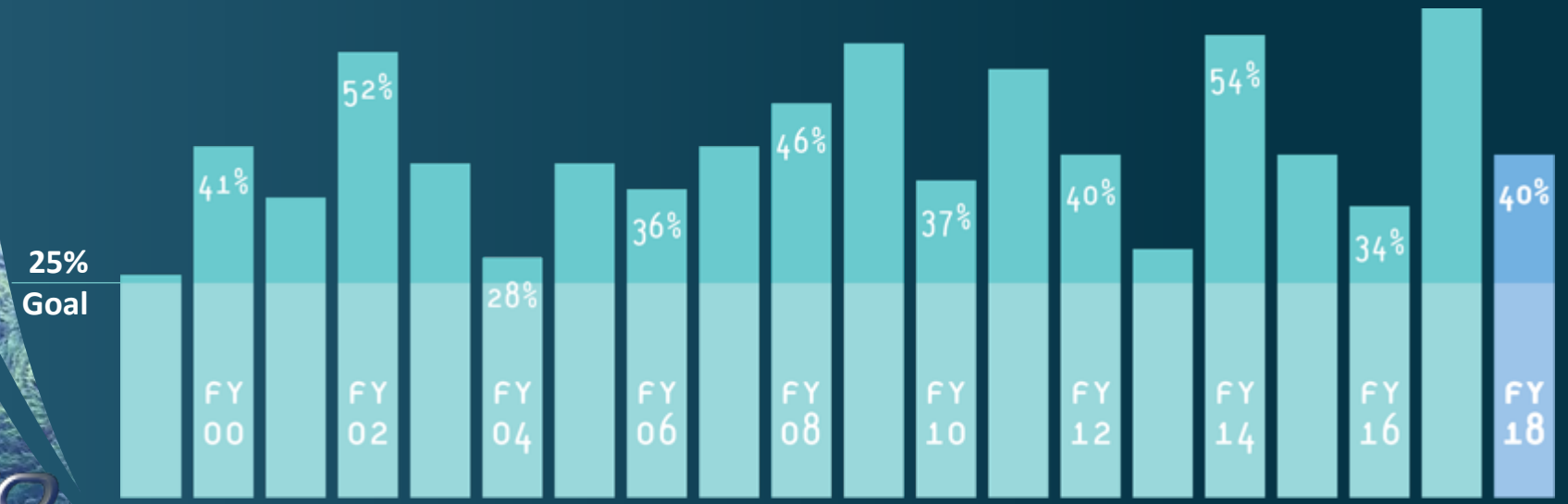
FY18 Program Metrics

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

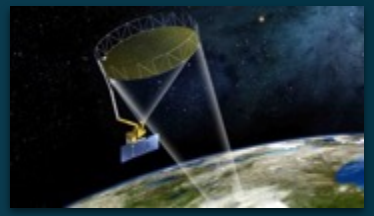


40% of ESTO technology projects funded during FY18 advanced one or more TRLs over the course of the fiscal year (9 advanced more than one TRL). The average TRL advancement for all years is 41%.

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)

ESTO

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)

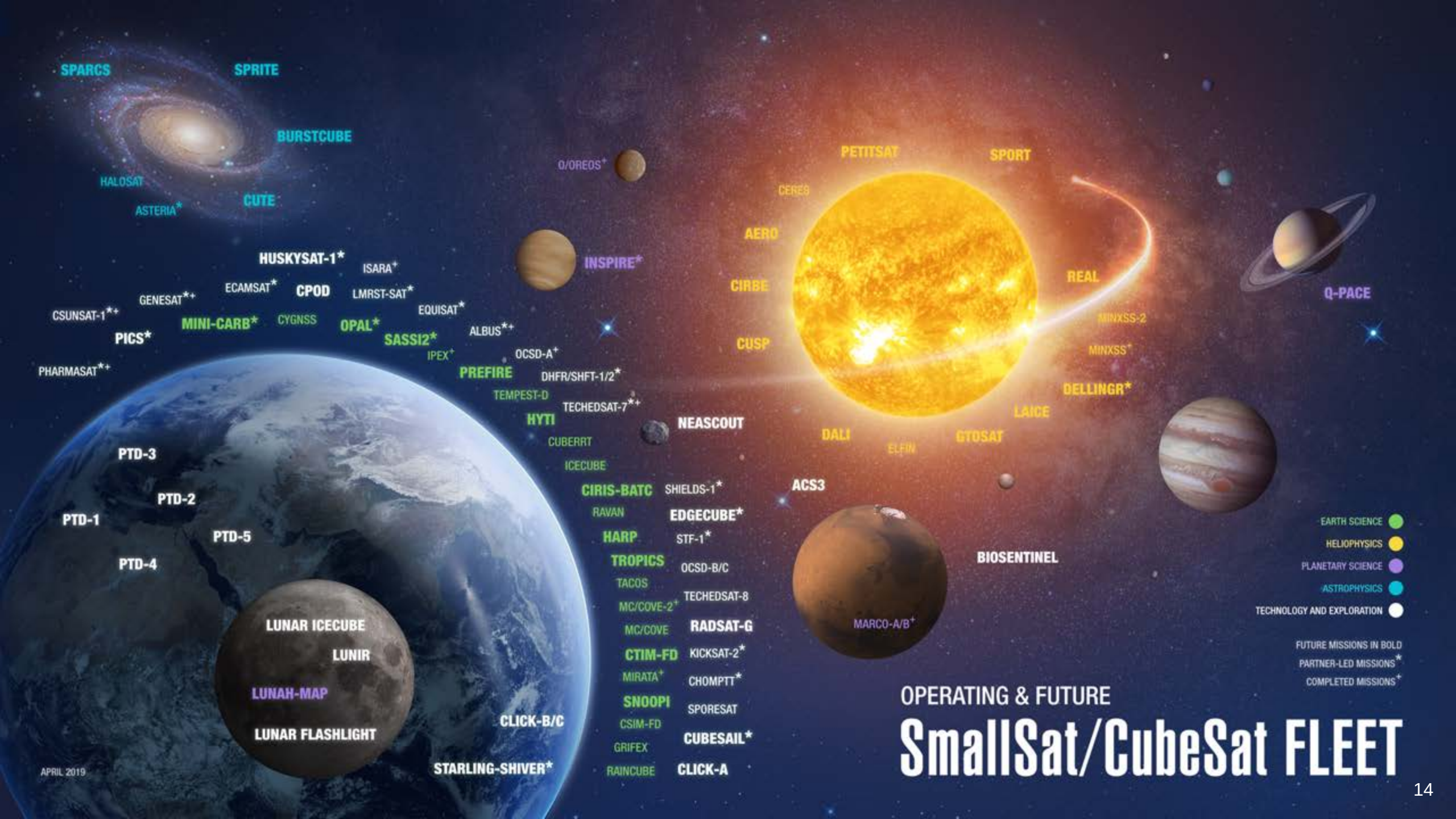
AO Proposal Infusions: 2
Athena-OAWL, Discovery-Lunar Volatiles Orbiter

