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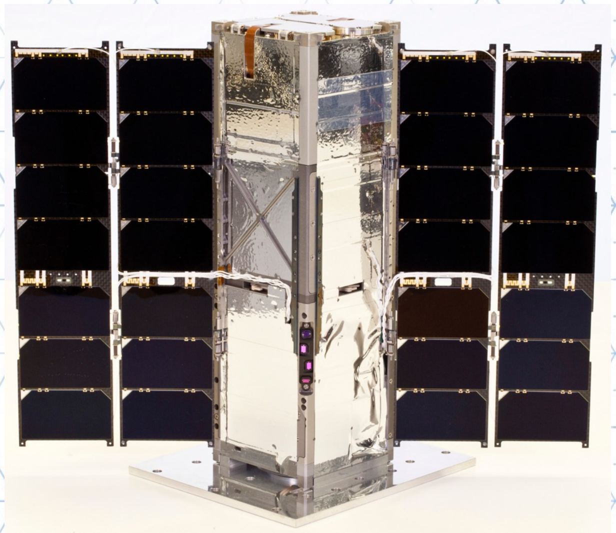
APPLIED PHYSICS LABORATORY

# The RAVAN CubeSat Demonstration of Earth Energy Budget Technologies: Challenges and Successes


William H. Swartz, Principal Investigator

Johns Hopkins University Applied Physics Laboratory


Funding: NASA Earth Science Technology Office

# et al.

- APL: Dewey Adams, Charles Anderson, Clint Apland, David Athman, Kimberly Bahr, Lance Baird, Kevin Balon, Lance Barley, Matthew Baughman, Debbie Berg, John Boldt, David Bonner, Gregory Bourn, Linda Bowles, Christopher Britt, Valerie Brockman, David Brownlie, Keith Bulkin, James Burgum, Richard Campbell, Carl Clayton, Christine Cook, Joseph Cook, David Copeland, Tina Craig, Misty Crawford, Alex Cruz, Jennifer Davis, **David Deglau**, Wayne Dellinger, Michael Desmarais, Anne Dietrich, Lars Dyrud, David Do, Robert Dobyns, Christian Drabenstadt, Peter Eisenreich, Lou Eline, Gregory Ellers, Howard Feldmesser, Terry Finney, Robert Focht, Johnny Fogle, John Folkerts, Malcolm Ford, Ryan Forrest, Robert Gaither, Michael Gardner, Donald Geyer, William Granger, Alan Grasley, Kimberly Griffin, Nymia Griffith, Steven Griffiths, Felicia Hastings, John Hayes, Kevin Heffernan, Mark Herring, Valerie Horky, Carolyn Hoskins, **Philip Huang**, Terry Huber, **Stephen Izon**, Walter Johnston, Matiwos Kafel, Lake Kee, Allen Keeney, Jaclyn Kilheffer, Jinho Kim, Henry Koenig, Haje Korth, Brittany Krok, Matthew Krok, Cidambi Kumar, Denise LaFluer, Wing Lam, David Lee, Sung Lee-Seck, Deborah Leopold, **Shawn Liang**, Sharon Ling, Timothy Lippy, Tara Lofton, William Luedeman, David Malick, **Kathryn Marcotte**, Michael Marley, Jacqueline Mattern, Douglas McKay, Ryan McMichael, Lauren Mehr, Jeffrey Metcalfe, Glenn Meyers, Robert Miller, Sharon Mills-Young, Elizabeth Mitchell, Cavin Mooers, Erica Morton, Hadi Navid, Kenneth Nelson, Matthew Noble, Marlene Nourbakhsh, Nicholas Nowicki, Miranda Oltman, Gary Palm, **Stergios Papadakis**, David Persons, Richard Pfisterer, Donna Pierce, Kevin Pionke, David Plank, Jonathan Prietz, Yatta Quire, Joseph Rahnis, Jane Ramsburg, Neal Reek, **Nolan Reilly**, **Sonia Reilly**, Kenneth Reinhardt, Matthew Reinhart, **Edward Reynolds**, Scott Robbins, David Roth, Rosemary Rubin, Robert Rye, Erika Sanchez, Andrew Santo, Cecil Santos, Anthony Scarpati, Charles Schlemm, Jean Schutt, Kevin Sibley, Fazle Siddique, David Sizemore, Raymond Smith, Ruthe Snyder, Sharon Stamer, Rhonda Strianese, Anthony Stump, Robert Summers, William Swartz, John Teehan, Jason Tiffany, Kenneth Turner, Zachary Ulbig, Rachel Verrill, James Walraven, Mary Washington, Andrew Webb, David Weir, Paul Weisman, Ed Wells, Paul Wescoat, Richard White, James Wiley, Curtis Wilkerson, Wendy Wyatt, Matthew Yeager, Joseph Yurek
- L-1 Standards and Technology: James Briscoe, **Steven Lorentz (also NISTAR)**, **Allan Smith**, Yinan Yu
- NASA/GSFC: **Warren Wiscombe, Dong Wu**
- Blue Canyon Technologies: **John Carvo**, **Tom Golden**, and others

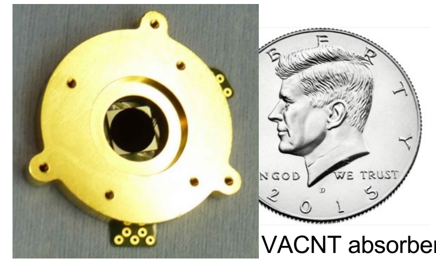
As of Oct 2017

# Outline

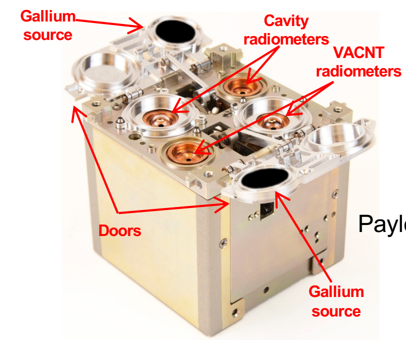
- Brief overview
  - Top-level summary
  - Key papers
  - Notable things about RAVAN
- Science motivation
- Technologies demonstrated
- (Selected) trials and tribulations
- RAVAN on-orbit results
- Lessons learned

# RAVAN is an Earth energy budget constellation pathfinder

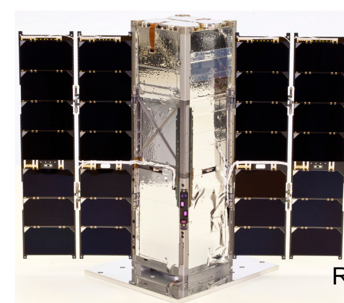
- RAVAN: Radiometer Assessment using Vertically Aligned Nanotubes
- CubeSat project **funded through NASA ESTO's InVEST program (InVEST-2012)**
- **Principally a technology demonstration**
- CubeSat = High-risk
- Led by Johns Hopkins University Applied Physics Laboratory (APL), Laurel, Maryland, USA
- Partners:
  - L-1 Standards and Technology (L-1): Steven Lorentz (NISTAR PI)
  - NASA/GSFC: Warren Wiscombe, Dong Wu
  - Blue Canyon Technologies (BCT)
- Pathfinder for an Earth energy (radiation) budget constellation
- Combines
  - **Vertically aligned carbon nanotube radiometer absorber** and black body emitter (APL)
  - **Gallium fixed-point black body calibration source** (L-1)
  - Compact, low-cost radiometer payload (L-1/APL)
  - 3U CubeSat bus, I&T, operations (BCT)
- Operated Nov 2016–Aug 2018



VACNT absorber

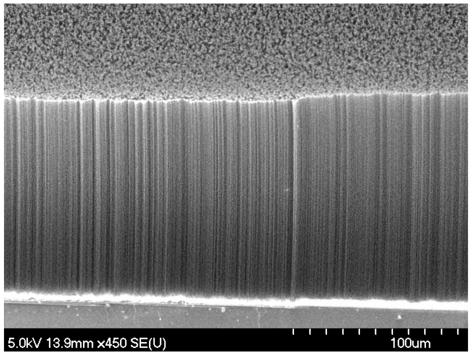



Payload



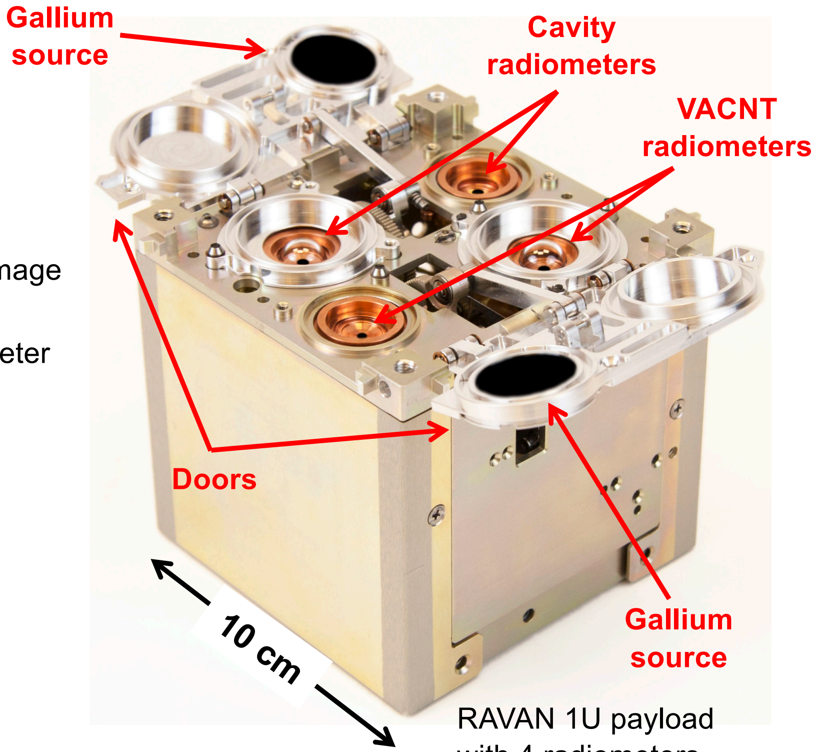
RAVAN

# Vertically aligned carbon nanotubes (VACNTs) are super black and compact—perfect for smallsat applications



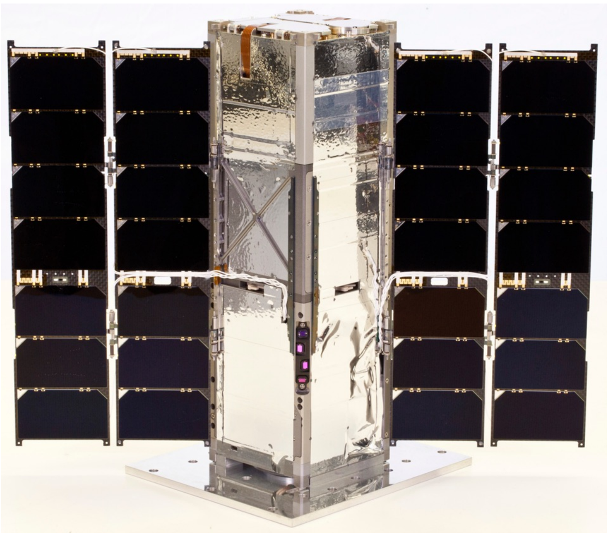

VACNT SEM image

RAVAN radiometer head

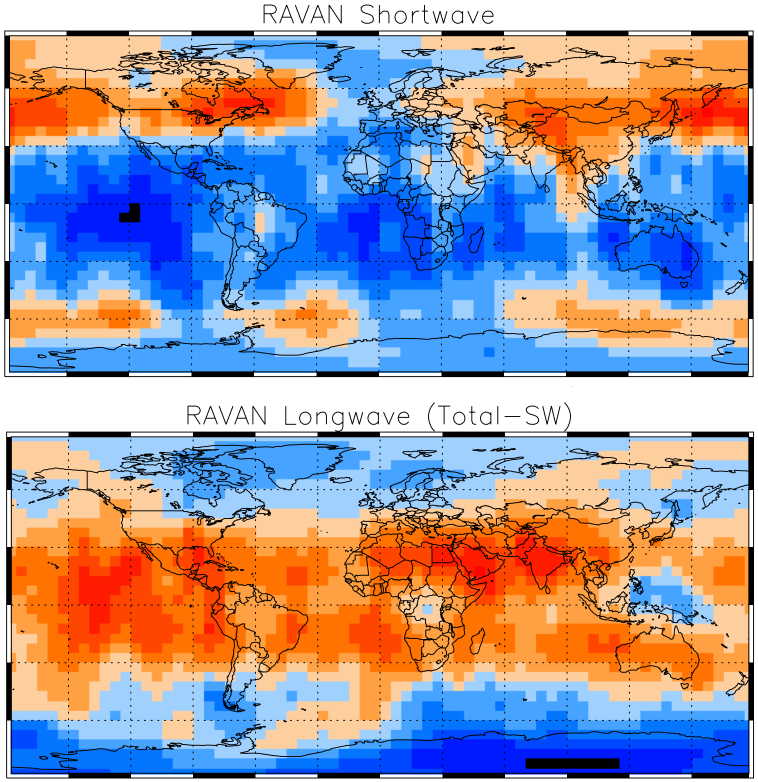



RAVAN 1U payload with 4 radiometers

# RAVAN proved VACNTs for Earth energy budget measurement from space



**RAVAN 3U CubeSat**
Nov 2016–Aug 2018 demo
(and still flying!)




Earth outgoing energy measurements from RAVAN [*Swartz et al.*, 2019]

VACNTs used as radiometer absorbers in new missions for solar irradiance and Earth energy budget:

- CSIM (2018)
- CTIM (2022)
- Libera, EVC-1 (2027)

# Principal RAVAN references

*remote sensing*

MDPI

*Article*

**RAVAN: CubeSat Demonstration for Multi-Point Earth Radiation Budget Measurements**

**William H. Swartz [1,*], Steven R. Lorentz [2], Stergios J. Papadakis [1], Philip M. Huang [1], Allan W. Smith [2], David M. Deglau [1], Yinan Yu [2], Sonia M. Reilly [1,†], Nolan M. Reilly [1,†] and Donald E. Anderson [1]**

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**Abstract:** The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) 3U CubeSat mission is a pathfinder to demonstrate technologies for the measurement of Earth's radiation budget, the quantification of which is critical for predicting the future course of climate change. A specific motivation is the need for lower-cost technology alternatives that could be used for multi-point

https://www.mdpi.com/2072-4292/11/7/796

SPIE

Invited Paper

**Carbon nanotube-based radiometers demonstrated on the RAVAN CubeSat mission**

William H. Swartz[a], Stergios J. Papadakis[a], David M. Deglau[a], Steven R. Lorentz[b], Allan W. Smith[b], and Philip M. Huang[a]

[a]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA
[b]L-1 Standards and Technology, Inc., Manassas, VA, USA

