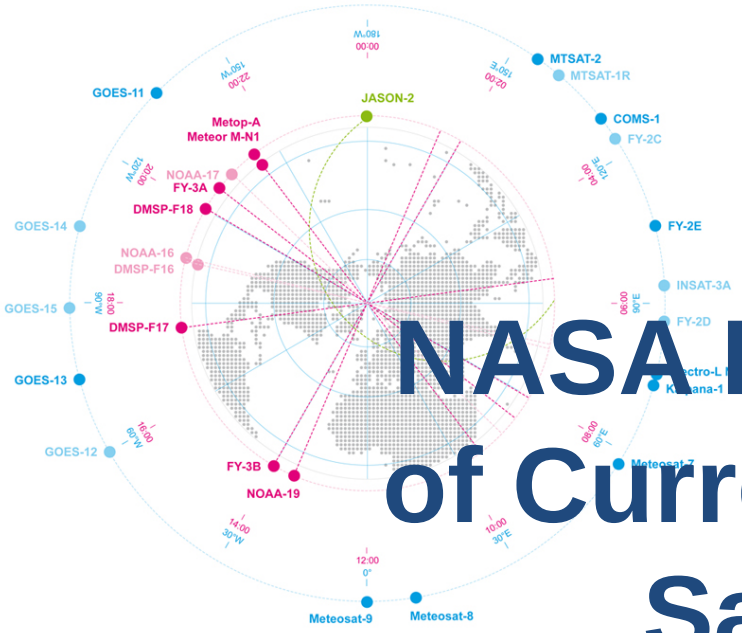

NASA Report on the Status of Current and Future Earth Satellite Systems

Presented to CGMS-44 Plenary Session, Agenda Item D.12

Presenter: Jack Kaye, NASA Headquarters

Report prepared based on inputs from numerous colleagues at NASA HQ, NASA Centers (GSFC, JPL, LaRC, MSFC) and broader research community

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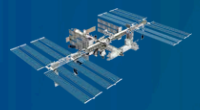
Earth Science Missions

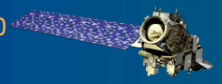


ISS Instruments

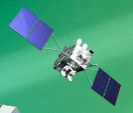
CATS, LIS, SAGE III
TSIS-1, ECOSTRESS, GEDI
CLARREO-PF*, TSIS-2

JPSS-2 Instruments

RBI*, OMPS-Limb



- Formulation
- Implementation
- Primary Ops
- Extended Ops



Landsat 9

PACE*

GeoCarb

TROPICS (12)

MAIA

Sentinel-6A/B

NISAR

SWOT

TEMPO

GRACE-FO (2)

ICESat-2

CYGNSS (8)

NISTAR*, EPIC*
(DSCOVR / NOAA)

SMAP

Landsat 7
(USGS)

QuikSCAT

SORCE,
TCTE (NOAA)

Suomi NPP
(NOAA)

Terra

Landsat 8
(USGS)

Aqua

CloudSat

CALIPSO

GPM

Aura

GRACE (2)

OSTM/Jason 2
(NOAA)

OCO-2

* Instrument operation or development continues through FY17 consistent with the FY2017 Consolidated Appropriations Act. Identified for termination in FY18 in the President's FY18 Budget Proposal released

05.17.17

Overview of NASA's current and future satellite systems

Mission	Launch (CY)	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
QuickScat	1999																										
Landsat-7	1999																										
Terra	1999																										
GRACE	2002																										
Aqua	2002																										
SORCE	2003																										
Aura	2004																										
CALIPSO	2006																										
CloudSat	2006																										
Jason-2	2008																										
Suomi-NPP	2011																										
Landsat-8	2013																										
GPM Core	2014																										
OCO-2	2014																										
CATS-ISS	2015																										
SMAP	2015																										
DSCOVR*	2015																										
CYGNSS	2016																										
SAGE-III_ISS	2017																										
LIS-ISS	2017																										
TSIS-1-ISS	2018																										
ECOSTRESS-ISS	2018																										
GRACE-FO	2018																										
ICESat-II	2018																										
CSIM	2018																										
GEDI-ISS	2019																										
TROPICS	2019																										
CLARREO PF-ISS*	2020																										
TSIS-2-ISS	2020																										
Landsat-9	2020																										
TEMPO	≥2020																										

Current Missions – 20 total (as of June 2017)

End dates may reflect NASA "Senior Review" approved dates, but these missions will likely operate longer.

By 2020, 5 spacecraft and 6 instruments launched (not including tech demo CubeSats)

Typical NASA missions are planned for 3 to 5 years but have operated much longer.

Future missions and instruments with launches >2020 *(not shown in the figure)*

SWOT, MAIA, NISAR, PACE, RBI*, GeoCarb*

* Instrument operation or development continues through FY17 consistent with the FY2017 Consolidated Appropriations Act. Identified for termination in FY18 in the President's FY18 Budget Proposal released May 23, 2017.