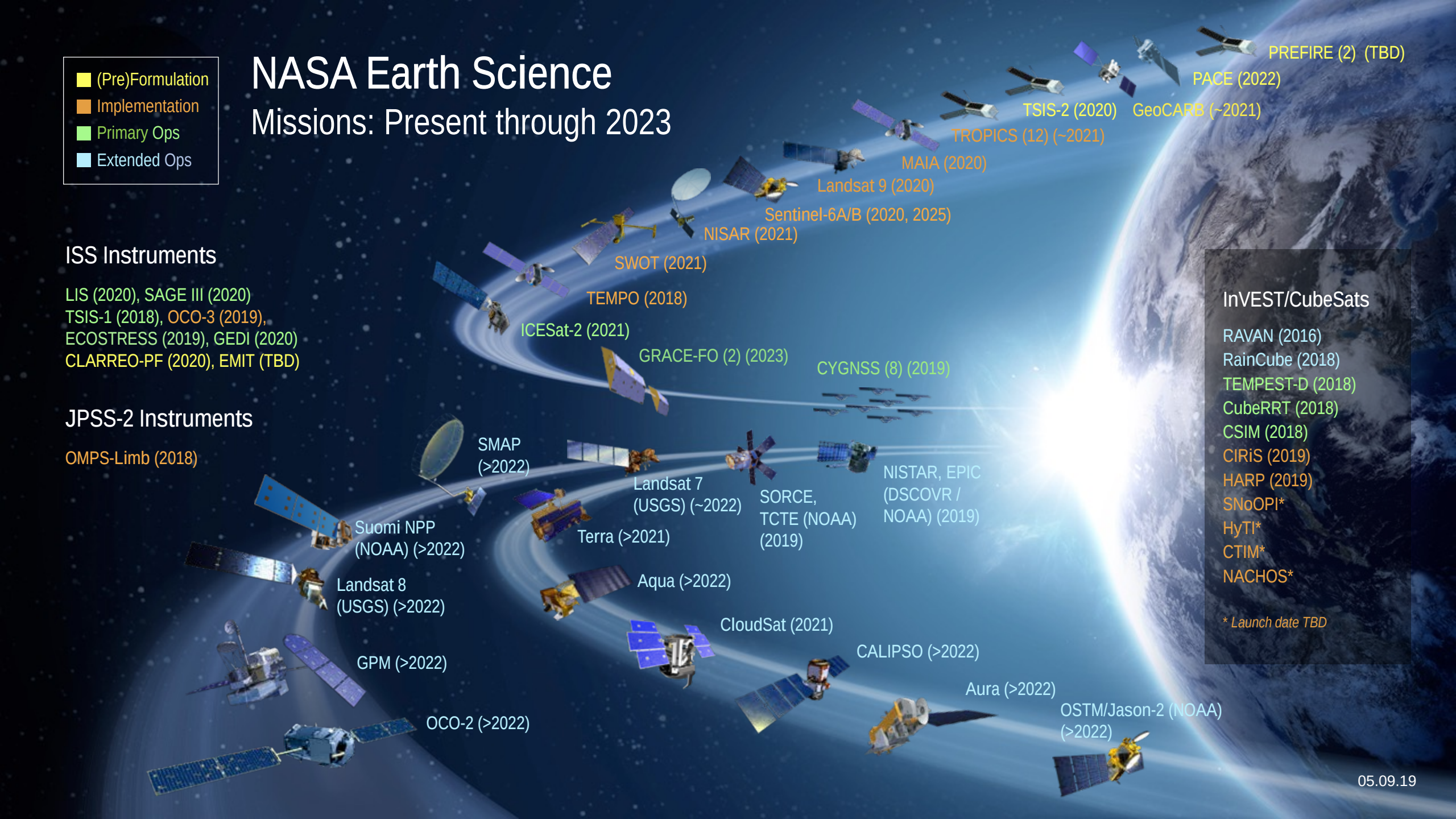
A Flexible, Science-driven Strategy

- 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

In-Space Validation of Earth Science Technology (InVEST)

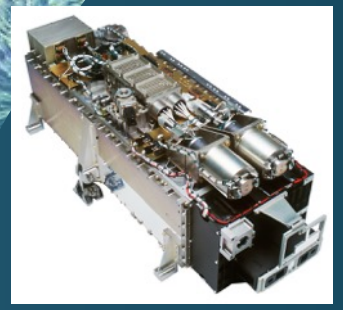
InVEST is on-orbit technology validation and risk reduction for small instruments and instrument systems.


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


(Pre)Formulation
Implementation
Primary Ops
Extended Ops
NASA Earth Science
Missions: Present through 2023
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

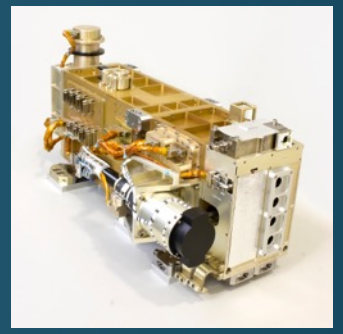
Mission Evolution: From a Large Satellite to CubeSat

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)



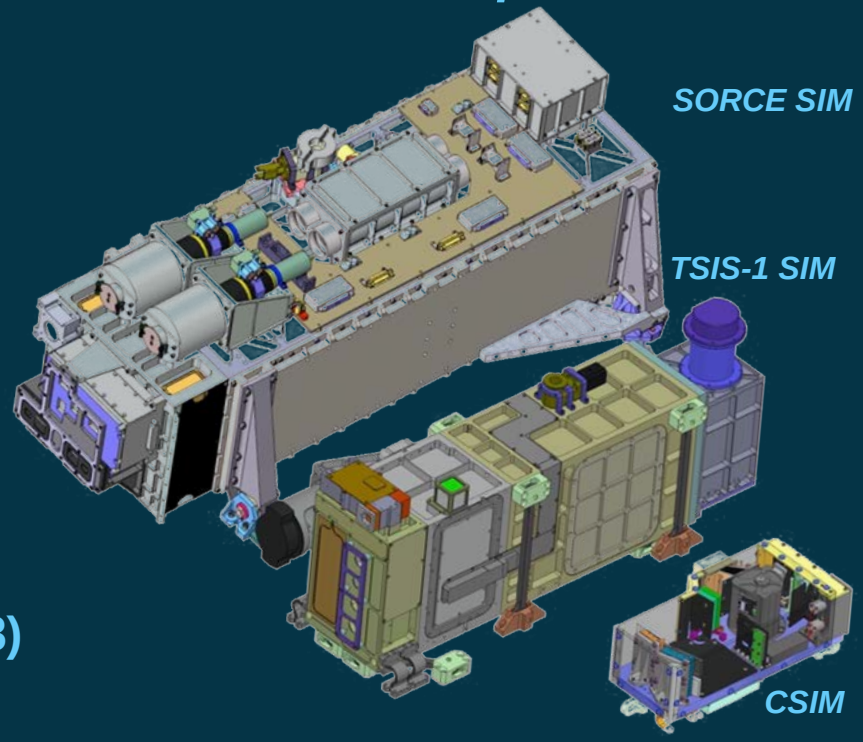
TSIS SIM (launched 15 Dec 2017)