**ABSTRACT**

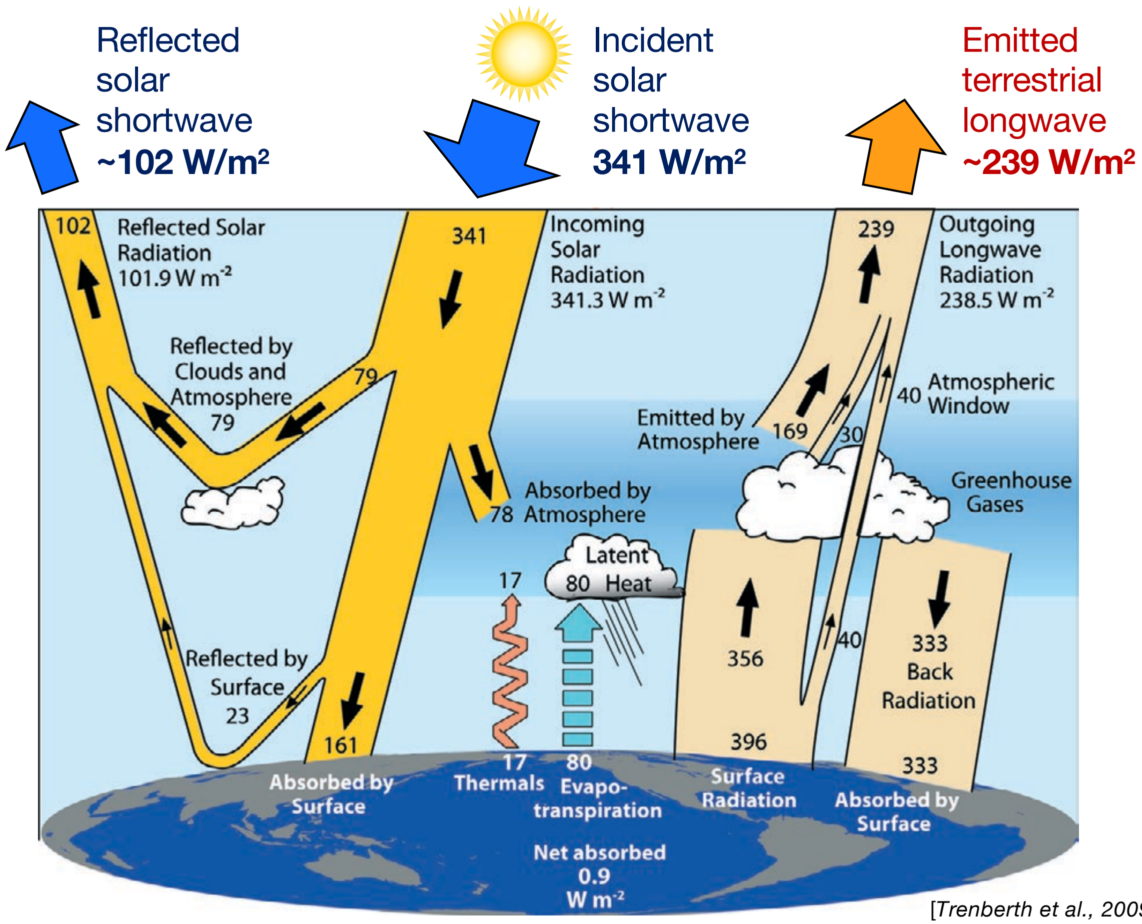
Measuring Earth's energy budget from space is an essential ingredient for understanding and predicting Earth's climate. We have demonstrated the use of vertically aligned carbon nanotubes (VACNTs) as photon absorbers in broadband radiometers flown on the Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) 3U CubeSat. VACNT forests are some of the blackest materials known and have an extremely flat spectral response over a wide wavelength range. The radiation measurements are made at both shortwave, solar-reflected wavelengths and in the thermal infrared. RAVAN also includes two gallium phase-change cells that are used to monitor the stability of RAVAN's radiometer sensors. RAVAN was launched November 11, 2016, into a nearly 600-km sun-synchronous orbit and collected data over the course of 20 months, successfully demonstrating its two key technologies. A 3-axis controlled CubeSat bus allows for routine solar and deep-space attitude maneuvers, which are essential for calibrating Earth irradiance measurements. Funded by the NASA Earth Science Technology Office, RAVAN is a pathfinder to demonstrate technologies for the measurement of Earth's radiation budget that have the potential to lower costs and enable new measurement concepts. In this paper we report specifically on the VACNT growth, post-growth modification, and pre-launch testing. We also describe the novel door mechanism that houses the gallium black bodies.

https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10982/109820G/Carbon-nanotube-based-radiometers-demonstrated-on-the-RAVAN-CubeSat-mission/10.1117/12.2518428.short?SSO=1

# RAVAN notables

- Funded as a part of the inaugural opportunity from NASA's Earth Science Technology Office (ESTO)'s In-Space Validation of Earth Science Technologies (InVEST) program, in 2012
- First ESTO InVEST CubeSat to fly
- First JHU/APL "science" CubeSat
- First Blue Canyon Technologies bus to fly
- RAVAN technology demonstration was a success

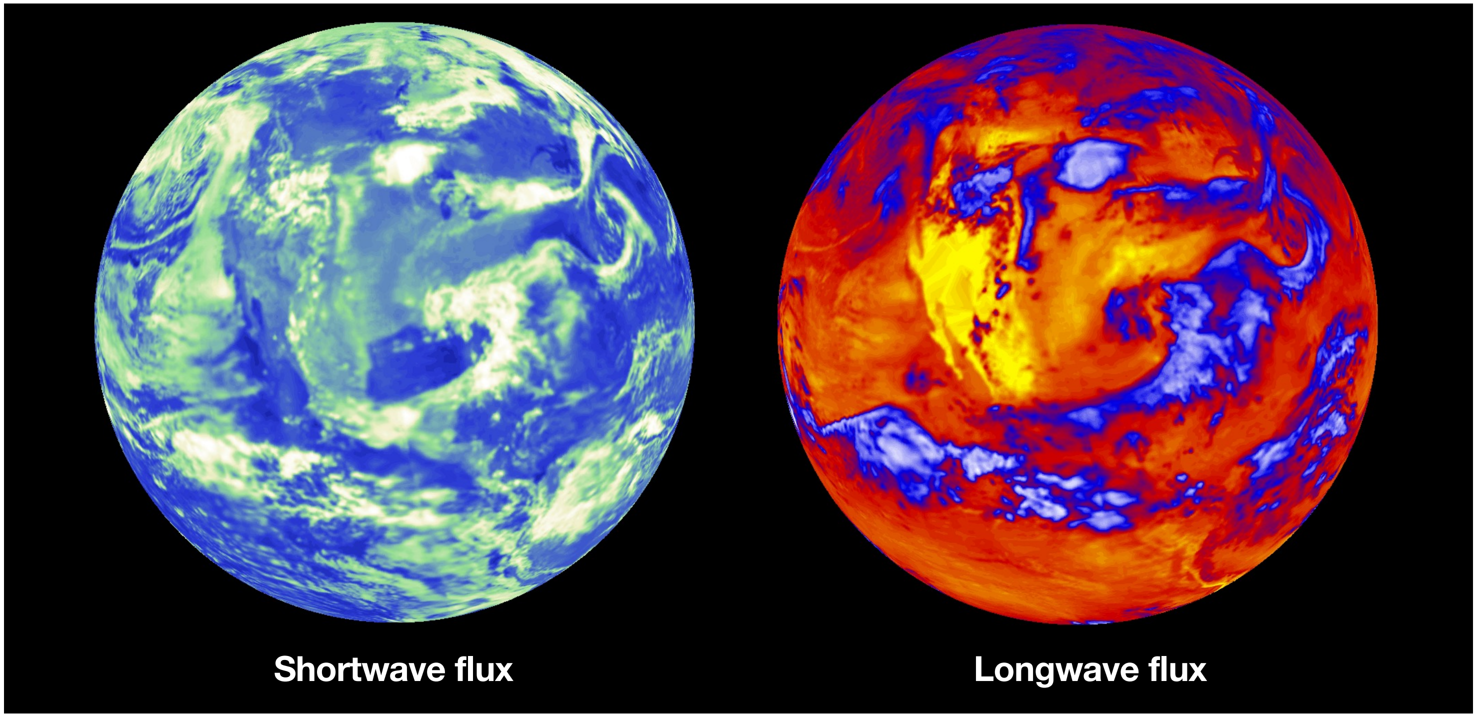
# A small energy imbalance drives climate change




Imbalance <1 W/m²

[*Trenberth et al., 2009*]

# Outgoing energy (radiation) highly variable, geographically and temporally




Current space-based assets cannot quantify Earth's outgoing radiation well enough to resolve the Earth energy imbalance from space (~1% accuracy...0.1% needed).

# We have been measuring EEB from space for a long time

TABLE 1. Selected Satellites and Missions Making Significant Contributions to Earth Radiation Budget Science

| Satellite Missions | Launch Date(s) | Altitude Range, km | Inclination Angle, deg | Orbit Time | Lifetime(s) | Contributions |
|---|---|---|---|---|---|---|
| | | | *First-Generation Missions* | | | |
| Explorer 7 | Oct. 13, 1959 | 550–1,100 | 51 | drifter | 7 months | first dedicated satellite providing usable ERB data |
| TIROS 2 | Nov. 23, 1960 | 717–837 | 48 | drifter | 1–5 months | first scanning radiometer with five SW/LW channels |
| TIROS 7 | June 19, 1963 | 713–743 | 58 | drifter | 12 months | provided 1 year of radiation balance observations |
| | | | *Second-Generation Missions* | | | |
| Research/ESSA | 1960s | ≈1,500 | 102 | 0900/1500 | 3–15 months | global data sets from WFOV nonscanning radiometers |
| Nimbus 3 | April 14, 1969 | 1,100 | 99 | noon | 1 year | detailed global radiation balance for 1 year |
| NOAA | 1970s | ≈1,500 | 102 | 0900 | years | combined data sets provided |
| TIROS-N/NOAA | 1978–1981 | ≈840 | 99 | 1500/0730 | years | 10 years of observations |
| | | | *Third-Generation Mission* | | | |
| Nimbus 7 ERB | Oct. 1978 to the present | 950 | 99 | noon | 6+ years | total and spectral solar monitoring; bidirectional reflectance and directional albedo models |
| | | | *Geostationary Missions* | | | |
| GOES-E/W (75°–135°W) | 1970s/1980s | 36,000 | 0 | 24 hours | years | diurnal variations of SW/LW exitances and cloud distributions; satellite Mission simulations |
| METEOSAT 1/2 (0° longitude) | 1977/1982 | 36,000 | 0 | 24 hours | years | |

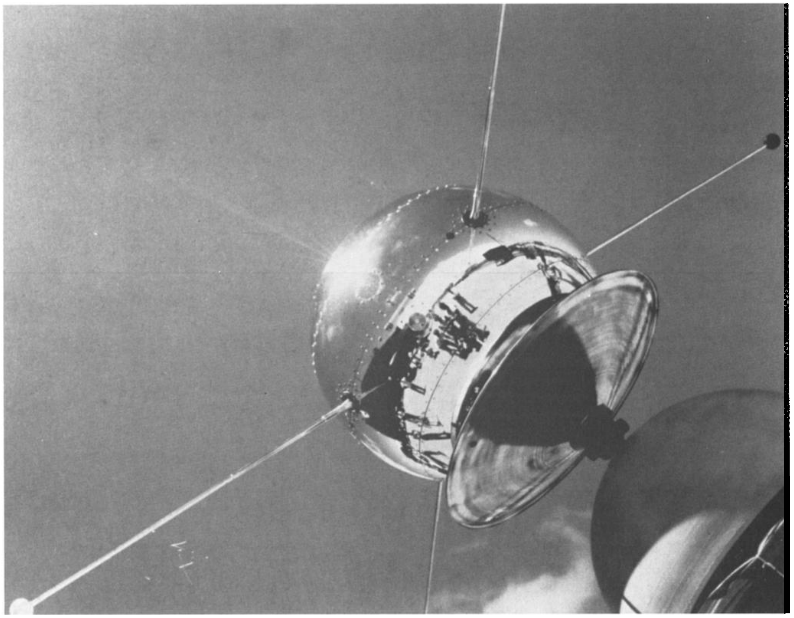


Fig. 2. First dedicated ERB satellite, Vanguard 2, mounted on the rocket prior to launch in 1959.

*House et al.* [1986]

# RAVAN is a LEO non-scanning (WFOV) radiometer

**Table 3.** Non-Scanning Broadband Earth Radiation Budget space instruments. IKOR: Short-wave outgoing radiation monitor; ERM: Earth Radiation Monitor; RAVAN: Radiometer Assessment using Vertically Aligned Nanotubes.

| Period | Instrument | References |
|---|---|---|
| 1975–1978 | ERB on Nimbus 6 | [25] |
| 1978–1987 | ERB on Nimbus 7 | [25] |
| 1984–1999 | ERBE on ERBS | [26] |
| 1985–1990 | ERBE on NOAA 9 | [26] |
| 1986–1994 | ERBE on NOAA 10 | [26] |
| 1994 | IKOR (SW only) on Meteor-3 7 | [27] |
| 1998 | IKOR (SW only) on Resurs-1 | [27] |
| 2008–2011 | ERM NS on FY3A | [28] |
| 2009–2014 | IKOR-M (SW only) on Meteor-M 1 | [29] |
| 2011 | ERM NS on FY3B | [28] |
| 2013–present | ERM NS on FY3C | [28] |
| 2014–present | IKOR-M (SW only) on Meteor-M 2 | [30] |
| 2016 | RAVAN | [31] |

LEO non-scanning (WFOV)

**Table 4.** Scanning Broadband Earth Radiation Budget space instruments on Low Earth Orbit satellites. CERES: Clouds and the Earth's Radiant Energy System; ScaRaB: Scanning Radiometer for Radiation Balance; TRMM: Tropical Rainfall Measuring Mission; NPP: National Polar-orbiting Operational Environmental Satellite System Preparatory Project.

| Period | Instrument | References |
|---|---|---|
| July-August 1975 | ERB on Nimbus 6 | [25] |
| 1978–1980 | ERB on Nimbus 7 | [25] |
| 1984–1989 | ERBE on ERBS | [26] |
| 1985–1987 | ERBE on NOAA 9 | [26] |
| 1986–1989 | ERBE on NOAA 10 | [26] |
| 1994–1995 | ScaRaB-1 on Meteor-3 7 | [32] |
| 1997–1998 | CERES on TRMM | [33] |
| 1998–1999 | ScaRaB-2 on Resurs-1 | [34] |
| 2000–present | CERES FM1 on Terra | [33] |
| 2000–present | CERES FM2 on Terra | [33] |
| 2003–present | CERES FM3 on Aqua | [33] |
| 2003–present | CERES FM4 on Aqua | [33] |
| 2008–2010 | ERM on FY3A | [28] |
| 2011–present | ScaRaB-3 on Megha-Tropiques | [35] |
| 2011–present | CERES FM5 on Suomi NPP | [33] |
| 2011 | ERM on FY3B | [28] |
| 2013–present | ERM on FY3C | [28] |

LEO scanning (NFOV)