Current NASA Satellites ... Recent News

- NASA is currently supporting operations of **20 Earth Science missions**.
- Three new missions have launched since CGMS-44. One constellation of 8 spacecraft : **CYGNSS**, and two instruments hosted on the ISS **SAGE III** and **LIS**.
- Several new missions are scheduled for launch next year. These include: **GRACE-FO, ICESat II, CSIM, TSIS-1-ISS, and ECOSTRESS-ISS.**
- The **RapidSCAT** mission on the ISS ended data collection in August 2016 due to an unrecoverable power anomaly. The **EO-1** mission was decommissioned in March 2017 per the Senior Review process, data continues to be available through the USGS EROS data center.
- All missions are currently producing data, but several also show signs of aging resulting in reduced data collection. Updadtes to issues reported on last year include:
  - The **GRACE** and **QuikSCAT** missions will likely end operations in approximately the next 12 months; and
  - Instruments with reduced capability include **Aqua AMSU** (Channels 1,2,4,5,7 have failed), **Aura's TES** (no global survey, and has experienced frequent stalls), and **SORCE and CloudSat** (battery degradation, collecting data in day only mode).
- Not mentioned in the past CGMS reports has been NASA's partnership with the USGS for the Landsat series of spacecraft. The current (**Landsat-7 and -8**) and planned (**Landsat-9**) missions have been added to this report for completeness.

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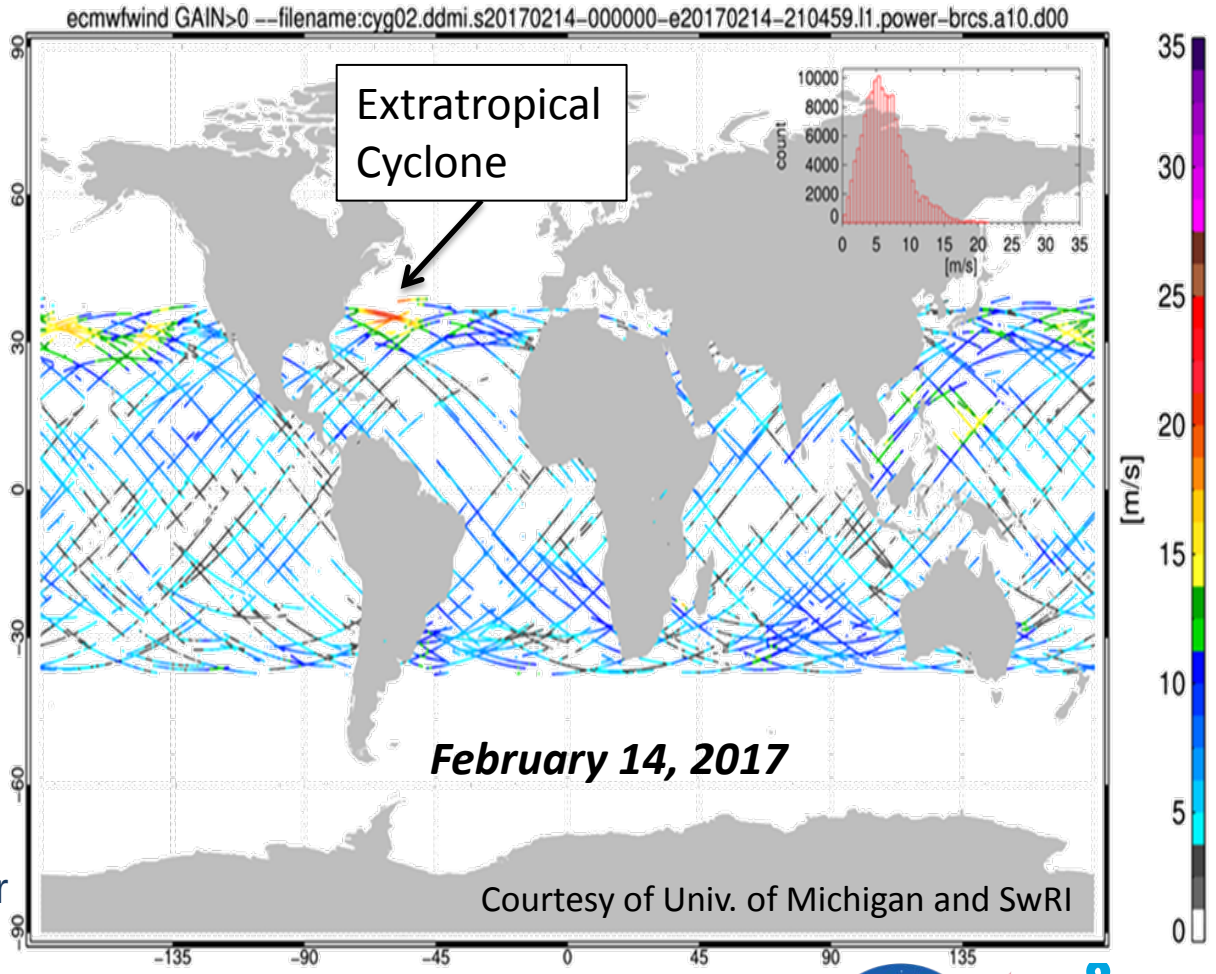
Current NASA Satellites ... Ongoing Activities

- NASA's missions were conceived as research missions, but have supported **operational and near-real-time applications** due to their recognized value, longevity, sustained calibration and validation, and data quality.
- Continued operation of the missions is determined through a biennial science review process, called the "**Senior Review**", which considers operational use but primarily uses science for defining factor for continuation. The latest Senior Review concluded in spring 2017, and results will be made available in summer 2017.
- **Direct Broadcast** is currently available for three NASA missions including: Aqua, Terra, and Suomi-NPP. More information can be found at NASA's Direct Readout Laboratory (DRL) website: http://directreadout.sci.gsfc.nasa.gov
- NASA also provides access to **Near Real-Time (NRT)** products from the MODIS (on Terra and Aqua), OMI and MLS (on Aura), and AIRS (on Aqua) instruments in less than 2.5 hours from observation from the Land and Atmosphere Near real-time Capability for EOS (LANCE) data system at http://earthdata.nasa.gov/lance