- 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

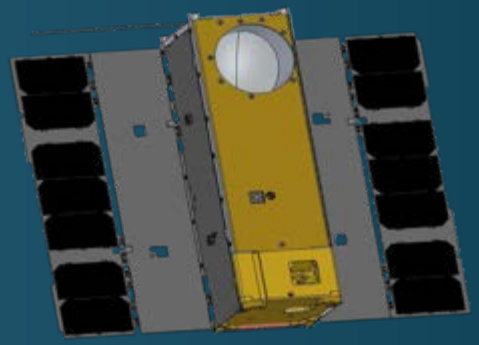
ESTO InVEST 2012 Program

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

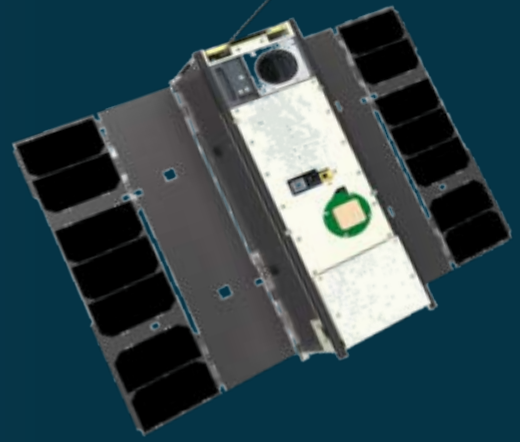
Vertically Aligned Carbon Nanotubes (VACNTs)

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

IceCube

GSFC

Launched: March 2017



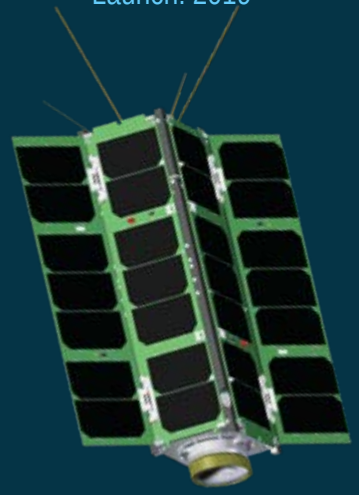
883 GHz submm-Wave radiometer

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

HARP

UMBC

Launch: 2019



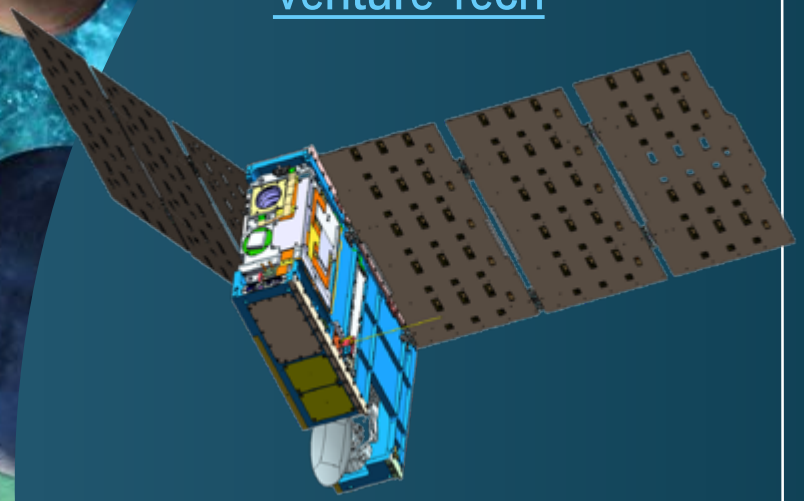
Wide FOV Rainbow Polarimeter

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

Venture Tech

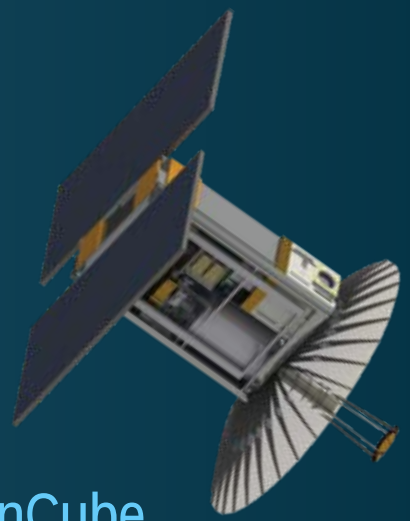


TEMPEST-D

Colorado State University
Launched June 2018

5 Frequency mm-Wave Radiometer
Technology demonstrator measuring the transition of clouds to precipitation

ESTO InVEST 2015 Program



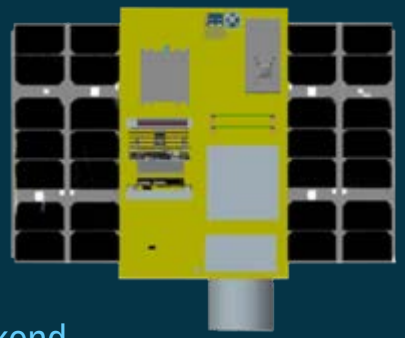
RainCube

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

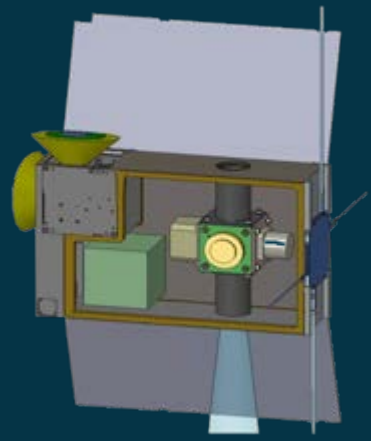
The *Ohio State University*
Launched: June 2018



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

CIRiS

Ball Aerospace
Launch: 2019

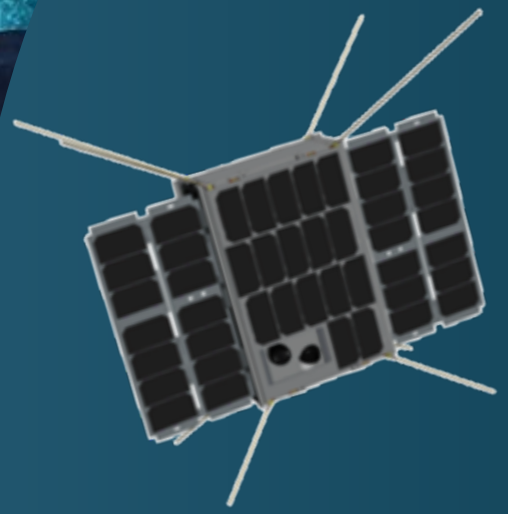


Infrared Radiometer
Validate an uncooled imaging infrared (7.5 um to 13 um) radiometer designed for high radiometric performance from LEO