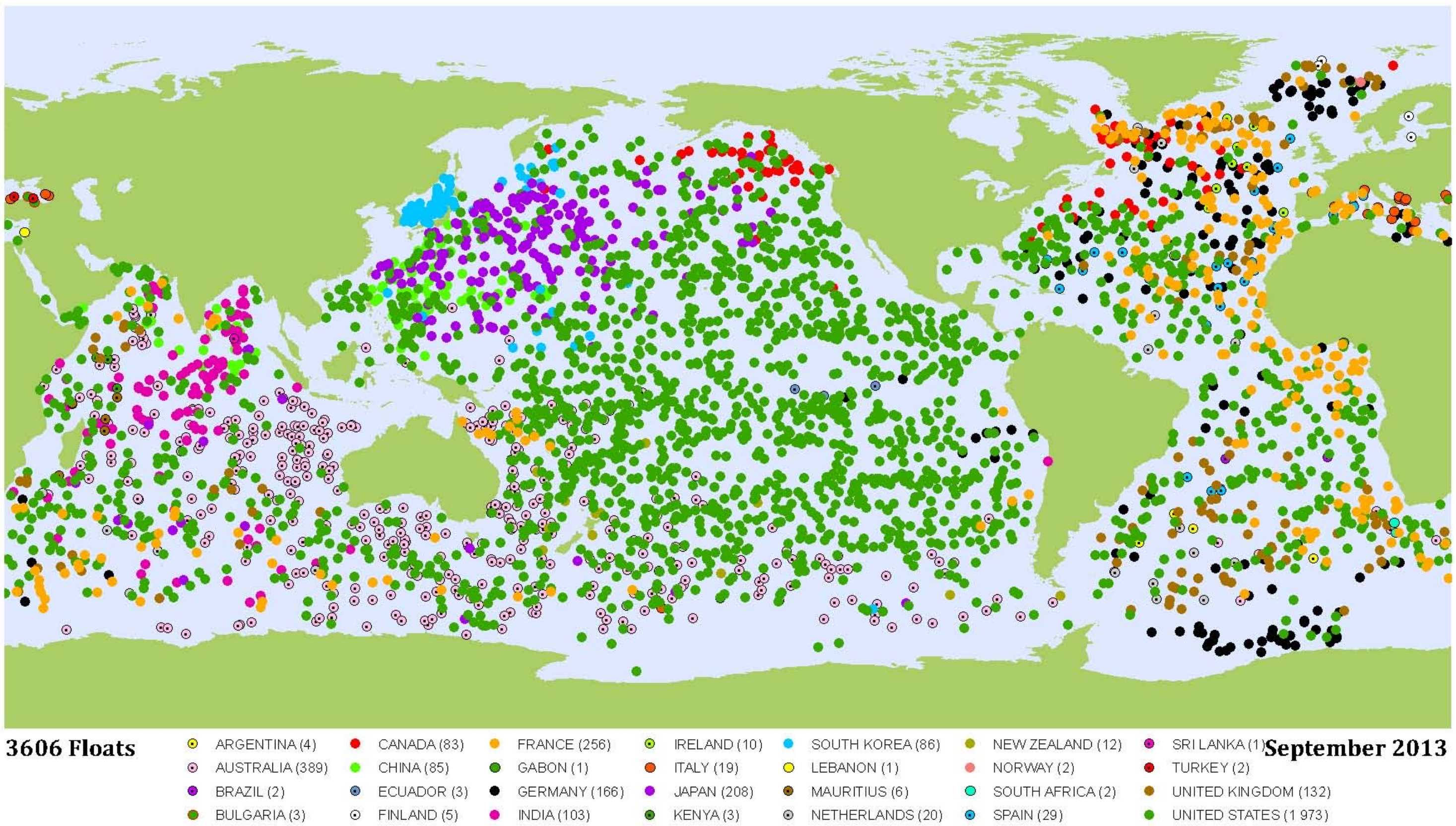
**Table 5.** Broadband Earth Radiation Budget space instruments on geostationary satellites. GERB: Geostationary Earth Radiation Budget; MSG: Meteosat Second Generation.

| Period | Instrument | References |
|---|---|---|
| 2003–present | GERB2 on MSG1 | [39,41] |
| 2007–2012 | GERB1 on MSG2 | [39,41] |
| 2012–present | GERB3 on MSG3 | [39,41] |
| 2015 | GERB4 on MSG4 | [39,41] |

GEO

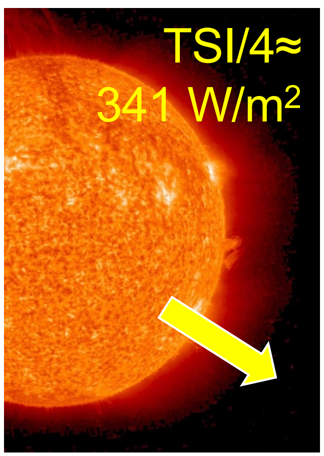
*Dewitte et al.* [2017]

# Energy budget measurement requires an extensive ocean-observing system like Argo

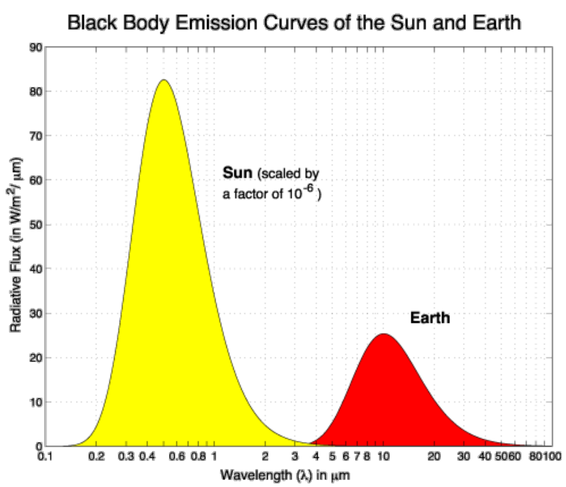


# Motivation for RAVAN: “Argo in space”

- The small imbalance (~1 W/$m^2$) between incoming solar irradiance and Earth outgoing energy (solar reflected + Earth’s thermal emission) drives climate change
- Current space-based assets cannot quantify Earth’s outgoing radiation well enough to resolve the Earth energy imbalance from space (~1% accuracy...0.1% needed)
- RAVAN is an Earth radiation (energy) budget constellation pathfinder

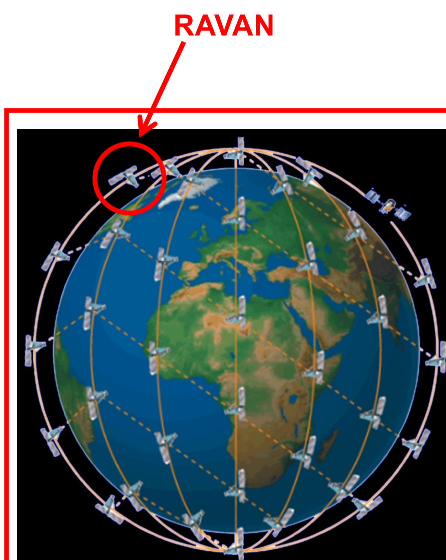



TSI = Total Solar Irradiance



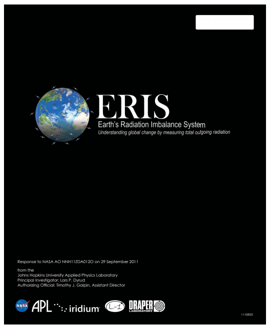


TOE = Total Outgoing Energy




RAVAN-like constellation

# RAVAN is part of a progression of effort toward a new Earth energy budget measurement

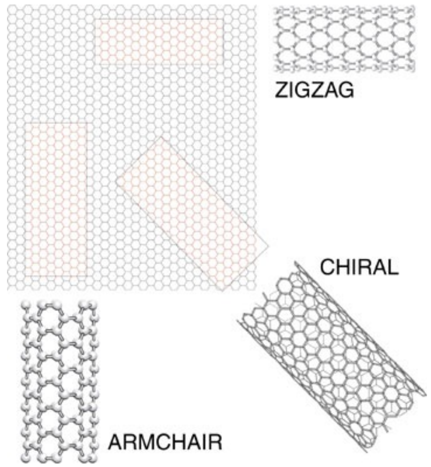


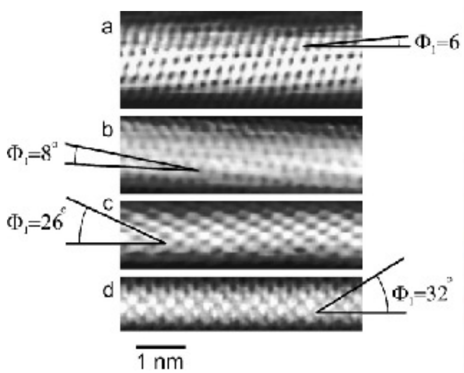

- **2011/APL: Earth Radiation Imbalance System (ERIS)**
  - Proposed to NASA Earth Venture program (not selected)
  - Fly ~69 radiometer payloads on Iridium NEXT constellation
  - Science: “The accurate ERIS measurements of TOR and ERI at high spatial and temporal resolution are highly relevant to NASA Earth science activities and science in general. There is no way that NASA, by itself, could reproduce these measurements for anything close to the proposed cost.” (from Earth Venture debrief)
  - Weaknesses:
    - Calibration not demonstrated (including Ga blackbody source)
    - Payload cost (thought to be too low, but there’s no precedent)
- **2012/APL: Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN)**
  - Proposed to NASA ESTO/InVEST (selected)
  - Fly single radiometer payload on a CubeSat: Technology demonstration
  - Pathfinder for an Earth radiation imbalance mission
  - Directly addresses ERIS weaknesses

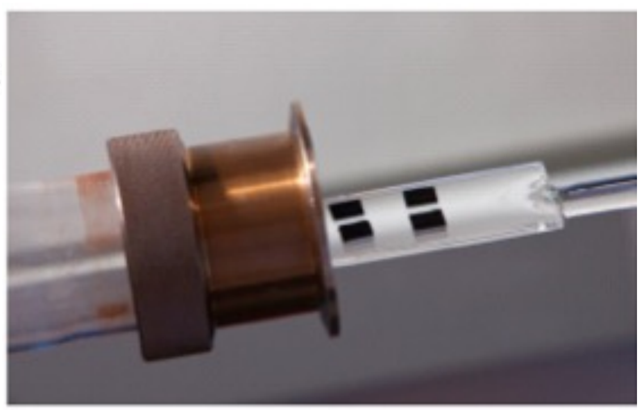
RAVAN
Radiometer Assessment Using Vertically Aligned Nanotubes

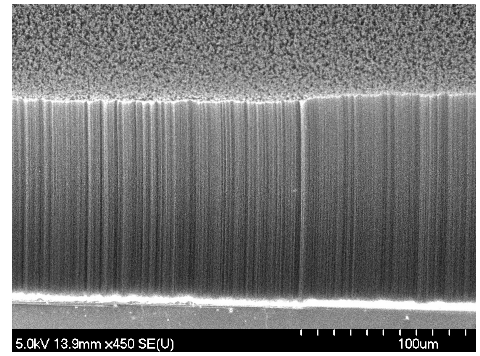
# (Vertically aligned) carbon nanotubes are at the heart of RAVAN

RAVAN carbon nanotubes developed at APL with previous internal/external investments



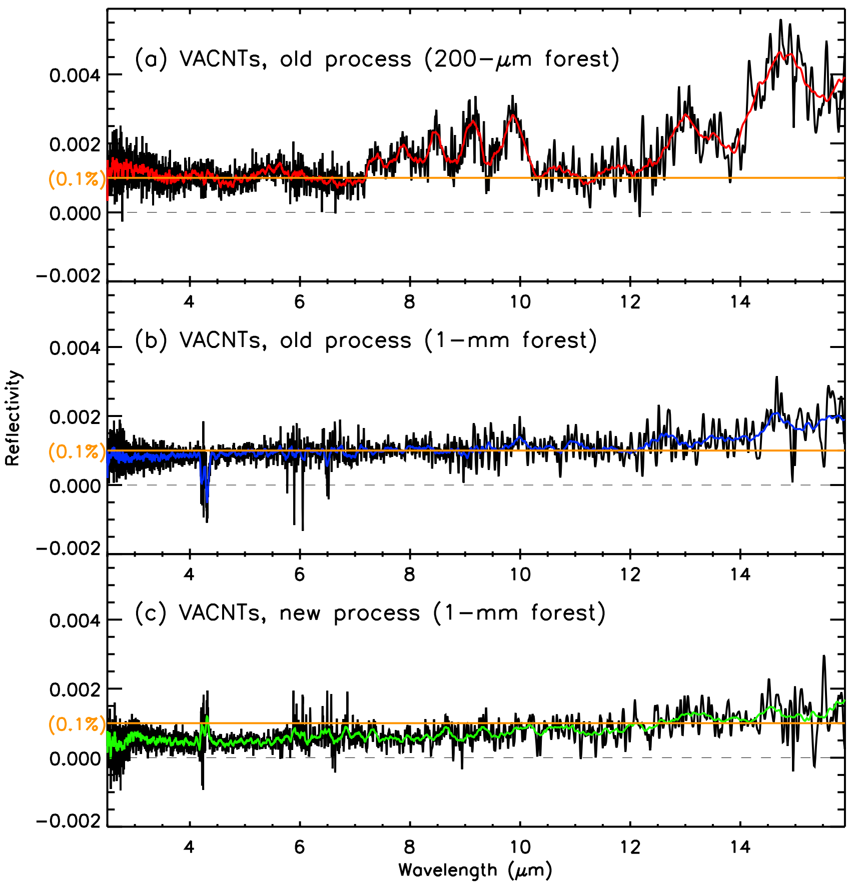



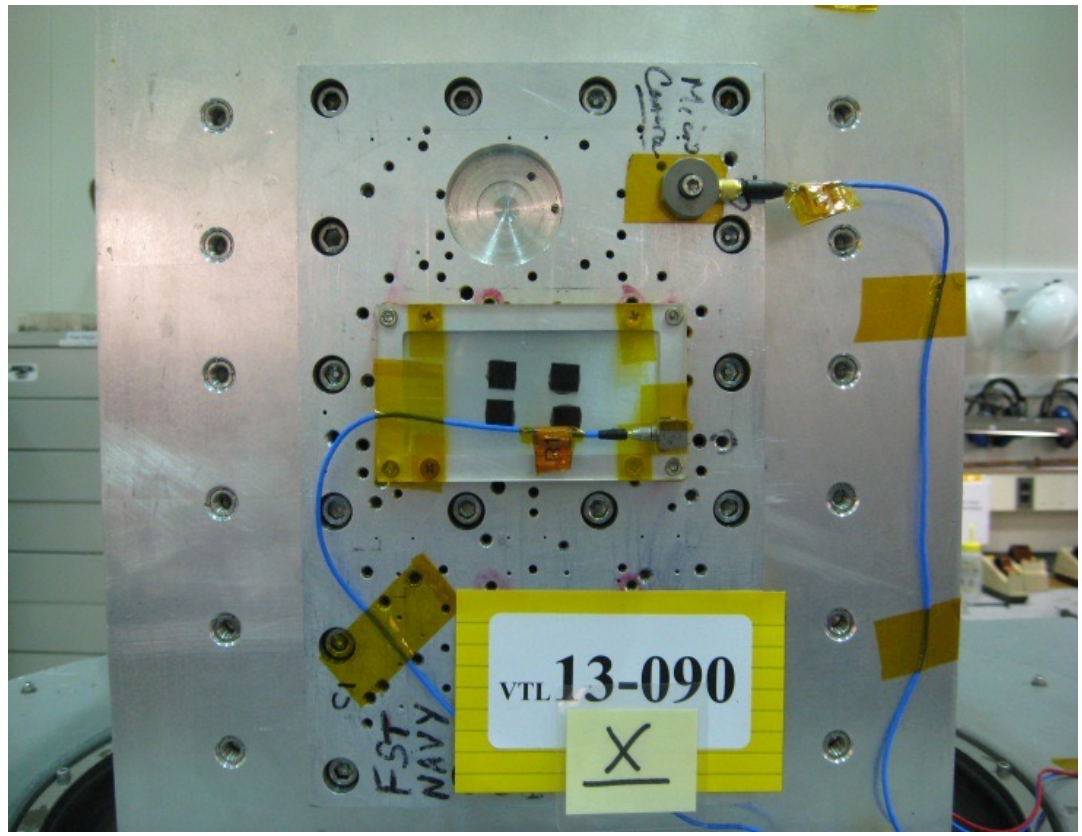



VACNT SEM image

RAVAN radiometer head

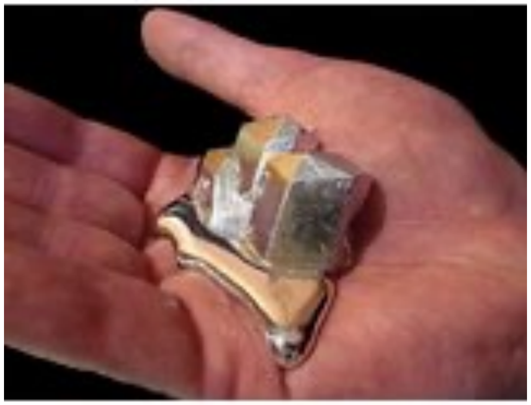
# VACNTs further developed and tested under RAVAN