Cyclone Global Navigation Satellite System (CYGNSS) Mission

- 1st in NASA's Earth Venture Mission series.
- Launched into low-inclination, low-Earth orbit over the tropics on December 15, 2016
- Successfully completed the development and on-orbit commissioning phases of its mission on March 23 and moved into the science operations phase (Phase E)
- The first science data released in May, 2017
- Demonstrated ability to observe surface winds in major storms during its flyover of Tropical Cyclone Enawo, on March 6, just hours before its landfall over Madagascar



Coverage of ocean surface wind measurements made by one of the eight spacecraft in the CYGNSS constellation over the course of 4 orbits (~6 hours)

Lightening Imager Sensor on ISS (LIS-ISS)

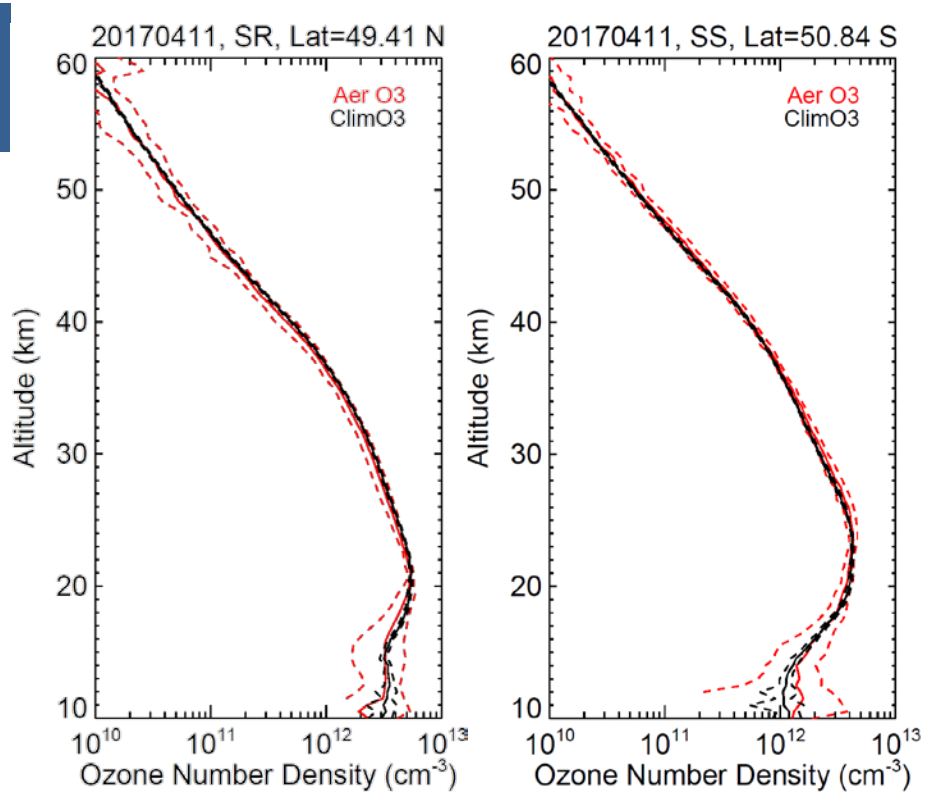
- Launched February 19, 2017. Saw first light February 27, 2017.
- Extends 17-year record of tropical lightning measurements from the Tropical Rainfall Measuring Mission, and expands coverage to higher latitudes.
- Supports cross platform cal/val with the new Geostationary Lightning Mapper (GLM), launched November 2016 on NOAA's GOES-16.
- Real-time data will be made available for the first time with this mission via NASA's Land, Atmosphere Near rea-time Capability for EOS (LANCE) program.

Stratospheric Aerosol and Gas Experiment III on ISS (SAGE III-ISS)

SAGE III-ISS, **launched on February 19, 2017**, will monitor the vertical distribution of aerosols, ozone, and other trace gases in the Earth's stratosphere and troposphere.

O_3 Profiles

- SAGE III-ISS zonal mean (**red line**) sunrise (SR) or sunset (SS) compared to Damadeo SAGE II Ozone Climatology (**black line**).
- Dotted red uncertainty lines represent the zonal variance.
- Dotted black uncertainty lines represent variance of QBO, Solar, ENSO, and other factors.