ESTO InVEST 2017 Program

U-Class Satellites Advancing TRLs for Future Earth Science Measurements

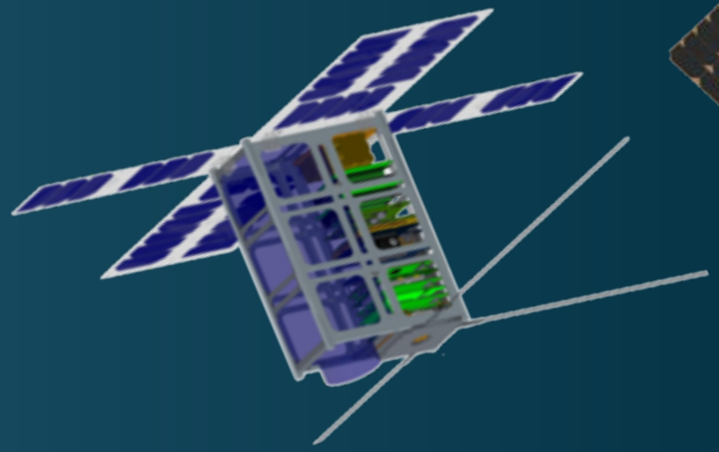
SNoOPI
Purdue University



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

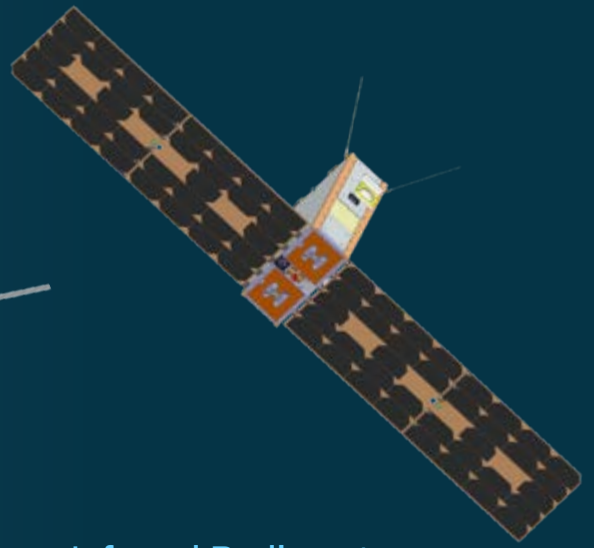
HyTI
University Of Hawaii



Hyperspectral Thermal Imager

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

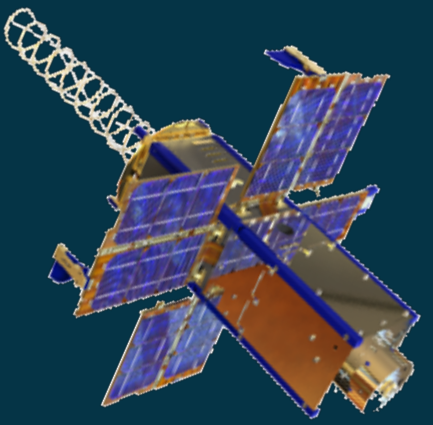
C-TIM FD
LASP-Univ of Colorado



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

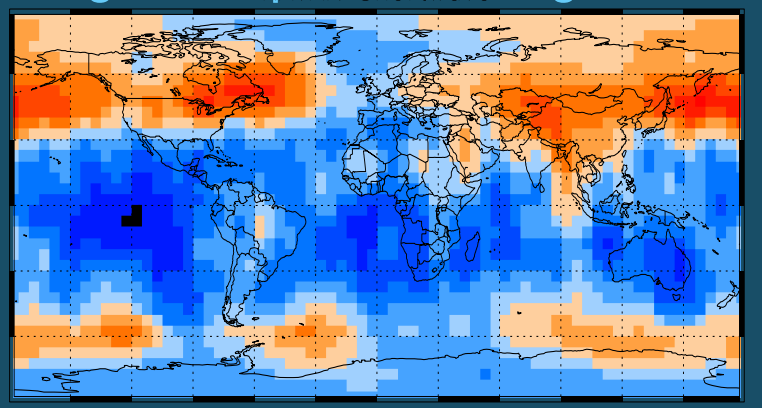
RAVAN

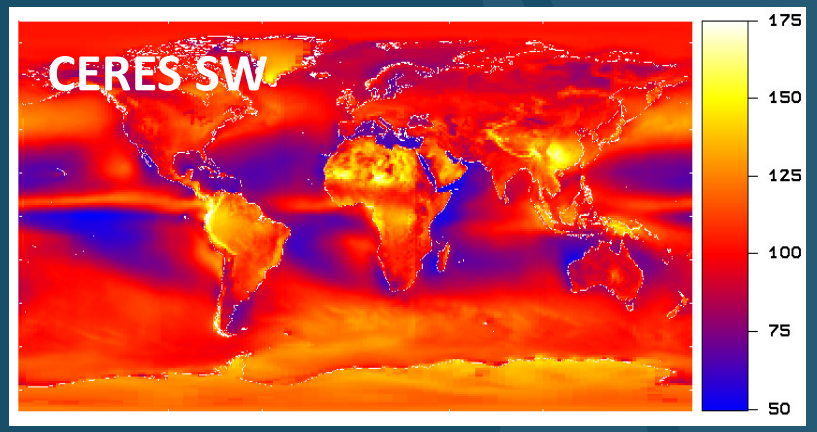
Measuring Earth Radiation

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

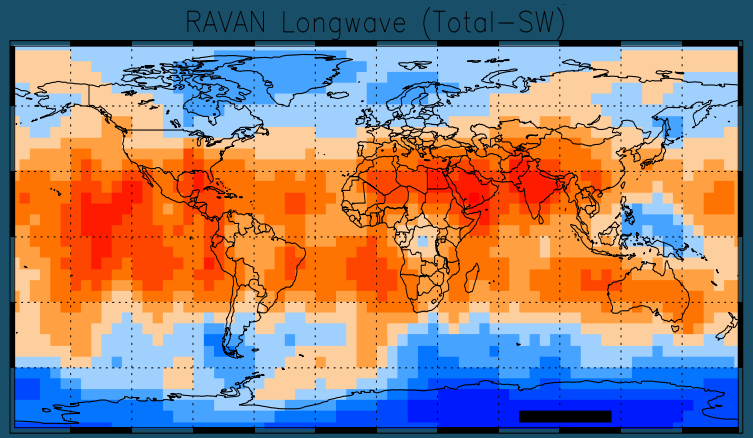
New technologies demonstrated:

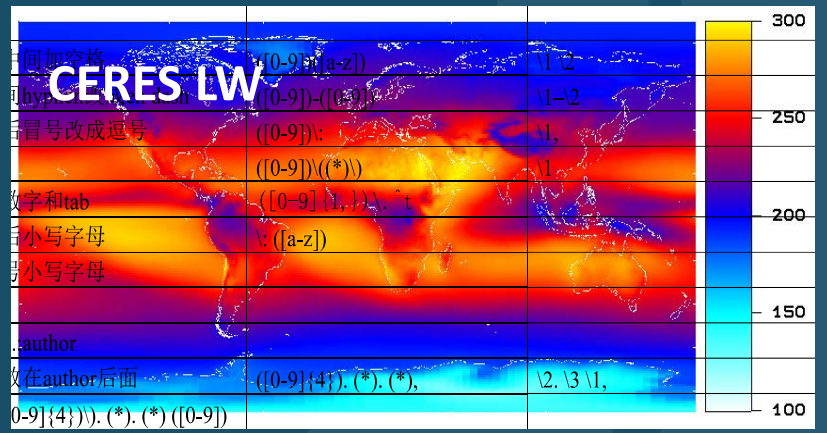
- carbon nanotube–based radiometers
- gallium phase-change cells