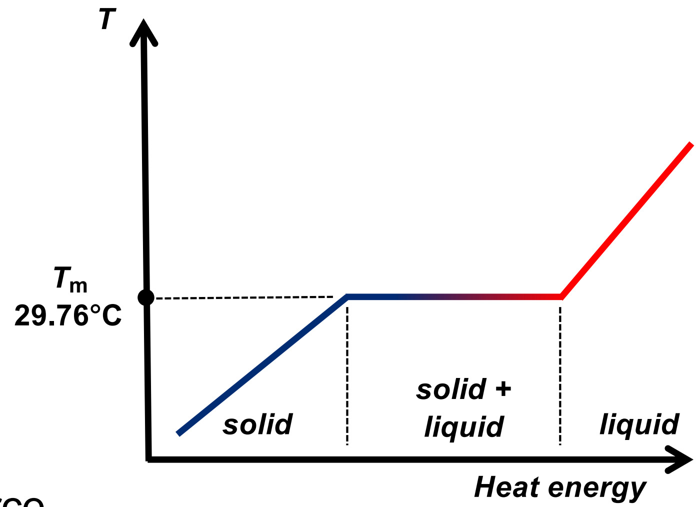


# Gallium phase-change black bodies also demonstrated

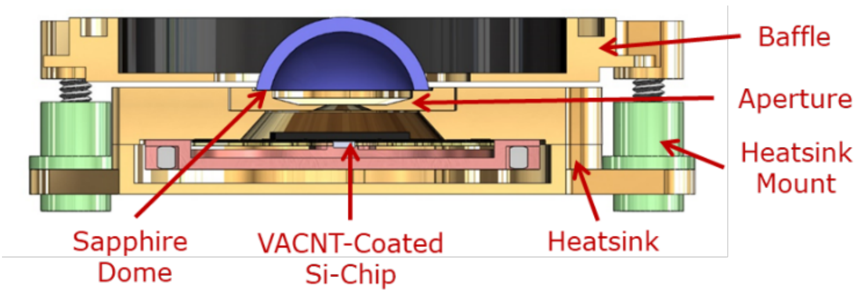
- Demonstrate the use of a gallium closed-cell source for stability monitoring

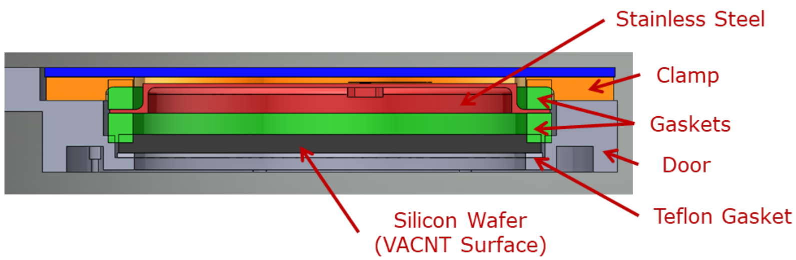


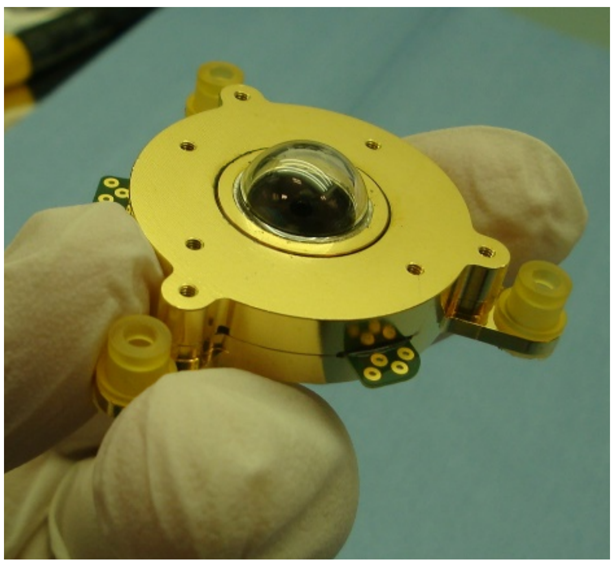


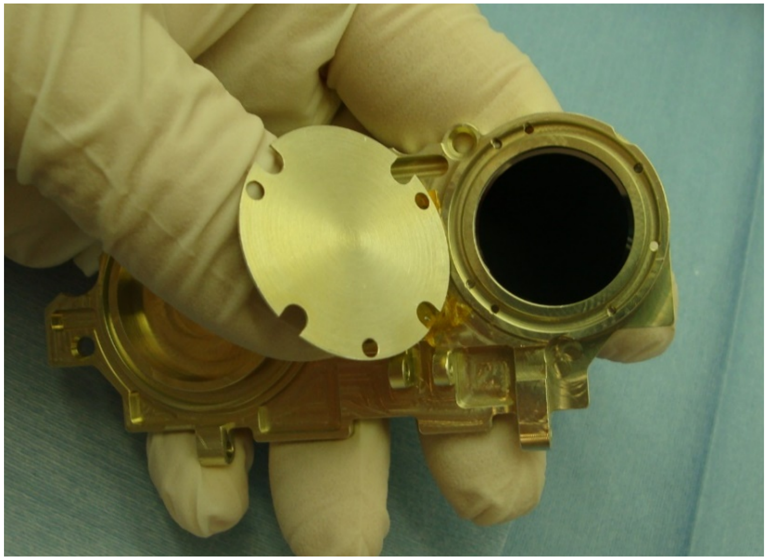

  - Repeatable, stable IR source
  - Degradation monitoring

# Radiometer, black body designs

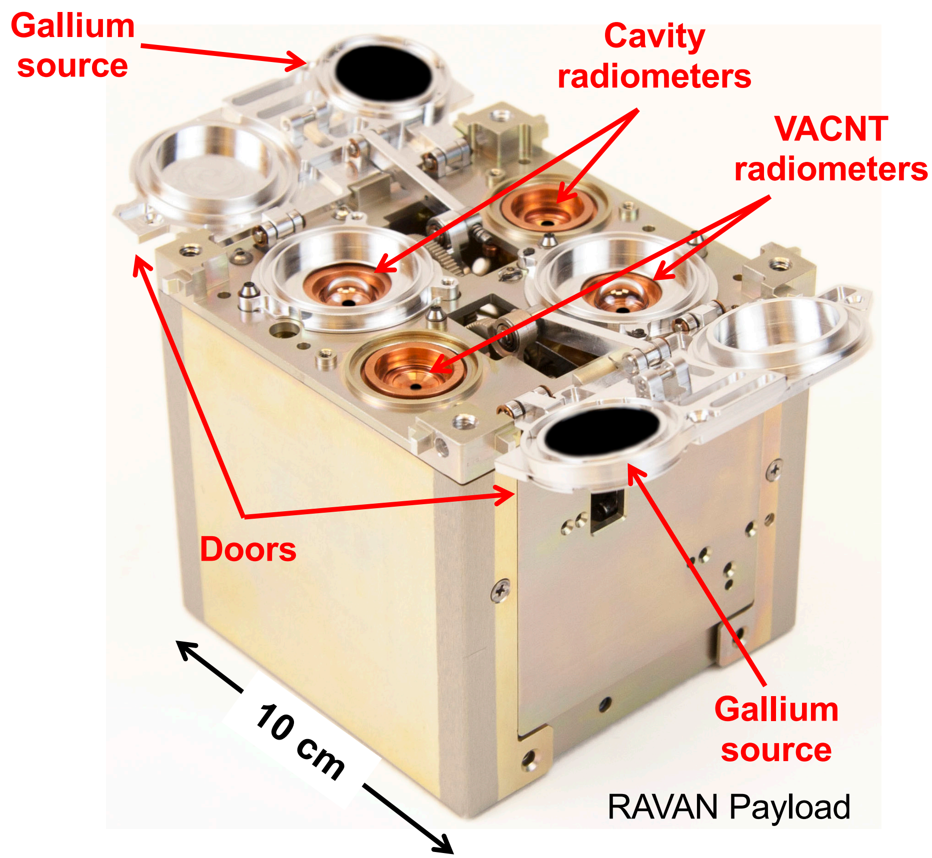


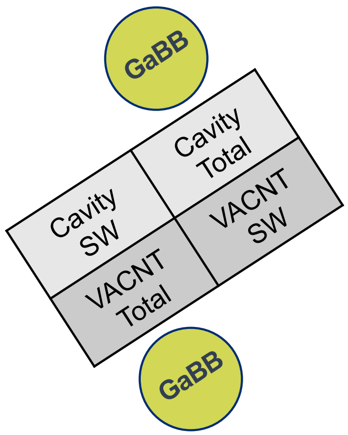



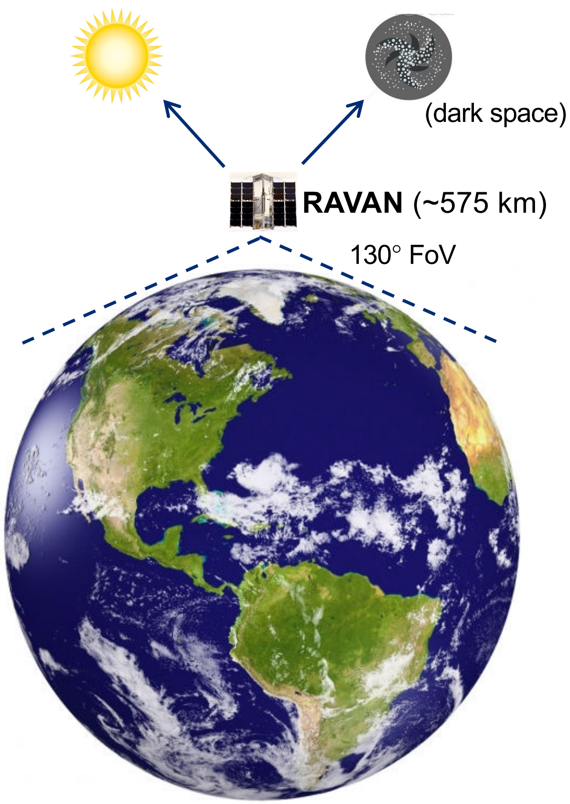


# Compact (1U) payload hosts radiometers, Ga black bodies



# Earth, solar, and cold space views

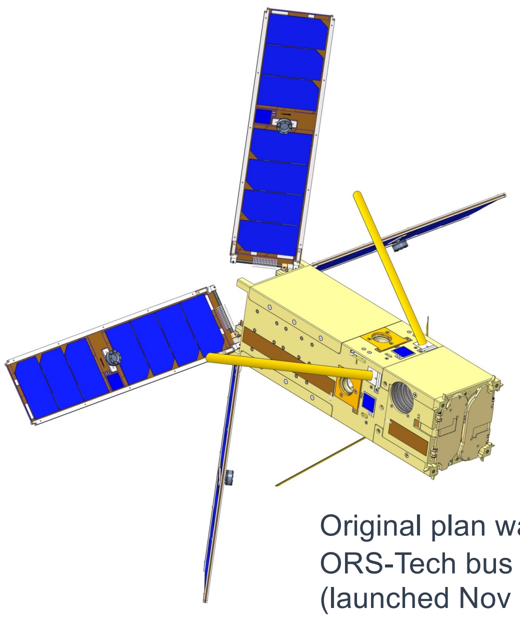


# Near-death experiences (selected)

*"Just wait. It will get worse."—Phil Huang*

- Proposed APL CubeSat bus not really an option

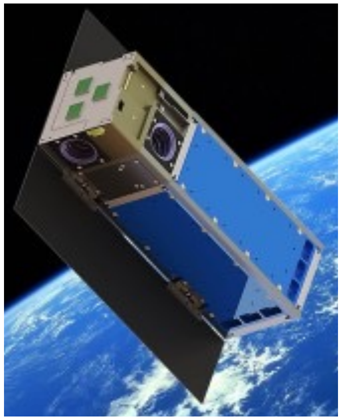
# Bus was a moving target



Original plan was APL ORS-Tech bus (launched Nov 2013)

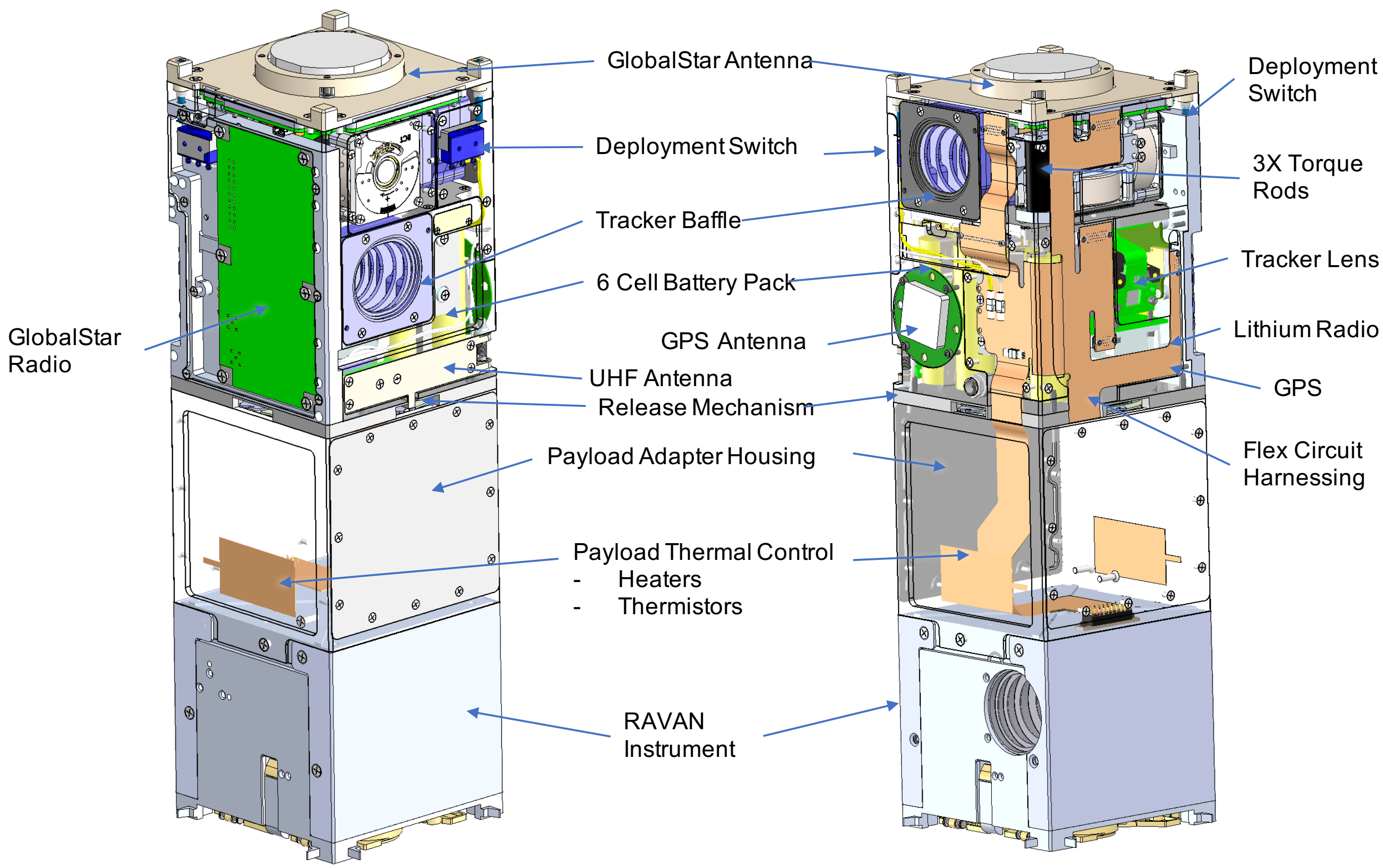
Quoting Y1 Annual Review (mid-2014):

- State-of-the-art advances since MBD (ORS Tech) design/development
- Radios need updating (frequency allocation)
- Attitude control (pointing limitations)