Future NASA Satellites

- NASA's plans include the launch of **14 missions and 8 instruments** in the future.
- **GRACE-Follow-on (FO) and CSIM** are scheduled for launch in early 2018 and will continue the precise measurement of the Earth's dynamic gravity field and solar spectral irradiance, respectively.
- **ICESat-2** is scheduled for launch in late 2018 and will provide measurements of ice sheet elevation change and global vegetation biomass.
- **TSIS-1 and ECOSTRESS** are hosted instruments to be deployed onto the International Space Station (ISS) in 2018. TSIS-1-ISS will measure solar spectral irradiance, and ECOSTRESS-ISS will measure plant-water dynamics.
- NASA is formulating and/or developing **more future missions and/or instruments** including:
  - Global Ecosystem Dynamics Investigation instrument on the ISS (**GEDI-ISS**)
  - Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (**TROPICS**) mission
  - CLARREO Pathfinder instrument on the ISS (**CLARREO PF-ISS***)
  - **Landsat-9** mission
  - Total and Spectral Irradiance Sensor 2 on the ISS (**TSIS-2-ISS**)
  - Tropospheric Emissions: Monitoring of Pollution (**TEMPO**) instrument on a GEO host mission
  - Geostationary Carbon Cycle Observatory (**GeoCarb**)
  - Radiation Budget Instrument (**RBI***) on the JPSS-2 satellite
  - Surface Water Ocean Topography (**SWOT**) mission
  - NASA ISRO-Synthetic Aperture Radar (**NISAR**) mission
  - Pre-Aerosols, Carbon and Ecosystems (**PACE***) mission
  - Multi-Angle Imager for Aerosols (**MAIA**) mission

* Development continues through FY17 consistent with the FY2017 Consolidated Appropriations Act. Identified for termination in FY18 in the President's FY18 Budget Proposal released May 23, 2017.

Evolution of the Solar Spectral Irradiance Monitor: SORCE to TSIS to CSIM

SORCE SIM (launched 2003)

- Two channel duty-cycled instrument
- First generation absolute Electrical Substitution Radiometer (ESR) detector with Nickel Phosphide (NiP) black coated bolometer
- 200-2400 nm (continuous)
- Abs. accuracy: 2-10% wavelength dependent (no-SI validation)

TSIS SIM (planned launch November 2017)

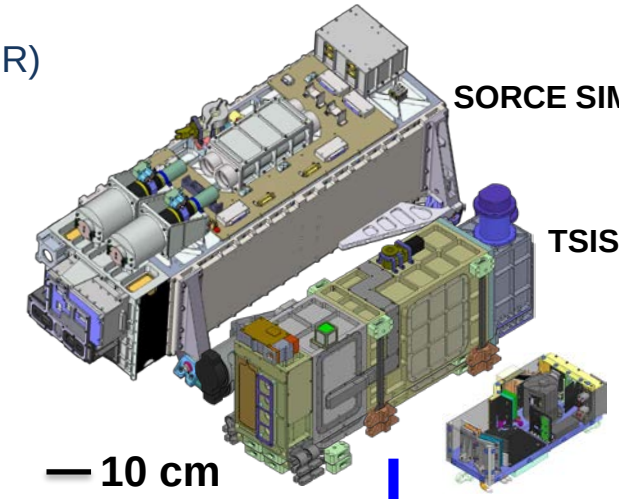
- Three channel duty-cycled instrument
- Second generation absolute ESR detector NiP black coated bolometer with improved noise performance
- 200-2400 nm (continuous)
- Abs. accuracy – 0.2 % (SI-traceable validation)

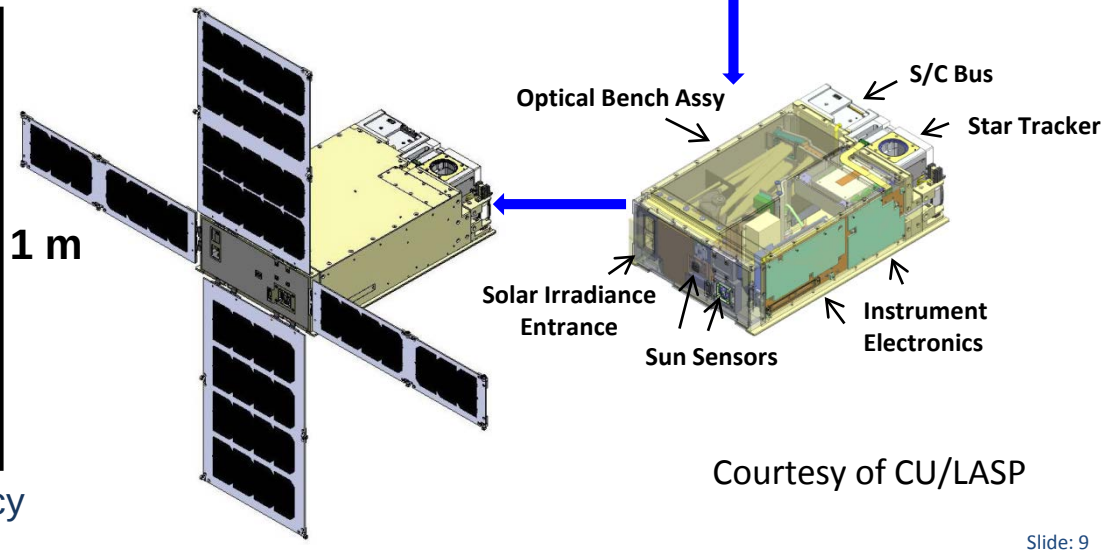
CSIM (6U CubeSat 2018)

- Two channel duty-cycled instrument
- Third generation absolute ESR detector with vertically–aligned C nanotube (VACNT) coated bolometer with best noise performance
- 200-2400 nm (continuous)
- Abs. accuracy – 0.2 % (SI-traceable validation)

CSIM offers new opportunities:

1) To develop and demonstrate novel technologies validated against dedicated state-of-the-art solar irradiance missions.
2) To meet required SI-traceable SSI accuracy and stability with reduced size and cost.