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



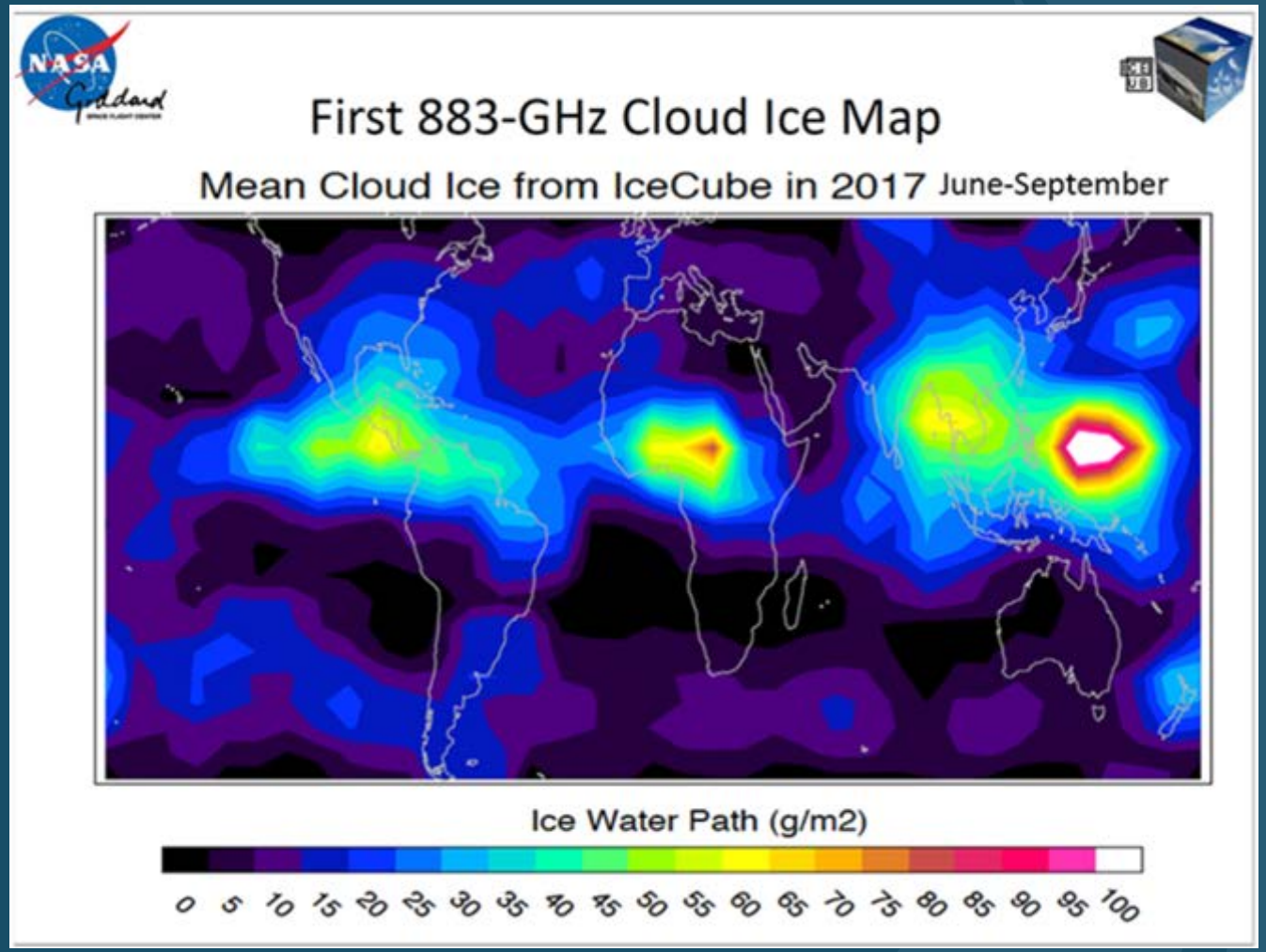


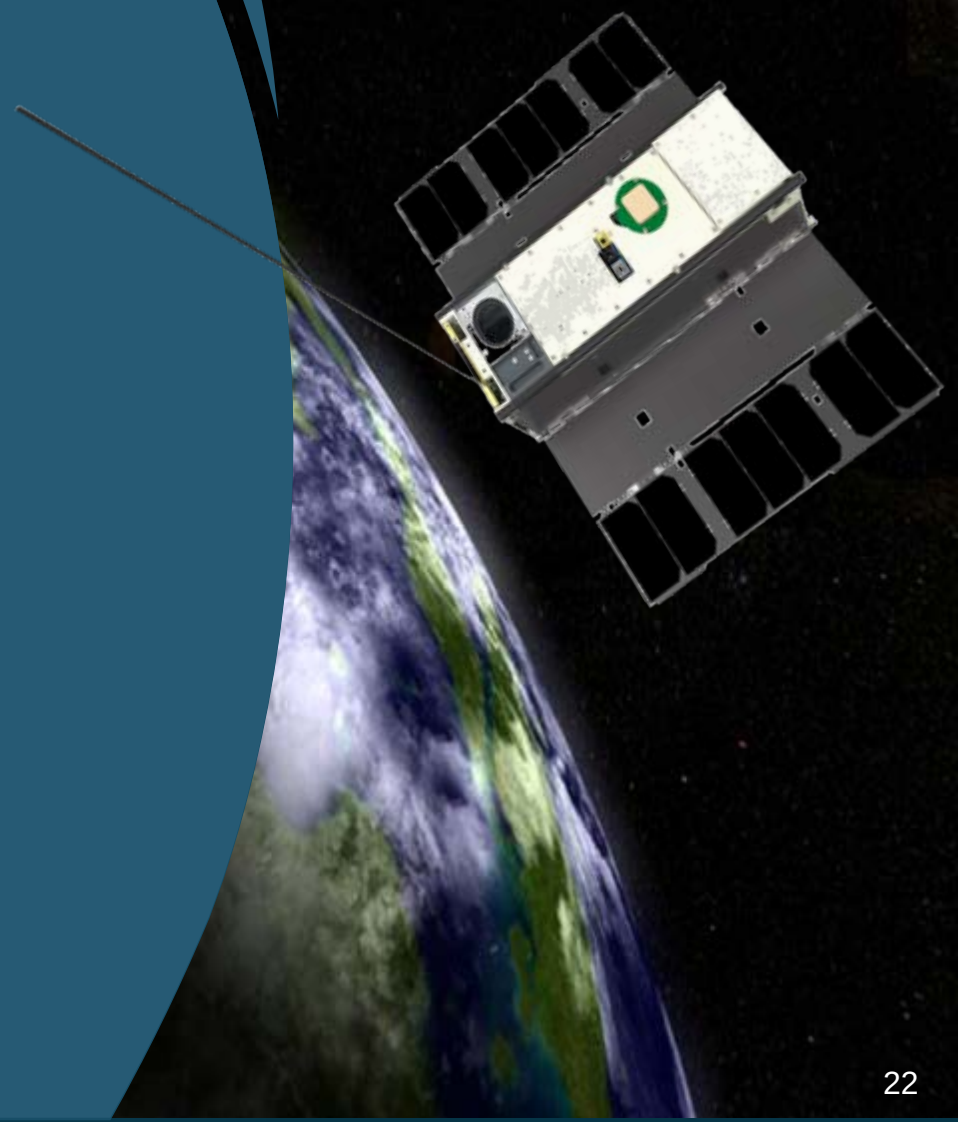
RAVAN demonstrates new technologies that enable future Earth radiation budget (ERB) measurements and establishes a benchmark for an ERB small satellite constellation.