Preliminary BCT concept

# Payload fits, with room to spare

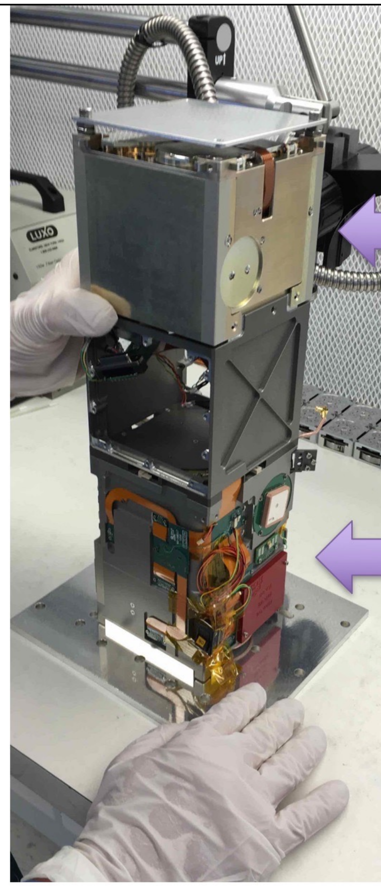


# Near-death experiences (selected)

*"Just wait. It will get worse."—Phil Huang*

- Proposed APL CubeSat bus not really an option
- Choice: Gamble on early, uncertain launch (with "success-oriented" schedule) vs. wait two years for CSLI
- Payload delivery delay and late-in-the-game bus problems use every bit of launch integrator schedule margin

# RAVAN at Blue Canyon

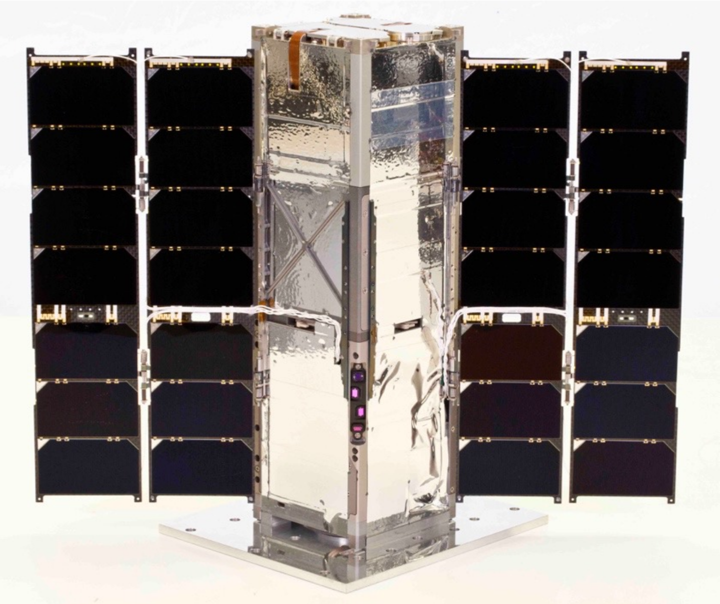


RAVAN payload

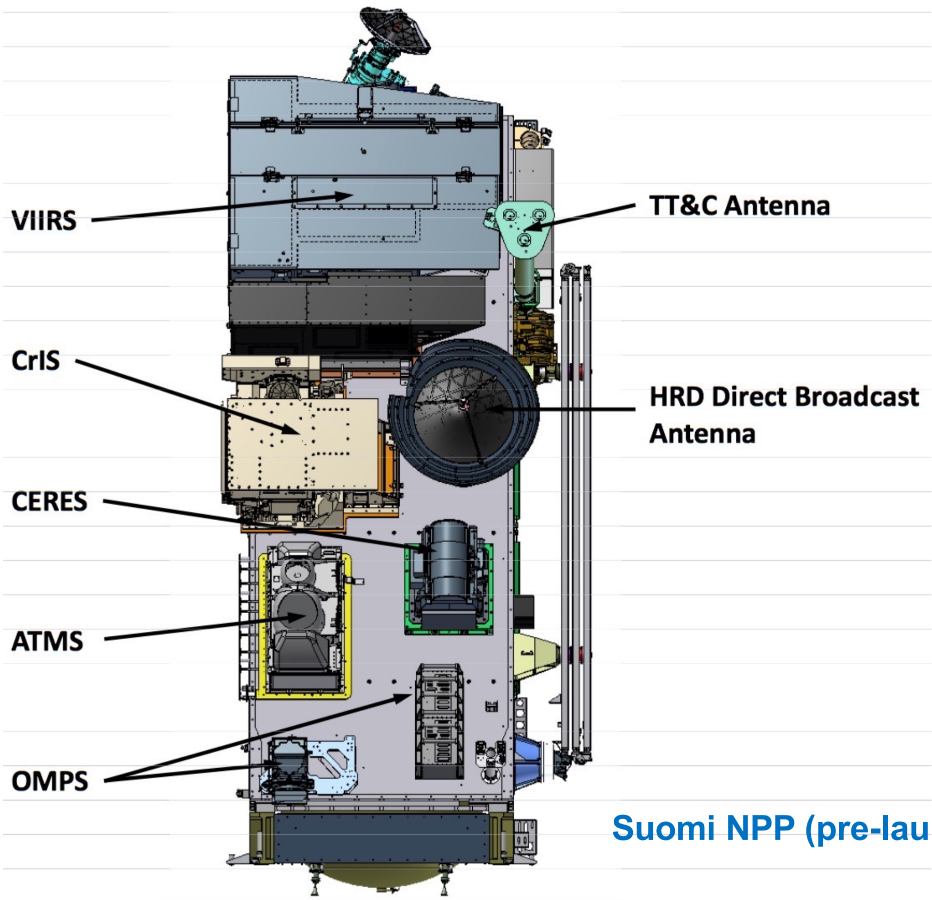
BCT XB1

**RAVAN**
**as of June 14, 2016**

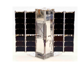
# RAVAN flight spacecraft



# RAVAN in perspective

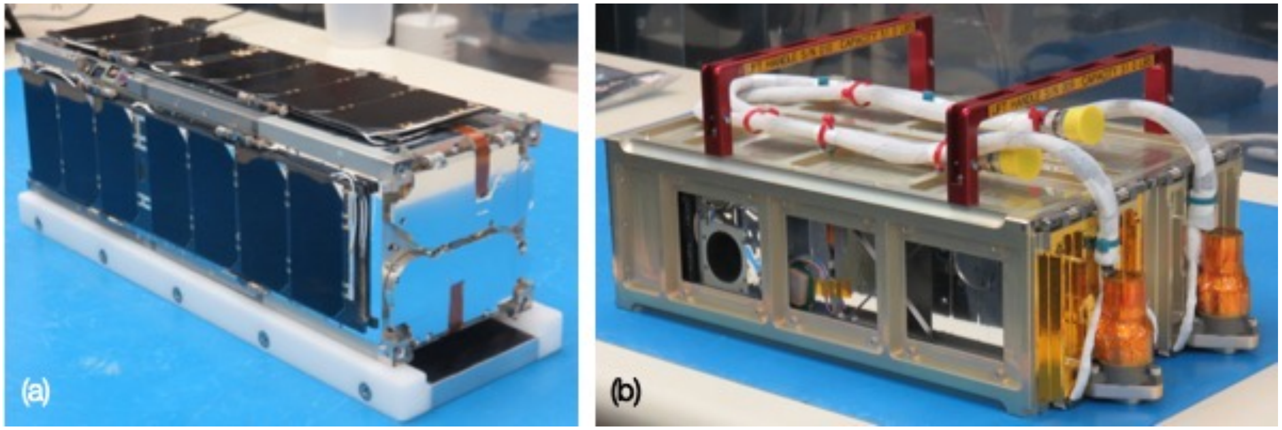



Suomi NPP (pre-launch configuration)



RAVAN

# RAVAN, ready for launch vehicle integration




(b) Credit: Tyvak/Cal Poly

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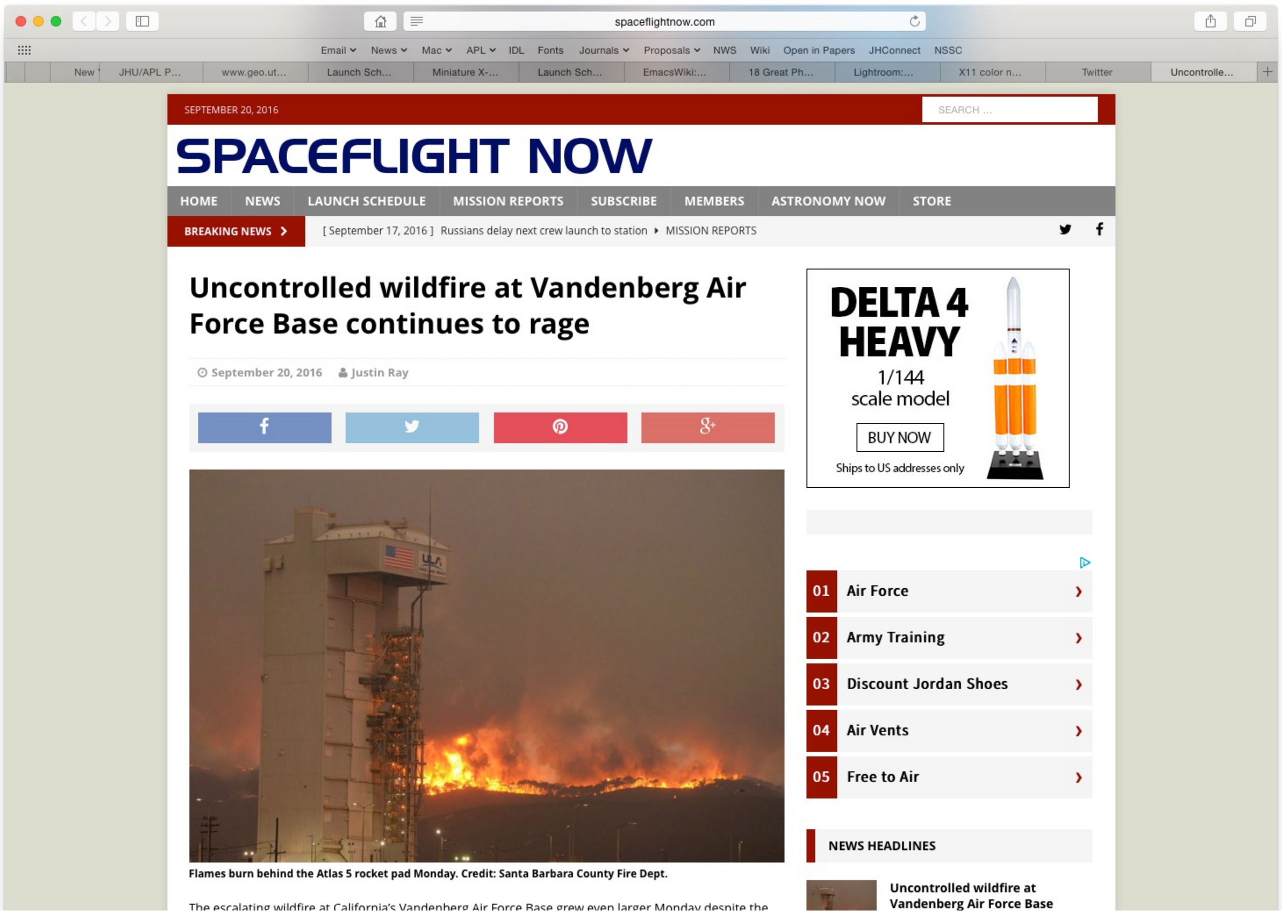
- Obtained FCC license one day before dis-integration from launch vehicle

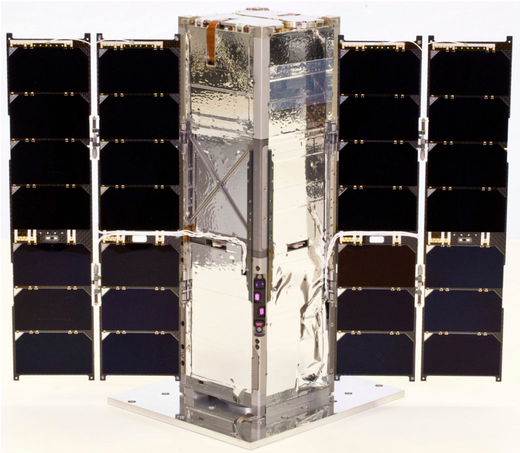
# Atlas V rocket, before original launch day (9/15/16)


Source: Spaceflight Now

# Launch scrub #2 (wildfires): Sun 9/18/16

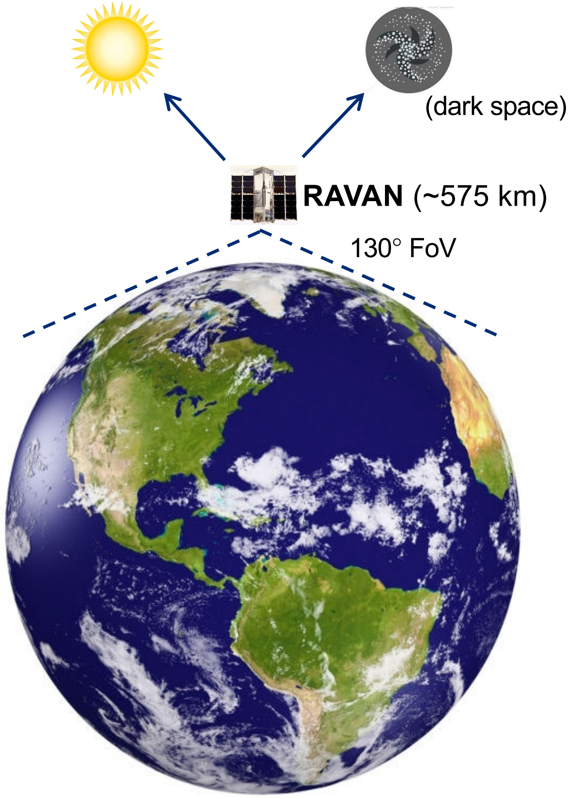


# Launched Nov 11, 2016



**RAVAN 3U CubeSat**
Blue Canyon Technologies bus


**Launch 11/11/16**



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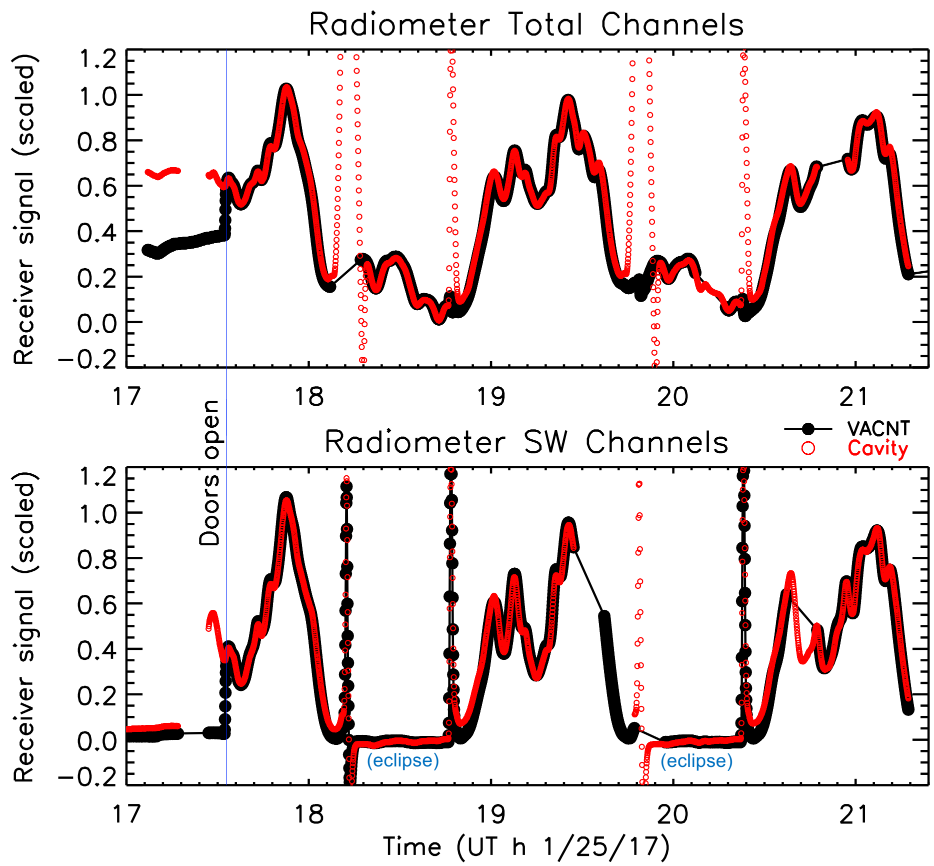
- Communication problems
  - None for first 11 days
  - Winter weather at ground station (Boulder, CO)
  - Ground interference