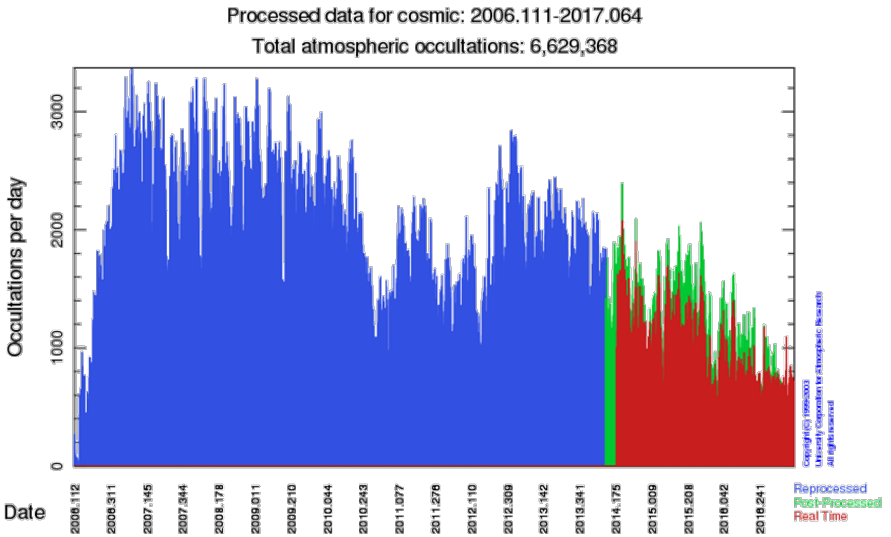




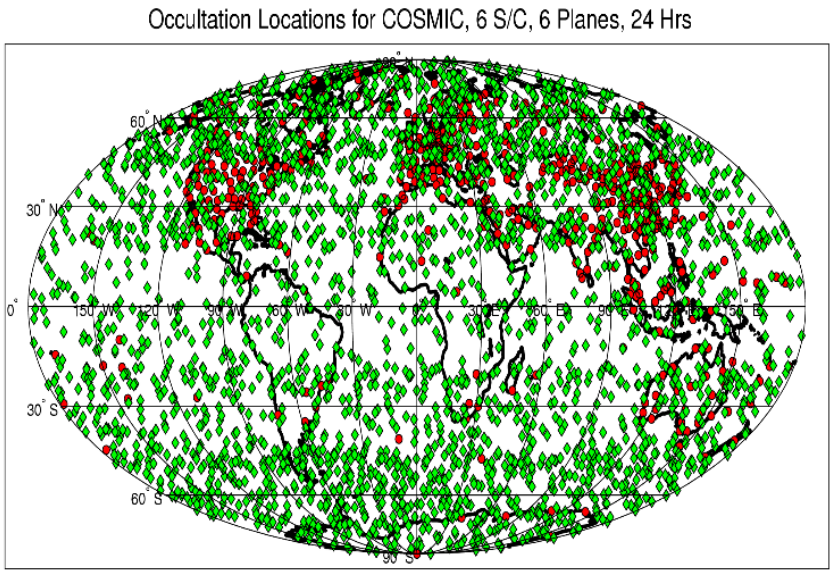
Courtesy of CU/LASP

COSMIC

- **Joint US/Taiwan GPS Radio Occultation mission**
  - 6 Satellites launched in April 2006
  - NASA/JPL developed GPS RO receiver
  - UCAR COSMIC Program performing mission operations, data processing, and research
  - NASA supports a multi-institution RO science team
- **Mission Objective: Global soundings for weather, space weather and climate applications**
  - Atmosphere: profiles of bending angle, refractivity, temperature, pressure, humidity
  - Ionosphere: total electron content, electron density profiles, scintillation
- **COSMIC-1 providing between 200 - 700 RO soundings per day from 2 satellites**
  - Demonstrated positive impact on NWP forecasts
  - >6.6M high-resolution profiles available for research
  - >440 COSMIC publications between 2006-15
  - >3,800 users from 88 countries
- **COSMIC-2/FORMOSAT-7 equatorial launch no earlier than December 2017 (six satellites)**



UCAR www.cosmic.ucar.edu



Successful Launch and Ops for RAVAN CubeSat

The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) CubeSat mission launched on **November 11, 2016** as a secondary payload on a ULA Atlas V rocket from Vandenberg Air Force Base.

Developed at Johns Hopkins Applied Physics Lab, with funding through the NASA InVEST program**, RAVAN is demonstrating new technology for measurements of Earth's radiation budget.** RAVAN features small, accurate radiometers to measure the strength of the Earth's total outgoing radiation across the entire spectrum of energy, from the ultraviolet to the far infrared.

Vertically aligned carbon nanotubes (VACNTs) serve as the radiometer's light absorber and are enabling the radiometers to gather virtually all the light reflected and emitted from Earth.

Gallium fixed-point black body calibration source serves as a stable and repeatable reference to track the long-term degradation of the sensor.