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

IceCube

883 GHz submm-Wave radiometer

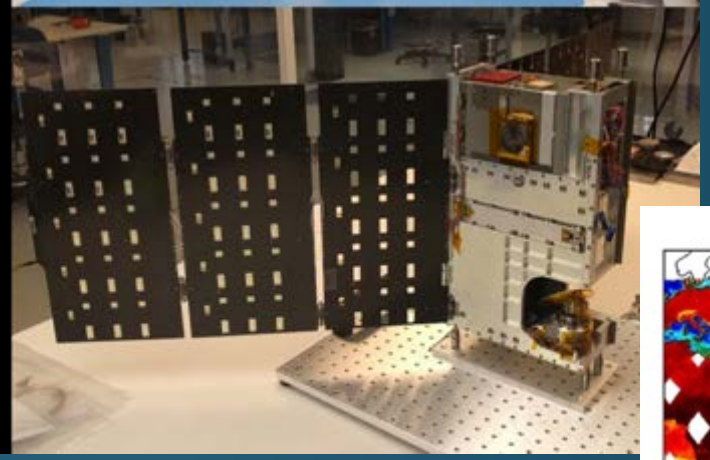




IceCube was the first ever global 883-GHz Cloud Ice Map.

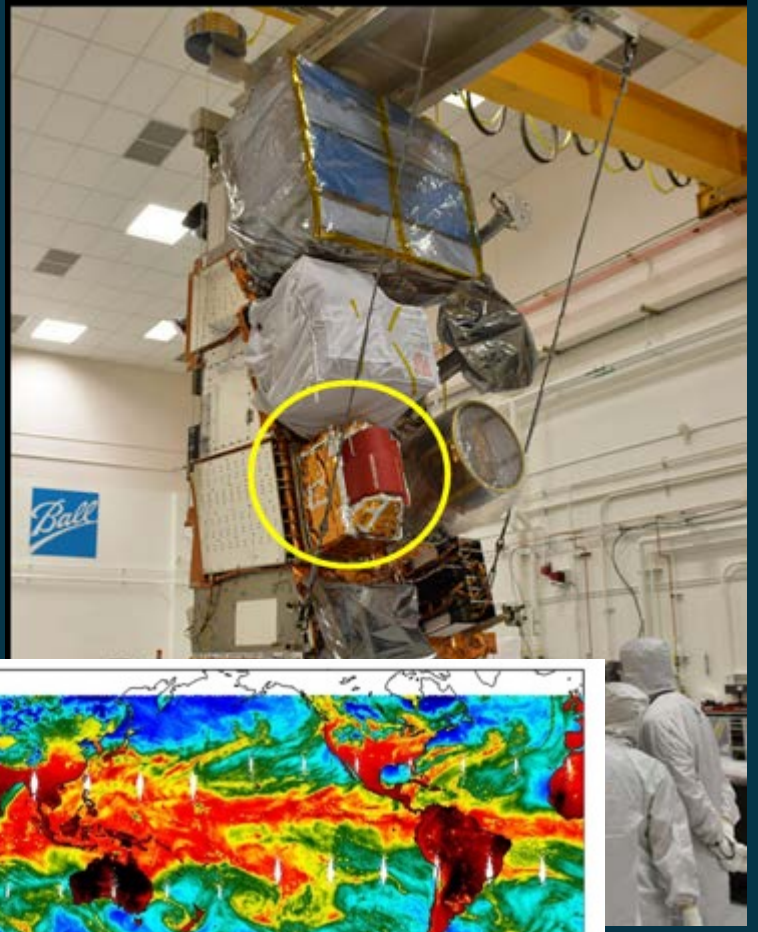
Comparison Between On-orbit Passive Microwave Sensors

Sensor A
TEMPEST-D
3.8 kg, 6.5 W,

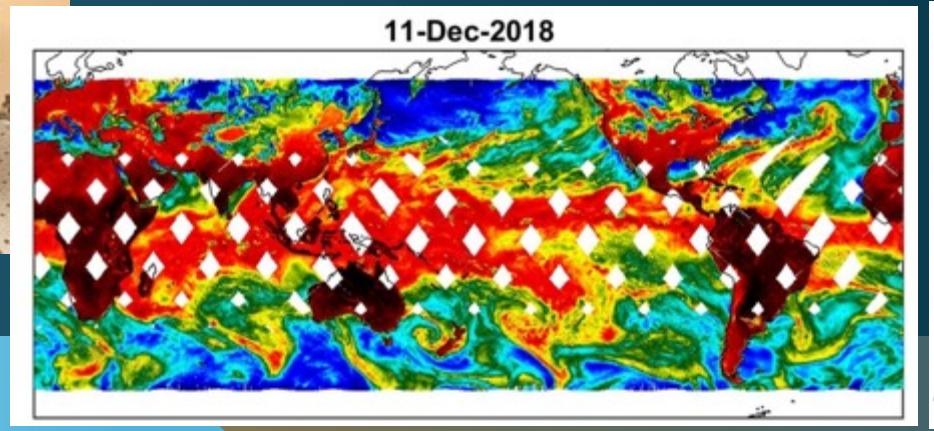


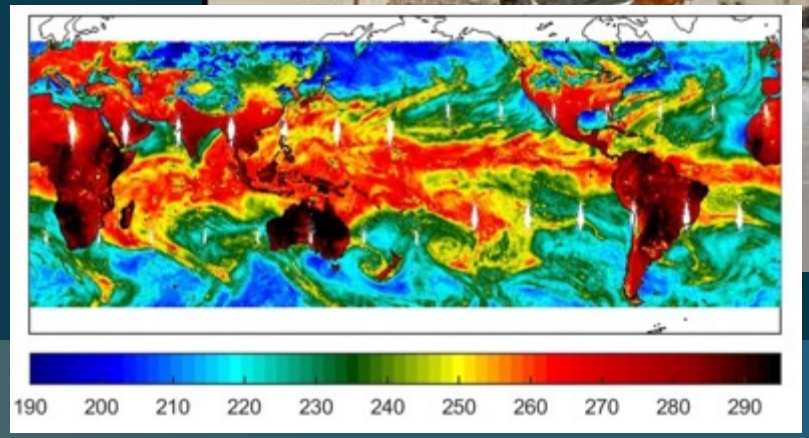
TEMPEST - D

Sensor B
NOAA Advanced Technology Microwave Sounder (ATMS)
75kg, 100W, $$$$



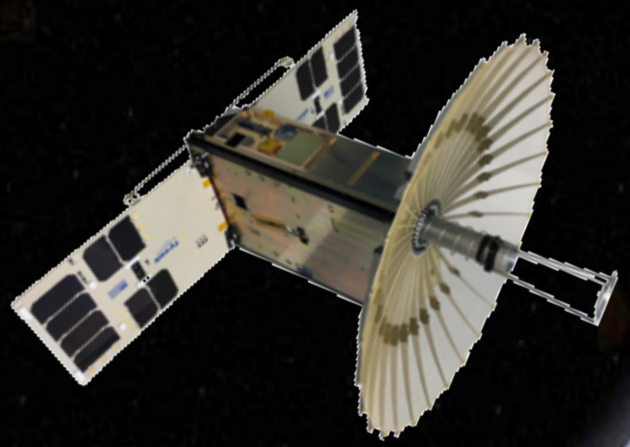
87 GHz Brightness Temperature (K)