# "First Light": The VACNT and cavity radiometers track very well

| | |
|---|---|
| Cavity SW | Cavity Total |
| VACNT Total | VACNT SW |



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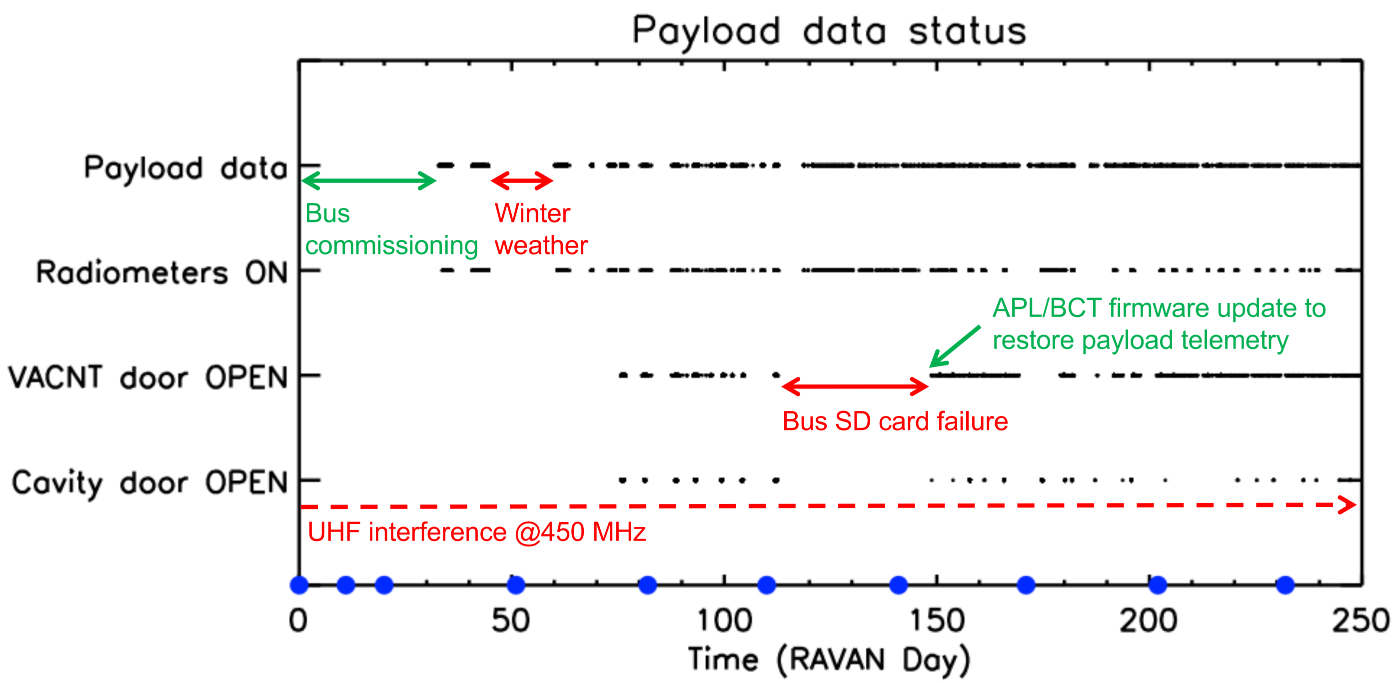
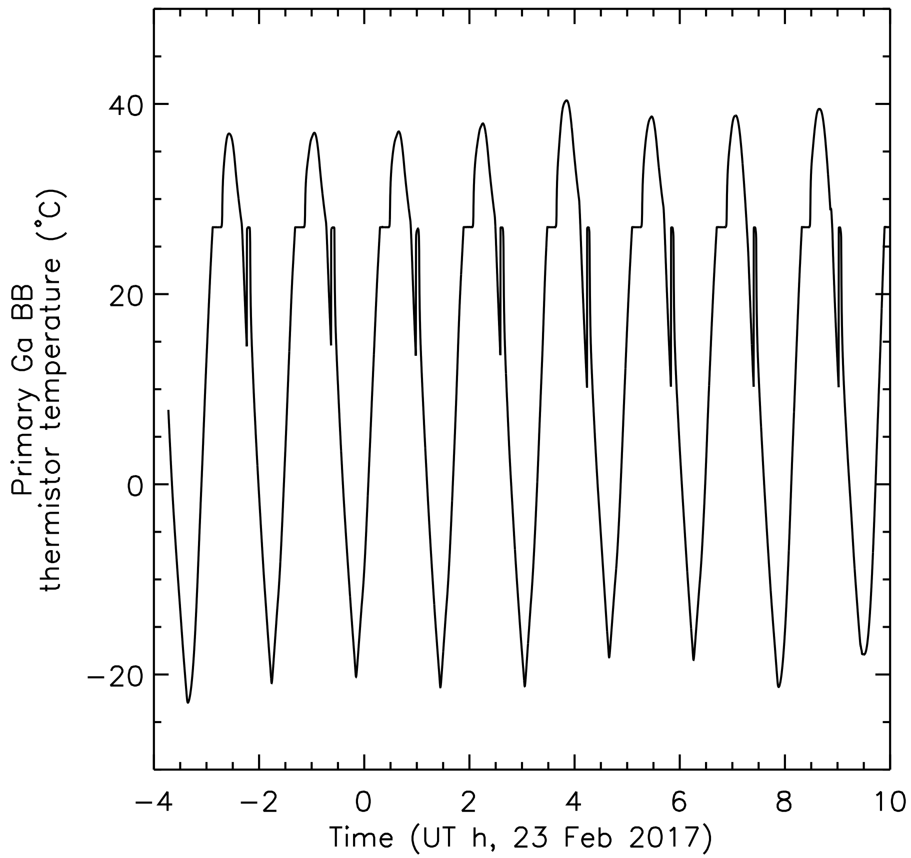
- Communication problems
  - None for first 11 days
  - Winter weather at ground station (Boulder, CO)
  - Ground interference
- Bus SD card failure

# Payload data not continuous but provided what we needed for tech demo

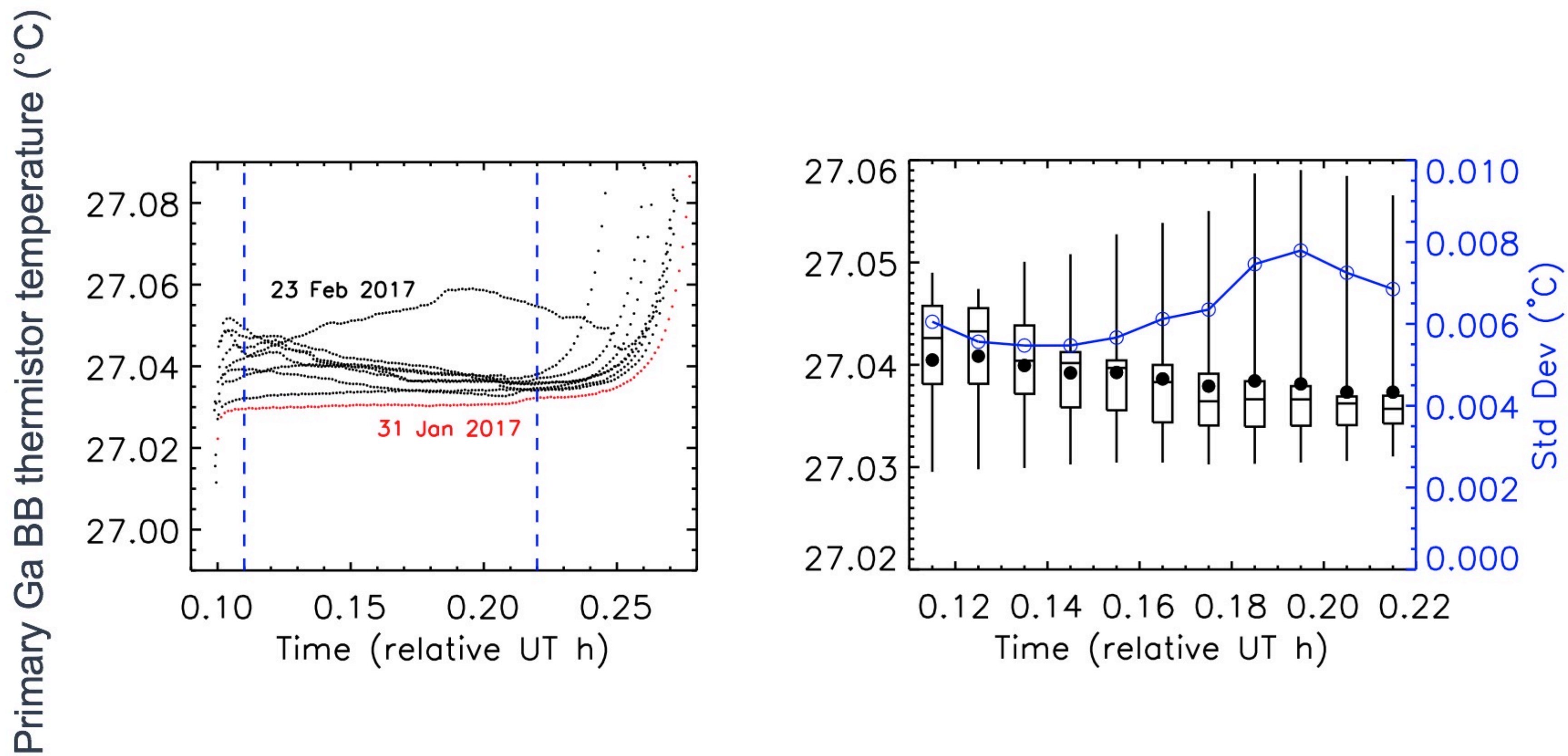



Lessons learned from RAVAN on-orbit operations have been implemented in future experiments

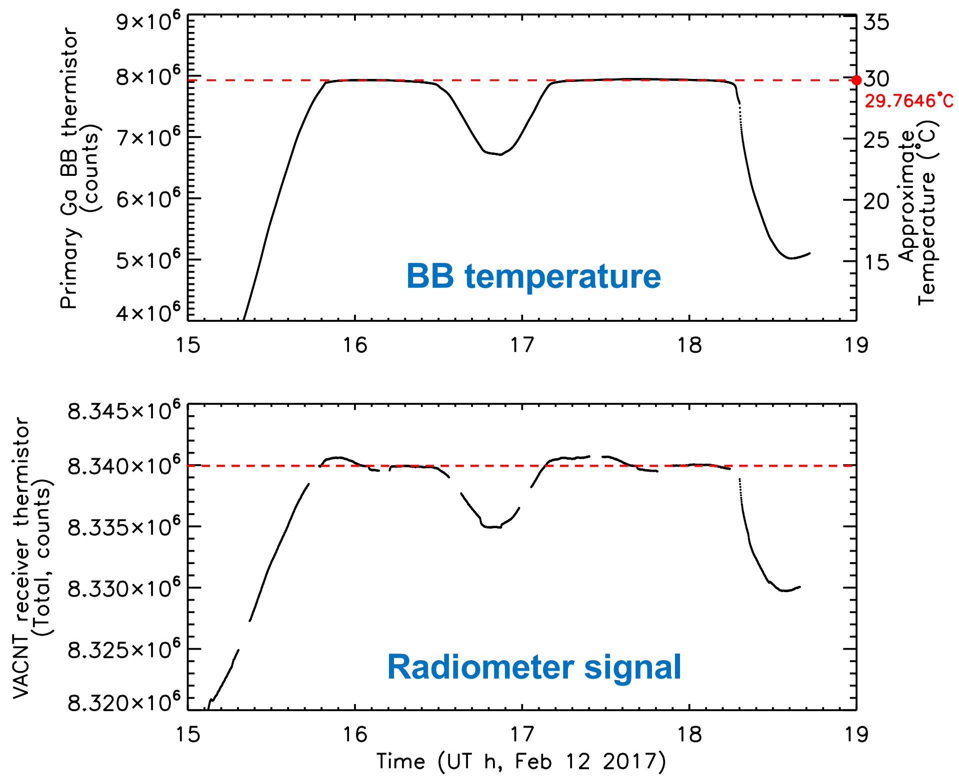
# Gallium melt provides repeatable reference