RAVAN was one of seven CubeSats aboard the Atlas 5A rocket that carried the WorldView-4 satellite into orbit.
(Credit: United Launch Alliance/Lockheed Martin)

Top Right: *Part of the VACNT Radiometer. The dark patch in the center is a small "forest" of nanotubes.* ***Middle Right:*** *An illustration featuring the RAVAN instrumentation.* ***Bottom Right:*** *A model of the RAVAN spacecraft with fully deployed solar panels*

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ESTO Earth Science Technology Office

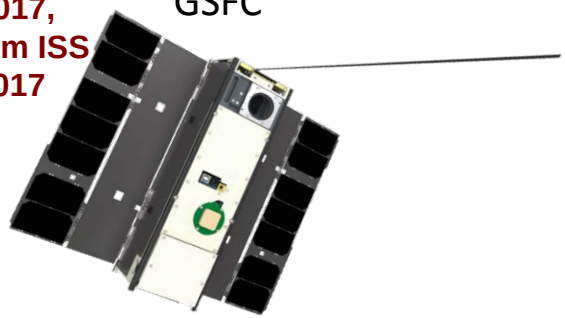
NASA

CGMS

3U CubeSats: (1) Deployed and (2) Manifested to Launch 2017

ICECube
GSFC

Launched April 18, 2017, Deployed from ISS May 16, 2017

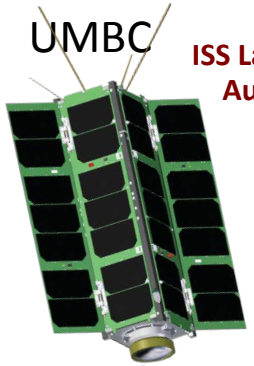


883 GHz submm-Wave radiometer

Validate sub-mm radiometer for spaceborne **cloud ice remote sensing**

HARP
UMBC

ISS Launch CRS NET August 1, 2017

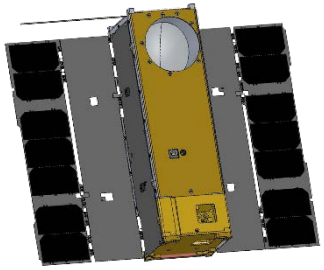


Wide FOV Rainbow Polarimeter

Validation of 2-4 km wide FOV hyperangular polarimeter for **cloud & aerosol characterization**

MiRaTA
MIT / MIT-LL

Launches with JPSS-1 NET Sept. 21, 2017



3 Frequency Radiometer and GPSRO

Validation of new microwave radiometer and GPSRO technology for **all-weather sounding**

6U CubeSats in Development for 2018-2019 Launch Readiness

RainCube
JPL

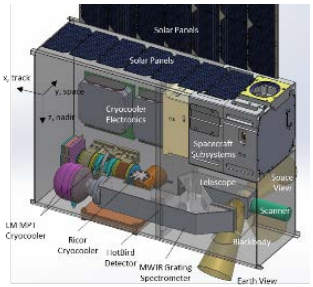
ISS Launch NET Q2 2018

Precipitation Radar

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

CIRAS
JPL

not manifested

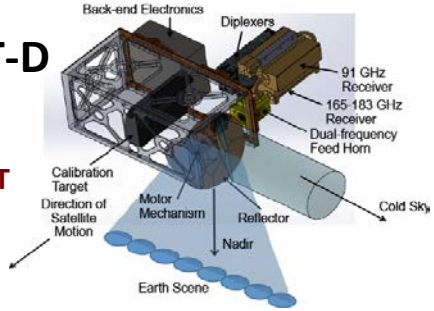


Infrared Atmospheric Sounder

Demonstrate ability to measure spectrum of upwelling infrared radiation and validate 2D infrared detector material and a grating spectrometer

TEMPEST-D
CSU

ISS Launch NET Q2 2018



5 Frequency mm-Wave Radiometer

Technology demonstrator **measuring the transition of clouds to precipitation**

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NASA

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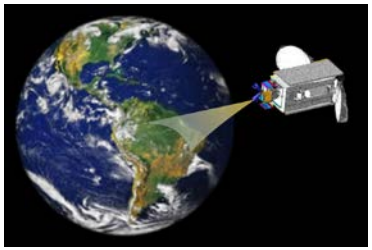
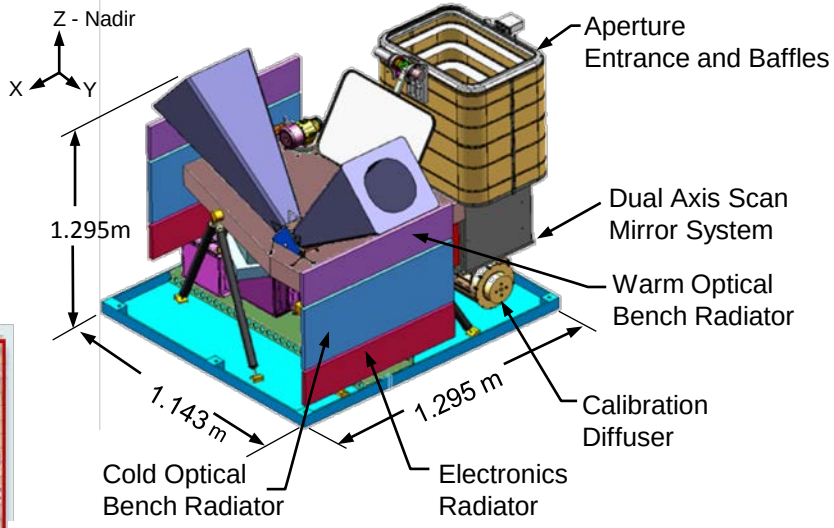
Recently Selected Research and Suborbital Investigations