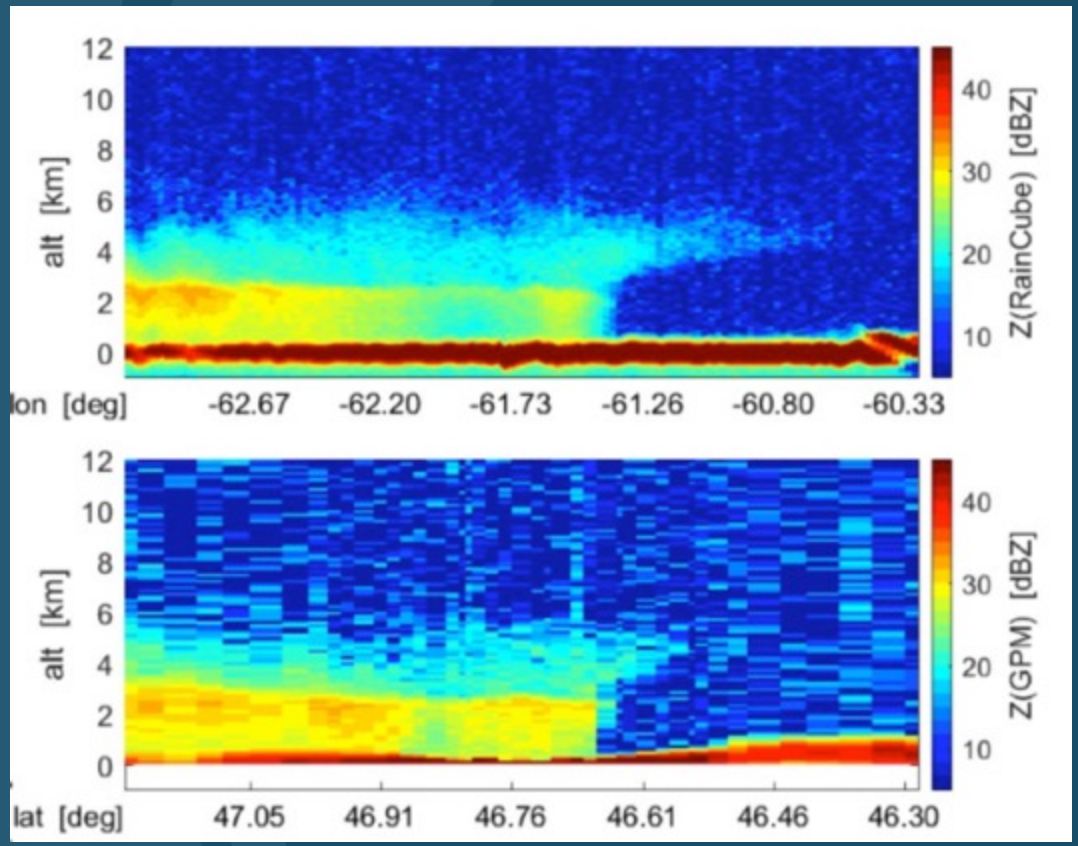


RainCube

First Ka-Band CubeSat Radar



RainCube / GPM Observations

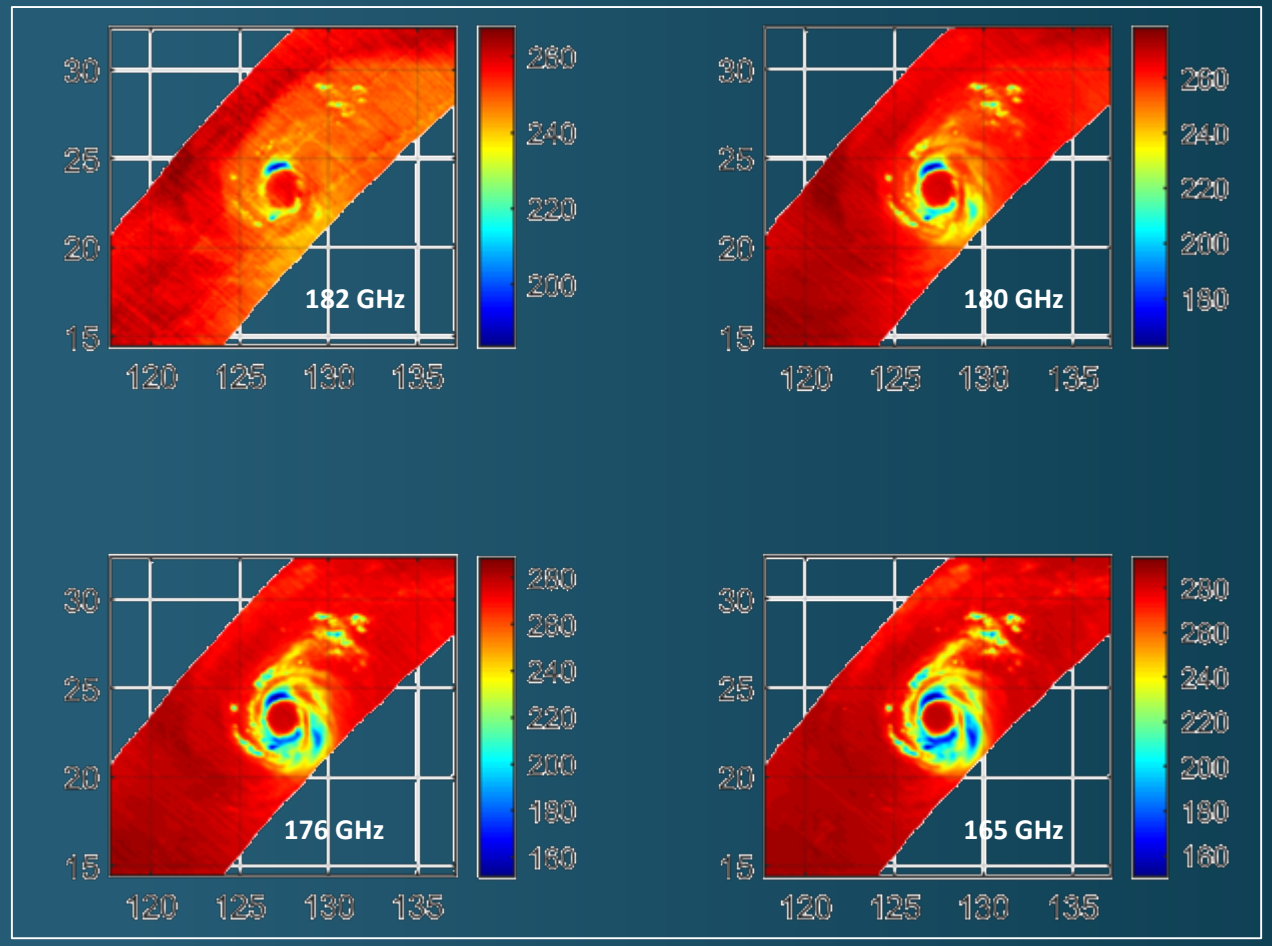


Jan. 2019 – Near-collocated measurements of vertical rain reflectivity profiles from RainCube (top) and GPM's Ka-band radar (bottom)