# Gallium melt temperature consistent



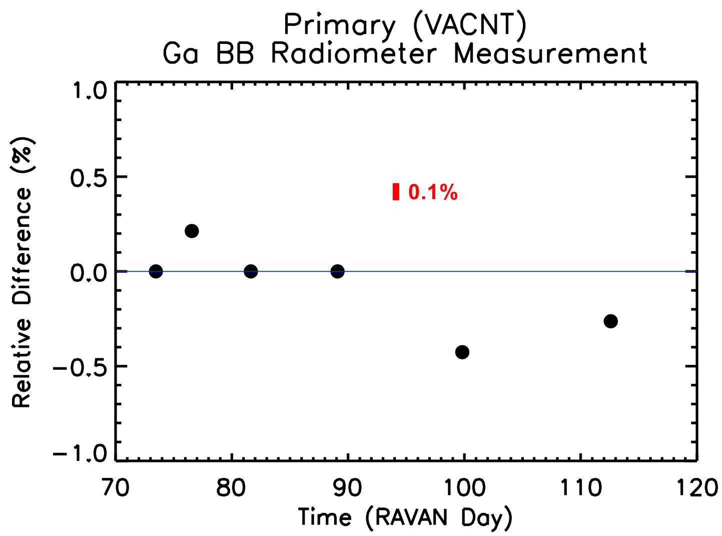
# Gallium melt observed by radiometer

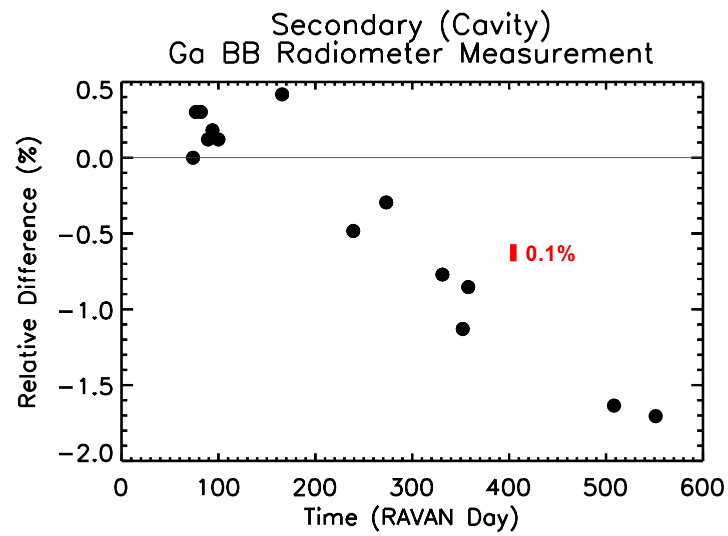


# BB: Instrument long-term stability, but short-term fluctuations

0.1% Climate accuracy goal

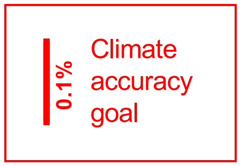
**Ga BB observations**



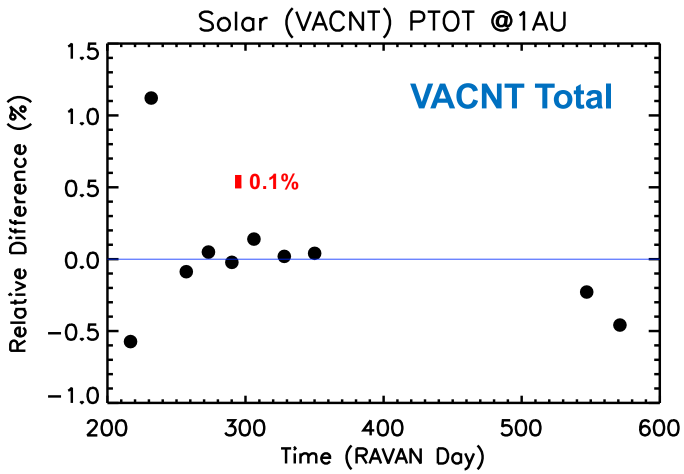



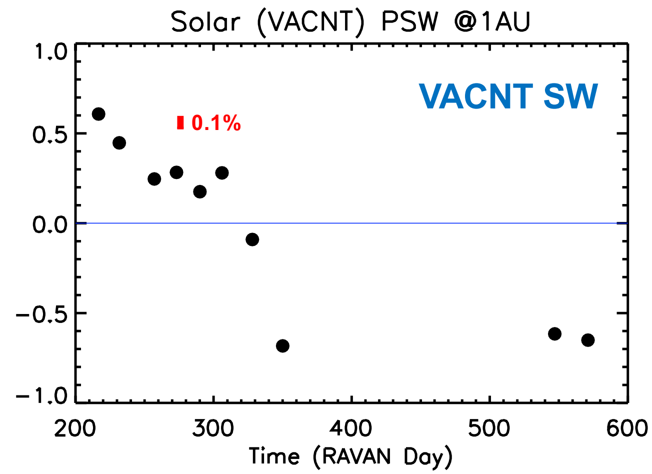

Black body for VACNT Total channel failed in March 2017

# Solar: Instrument long-term stability, but short-term fluctuations

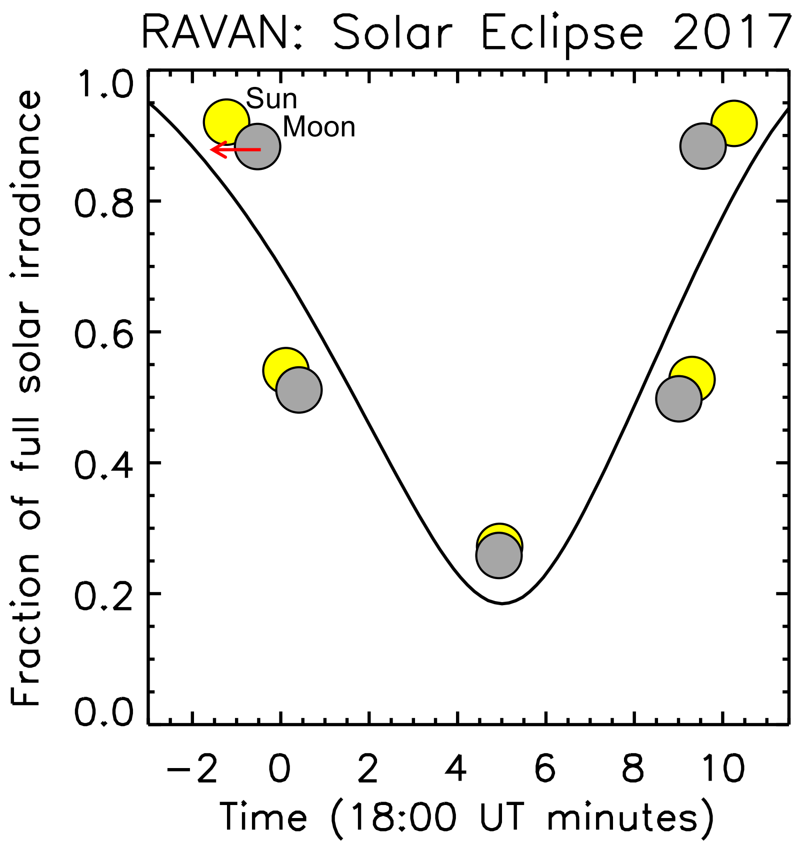



Solar Stares

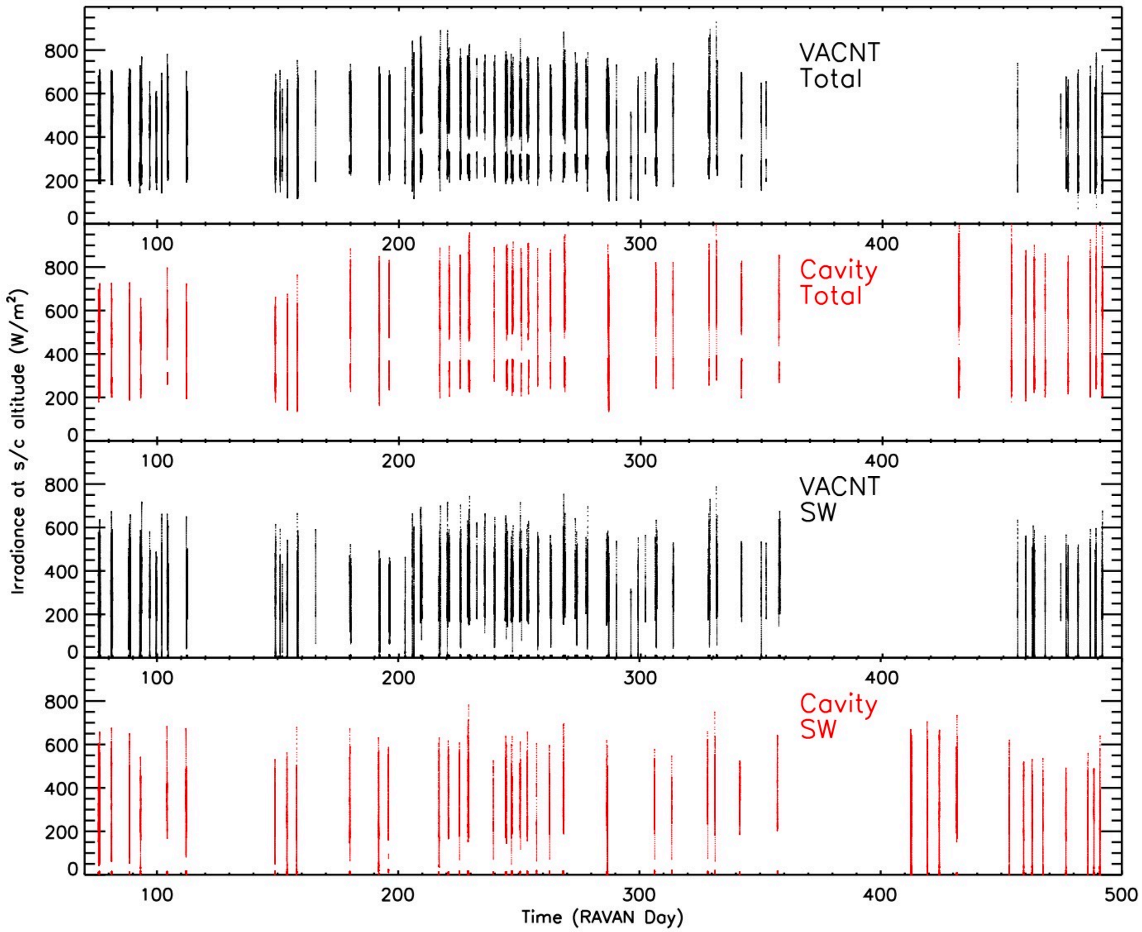


# Solar (eclipse) observations

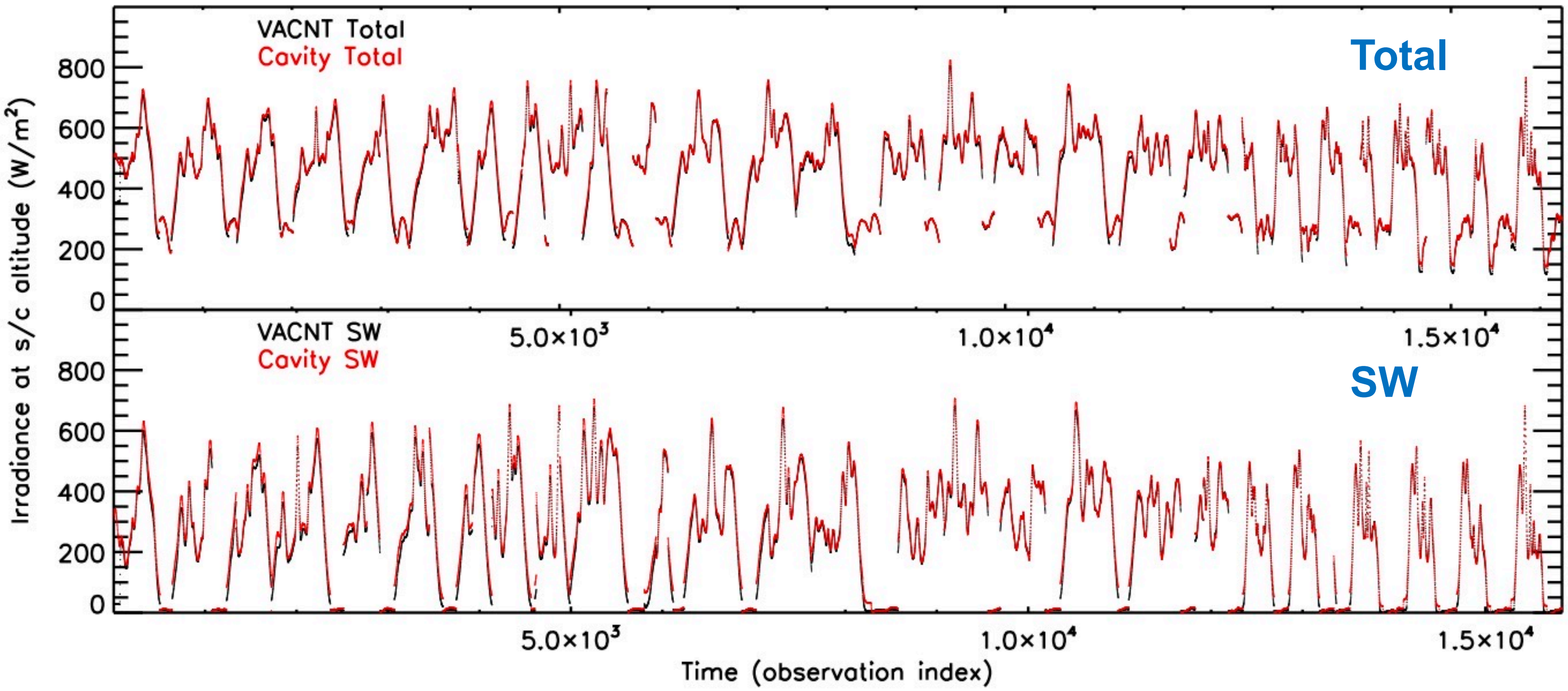


# Earth-viewing dataset is episodic (not by design!)

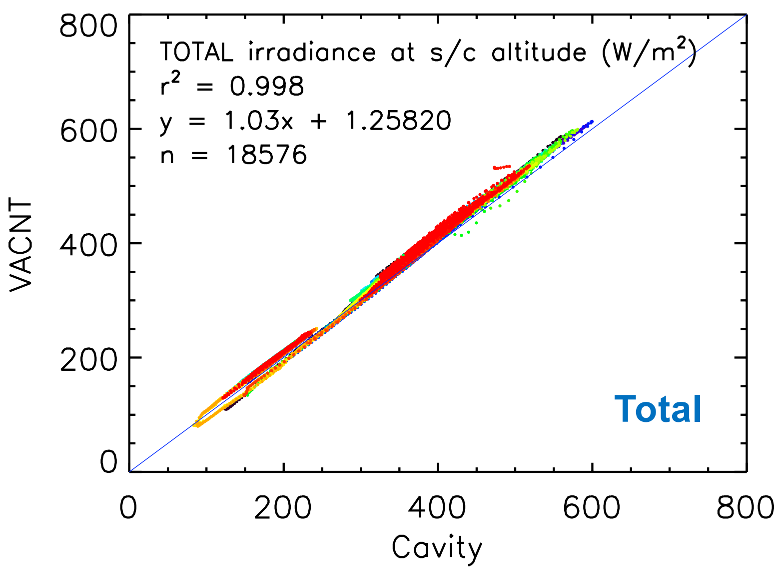


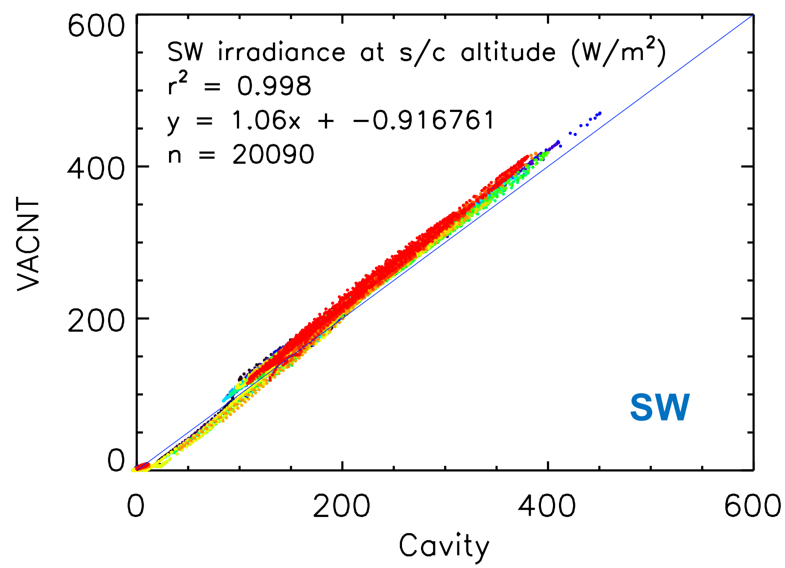

Data downlink hampered by ground-level UHF interference

# Nadir observations of outgoing flux well correlated: Old tech vs. new tech



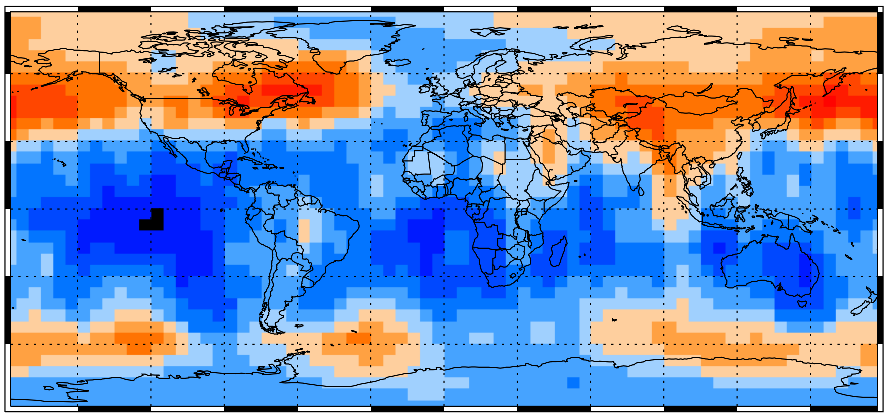
# VACNT and cavity radiometers well correlated, but with absolute differences of 3 and 6%