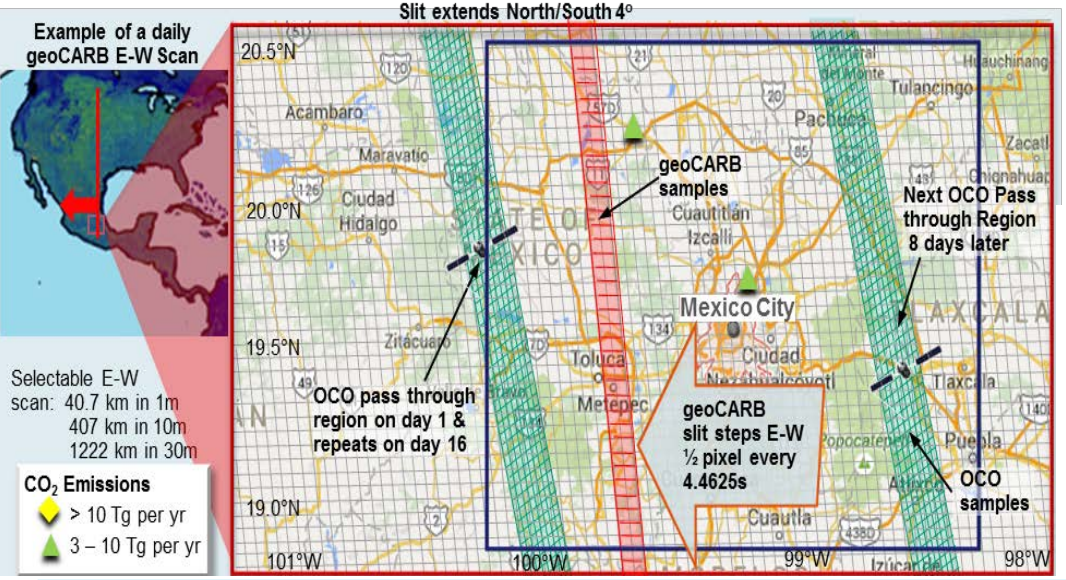


GeoCarb (*Geostational Carbon Observatory*): Will monitor plant health and vegetation stress throughout the Americas, and probe, in unprecedented detail, the natural sources, sinks and exchange processes that control carbon dioxide, methane, carbon monoxide and solar induced chlorophyll fluorescence (SIF) in the atmosphere

- 2nd in the NASA Earth Venture Mission series
- Expected launch in 2021 as hosted payload on commercial satellite
- Deployed in a GEO orbit above 85° West longitude
- Measures O_2, CO_2, CH_4, CO, and SIF at a spatial resolution of 5-10 km multiple times each day

Instrument Complement





- Moving the slit from East to West, GeoCarb provides continental-scale “mapping-like” coverage.

Left: *Grid pattern produced by GeoCarb sampling superimposed on map of OCO-2 tracks (green). Red shading indicates a single GeoCarb observation time, individual red boxes represent GeoCarb footprints.*

Recently Selected Research and Suborbital Investigations

Satellite Calibration Interconsistency Studies *(SCIS)*: 12 projects were selected in August 2016 to conduct quantitative comparisons of satellite data products from multiple providers, facilitating development of multi-instrument/-platform datasets; total funding is approximately $5.5M for a period of 3-years

Principal Investigator	Organization	Project Title
Brian Barnes	University of South Florida	Tampa Synergistic Multi-Sensor Calibration for Global and Coastal Observations of Aquatic Environments
Andreas Colliander	NASA/Jet Propulsion Laboratory	Intercalibration of Low Frequency Brightness Temperature Measurements for Long-Term Soil Moisture Record
Jeffrey Czapla-Myers	University of Arizona	Intercalibration of GEO and LEO Sensors Using the Radiometric Calibration Test Site (RadCaTS) at Railroad Valley, Nevada
David Doelling	NASA Langley Research Center	Open Access Spectral Band Adjustment Factors for Consistent Inter-Satellite Calibration and Retrievals
Eric Fetzer	NASA/Jet Propulsion Laboratory	A Merged Temperature and Water Vapor Record from Modern Sounders
Mathew Gunshor	University of Wisconsin, Madison	Re-Calibrate Water Vapor Bands from International Geostationary Satellites for Consistency with AIRS
Christian Kummerow	Colorado State University	A Long-Term Satellite Climate Data Record of Global Precipitation
Can Li	University of Maryland, College Park	Producing Consistent Trace Gas Retrievals Through Inter-Calibration of Hyperspectral UV Measurements from OMI and GOME-2A
Hamidreza Norouzi	New York City College of Technology	A Multi-Sensor Calibration Algorithm for Improving Emissivity Retrieval by Integrating Microwave Brightness Temperature Diurnal Cycle
Lawrence Strow	University of Maryland Baltimore County	A Homogenous Infrared Hyperspectral Radiance and Level 3 Climate Record Combining NASA AIRS, JPSS CrIS, and EUMETSAT IASI
Eric Vermote	NASA Goddard Space Flight Center	Toward a Consistent Land Long Term Climate Data Record from Large Field of View Polar Orbiting Earth Observation Satellites
Juying Warner	University of Maryland, College Park	Tropospheric Ammonia Derived from AIRS and CrIS for a More Continuous Data Record Using a Uniform Retrieval Algorithm