RainCube points Nadir while GPM scans along-track

RainCube/TEMPEST-D Observing Typhoon Trami

Spacecraft constellation separated by 5 minutes revealing 3D storm structure



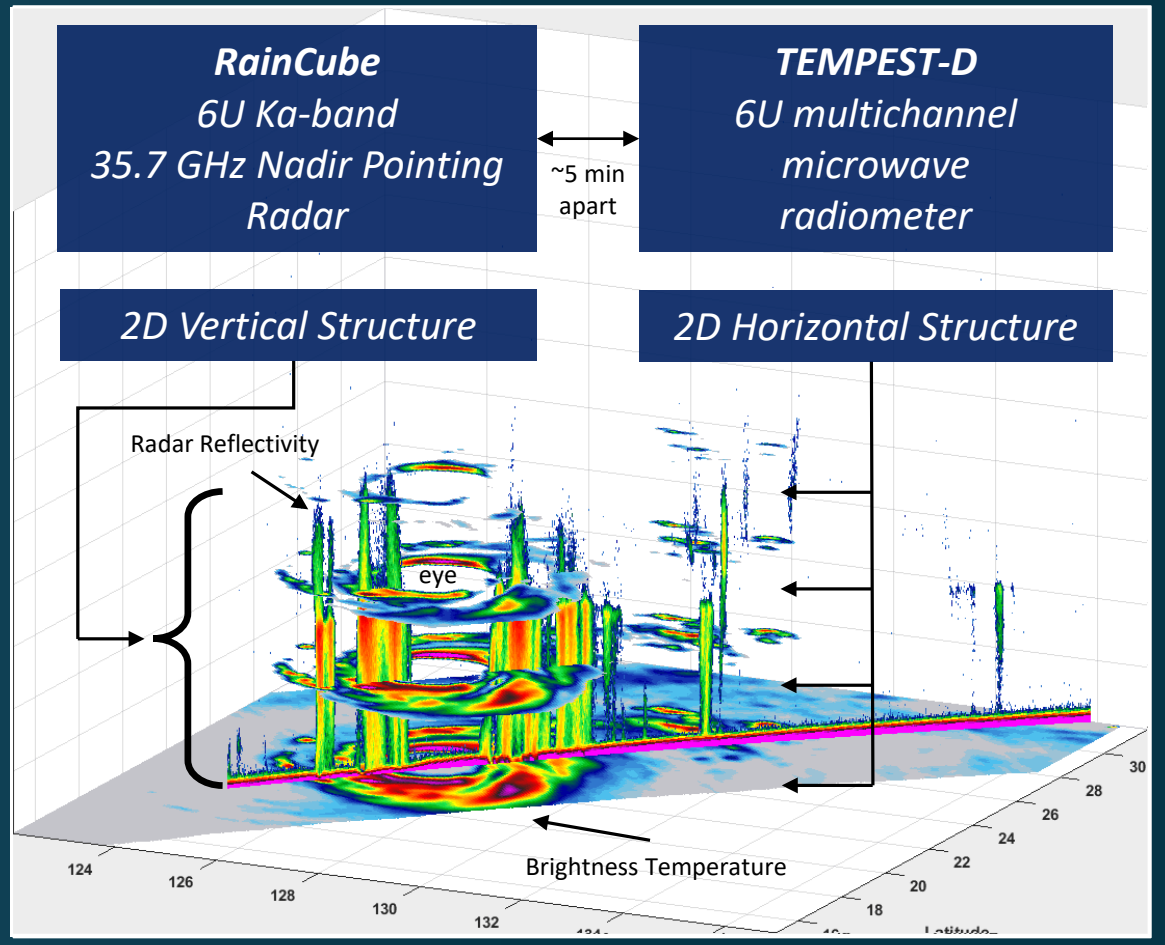


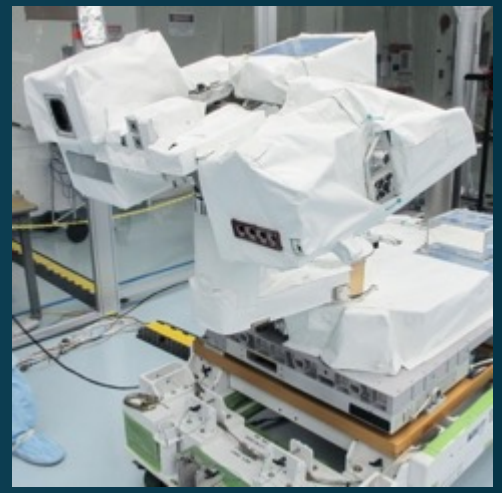
Illustration of complementary nature of these sensors flown in constellation for observing precipitation

CSIM-FD

Compact Solar Irradiance Monitor Flight Demonstration

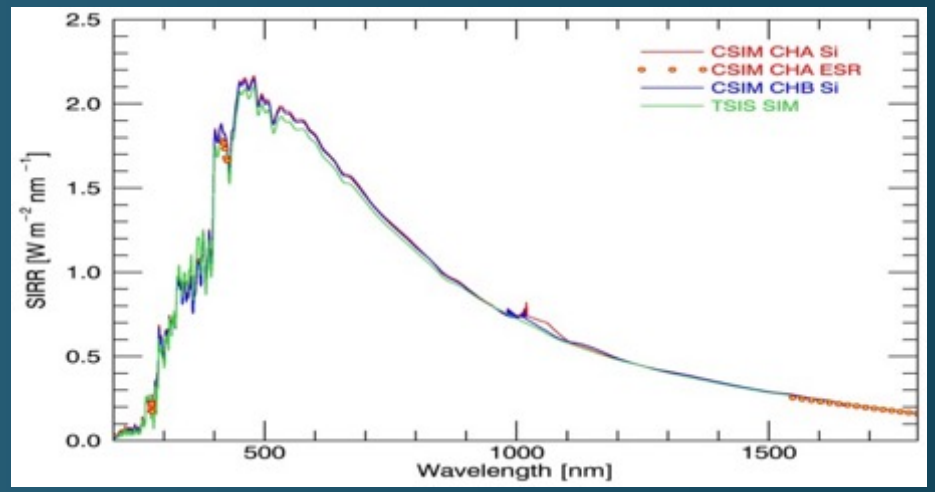
Measuring solar spectral irradiance (SSI), and how solar variability impacts the Earth's climate, contributing to long-term continuity measurements from SORCE SIM and TSIS SIM

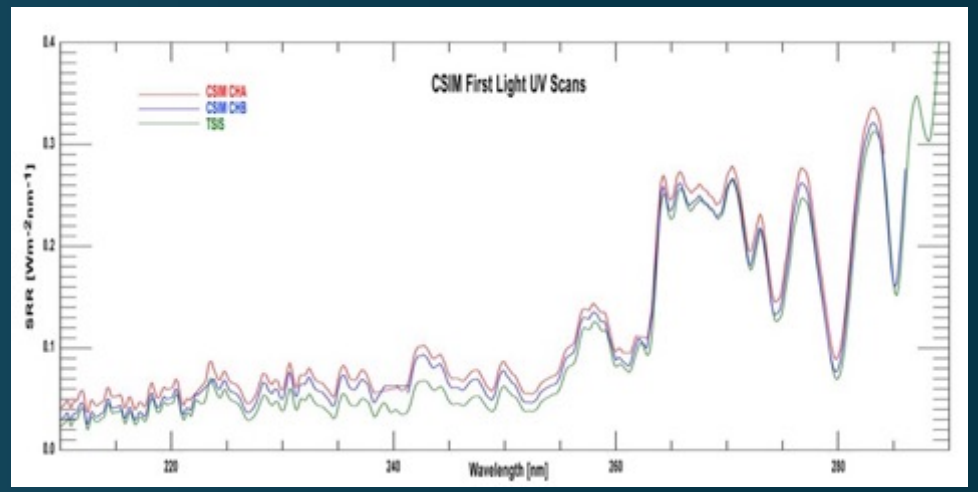
CSIM is 11 kg based on a Blue Canyon Technologies bus



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

EXPLORE EARTH

Summary

- The InVEST Program has 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