Recently Selected Research and Suborbital Investigations

Earth Science U.S. Participating Investigators *(USPI)*: 7 projects were selected in February 2017 that will expand scientific links with future European and Asian space missions; total funding is approximately $5.1M for a period of 5-years

Principal Investigator	Organization	Project Title
Ralf Bennartz	Vanderbilt University	Information Content Analysis and Algorithm Development Passive Microwave Systems for Atmospheric Monitoring
Douglas Mach	Universities Space Research Association, Columbia	U.S. and European Geostationary Lightning Sensor Cross-Validation Study
Peter Minnett	University of Miami, Key Biscayne	Sea-Surface Temperatures from Copernicus Sentinel-3s and EUMETSAT Polar System Second Generation (EPS-SG)
Vijay Natraj	NASA Jet Propulsion Laboratory	Retrieval of Aerosol Composition and Vertical Distribution Using Oxygen A-Band and Multi-angle Polarimetric Measurements from the EUMETSAT Polar System–Second Generation Satellite
Sassan Saatchi	NASA Jet Propulsion Laboratory	Development and Validation of Tropical Forest Aboveground Biomass Estimation from BIOMASS Mission Observations
Omar Torres	NASA Goddard Space Flight Center	Implementation of NASA-GSFC Tropospheric Ozone, Sulphur Dioxide and Aerosol Retrieval Algorithms at GEMS Viewing Geometry
Eric Vermote	NASA Goddard Space Flight Center	Sentinel 3 Data for Land Science: Calibration, Algorithm Development, Product Evaluation, Generation, and Validation

ACKNOWLEDGMENTS

Contributions to this report were made by the following:

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California Institute of Technology

Brian Killough
NASA Langley Research Center

Richard Blakeslee
NASA Marshall Space Flight Center

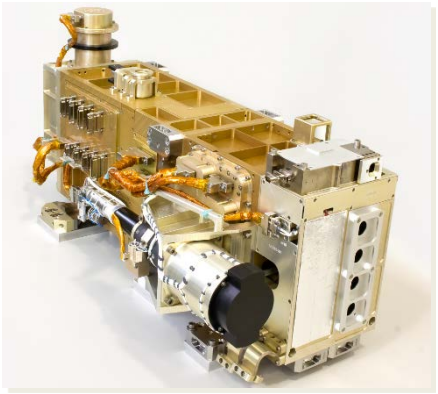
Peter Pilewskie and Erik Richard
University of Colorado Boulder
Laboratory for Atmospheric and Space Physics

William Schreiner
University Corporation of Atmospheric Research

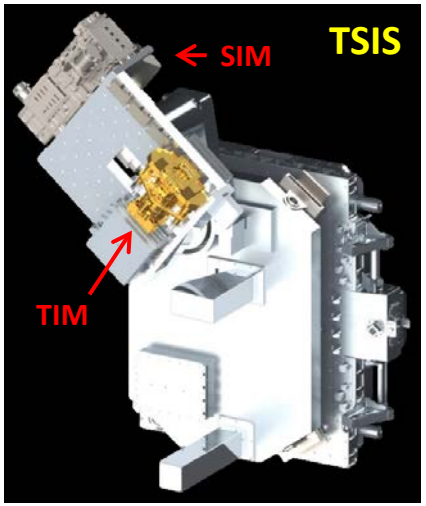
BACK UP

Total and Spectral Solar Irradiance Sensor on ISS (TSIS-1-ISS)

- Instruments: Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM)
- November 2017 launch and deployment on the International Space Station (ISS) with 5 year operational lifetime
- Continuation of total and spectral solar irradiance (TSI & SSI) measurements currently made by NASA's Solar Radiation and Climate Experiment (SORCE) & the Total solar irradiance Calibration Transfer Experiment (TCTE)



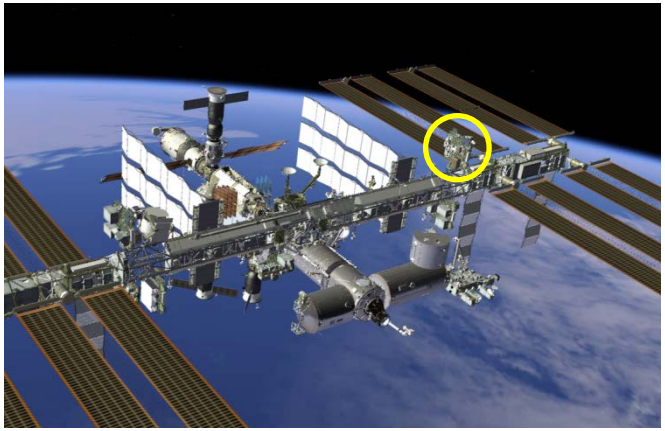
TSIS SIM instrument



TSIS with SIM and TIM instruments

Spectral Solar Irradiance Monitor (SIM)

- Measure SSI from 200 to 2400nm with 0.2% absolute accuracy, 0.01% relative measurement precision, corrected for instrument drift at <0.05 %/year
- Incorporates design changes from SORCE SIM to improve: long-term stability, wavelength registration, noise performance, and dynamic range
- Realizes improved absolute accuracy in absolute, NIST-traceable pre-launch calibration using LASP's Spectral Radiometer Facility (SRF)



November 2017 ISS location of TSIS on Express Logistics Carrier-3 (ELC-3)

Courtesy of CU/LASP

Coordination Group for Meteorological Satellites