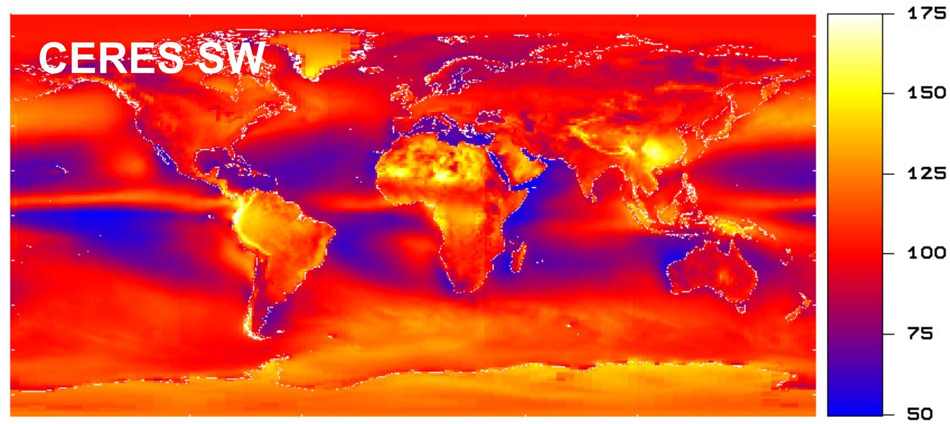


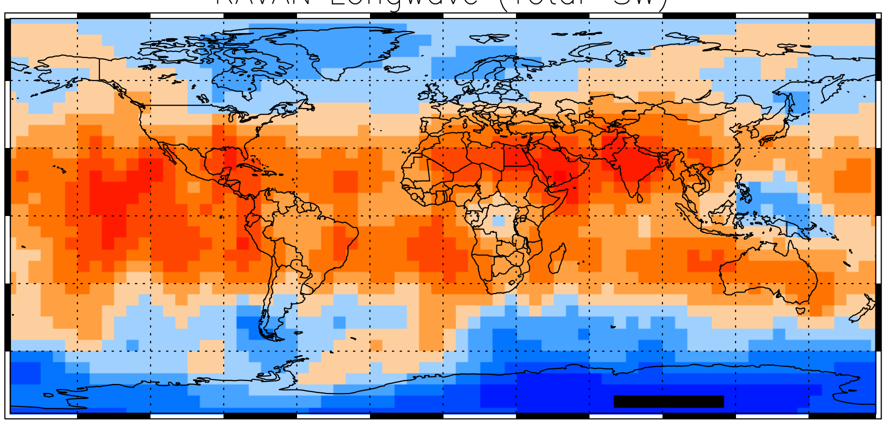
# Qualitative agreement with CERES TOA flux

RAVAN Shortwave

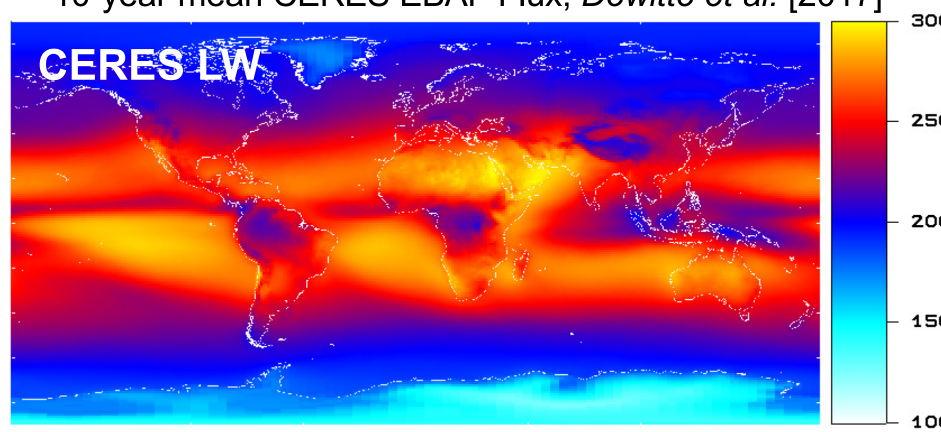




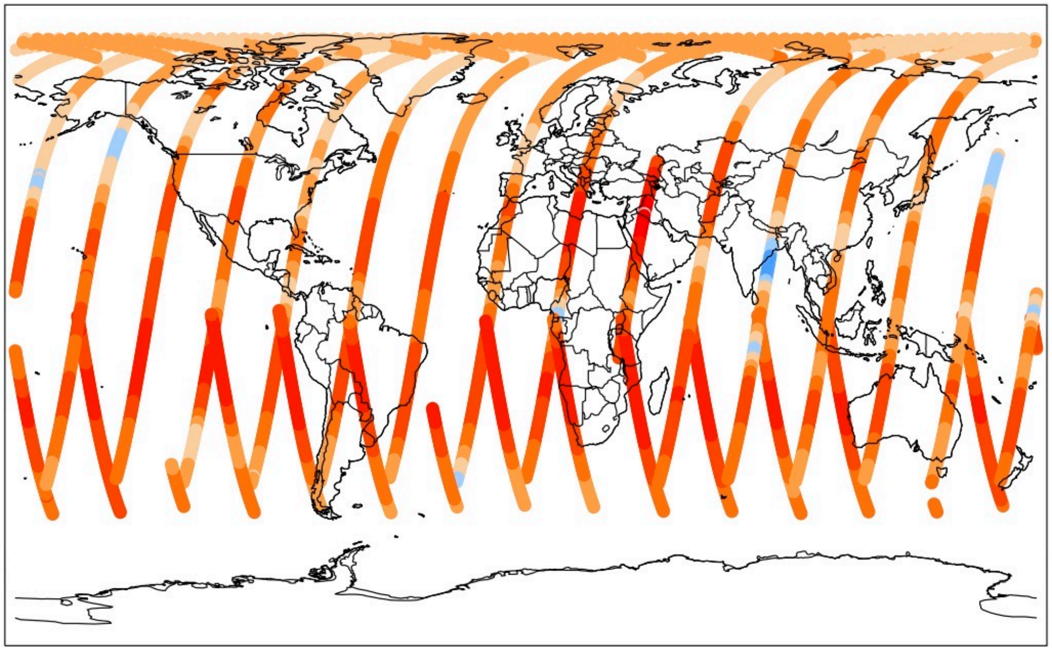

RAVAN Longwave (Total–SW)



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

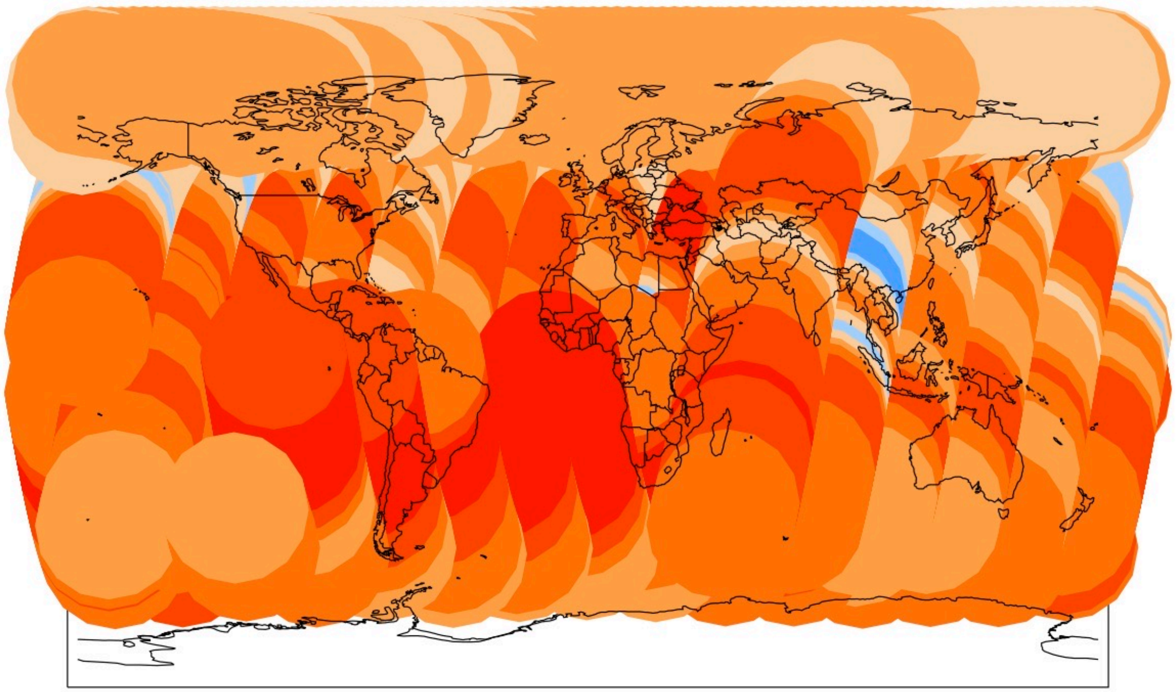


# "Single-pixel camera" contains spatial information



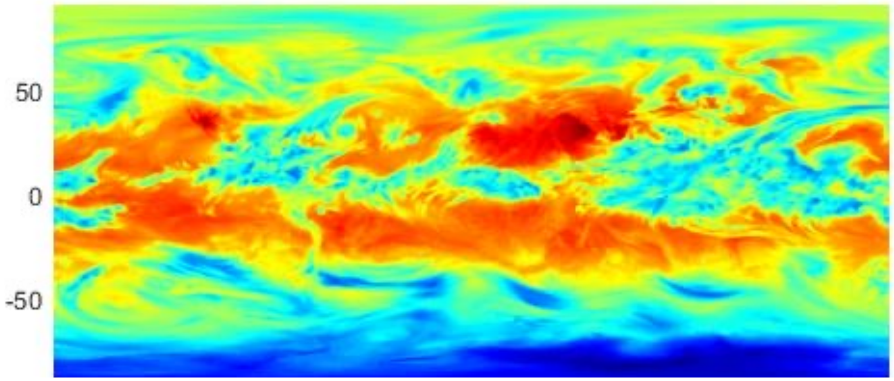
**Single day (June 27, 2017) of RAVAN LW flux (Total – SW)**

# ...however, wide FOV (130°)

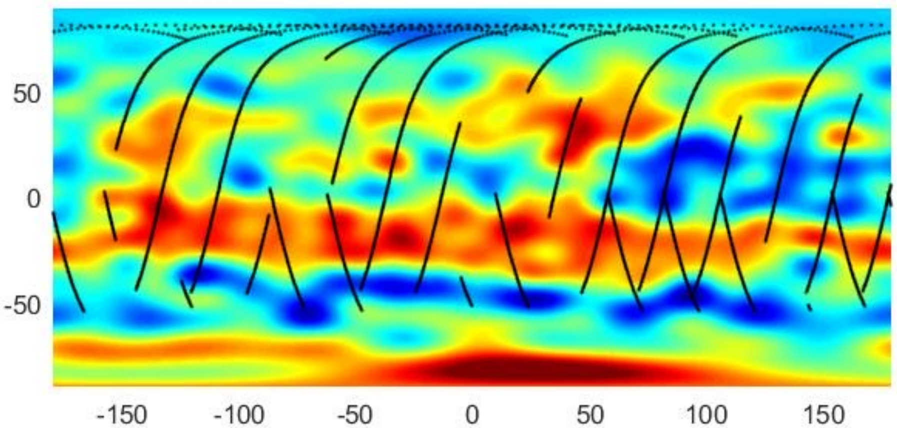


**Single day (June 27, 2017) of RAVAN LW flux (Total – SW)**

# Spatial reconstruction from a single day of data

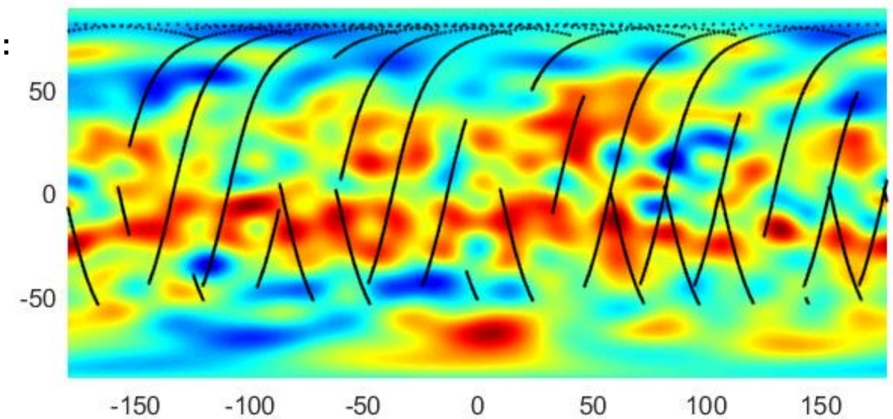



**MERRA-2** reanalysis, TOA LW flux, daily mean June 27, 2017

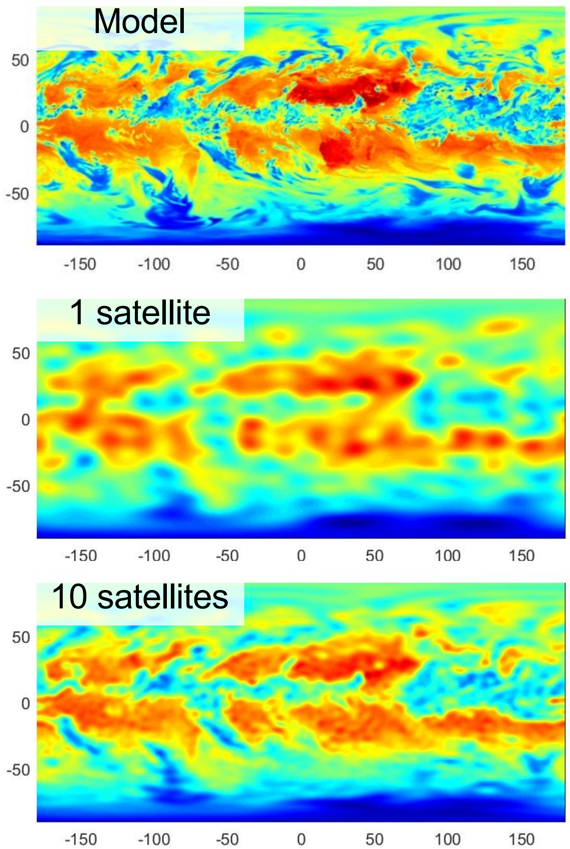


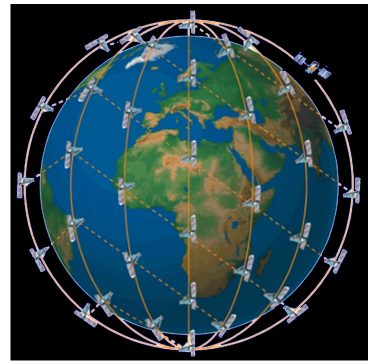

**Reconstruction: RAVAN sampling of MERRA-2** hourly TOA LW flux

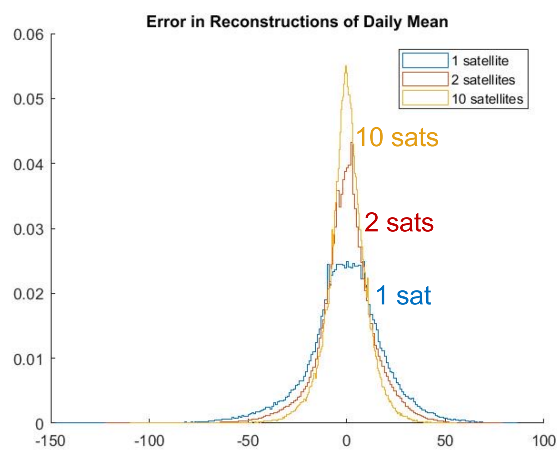
**Reconstruction: RAVAN LW flux data**



# More satellites provide greater spatial (and temporal) resolution and less error



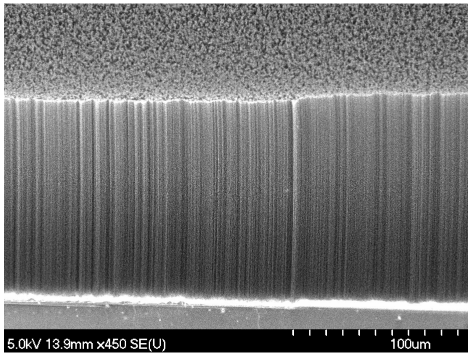



PDF of absolute error ($W/m^2$) of individual pixels

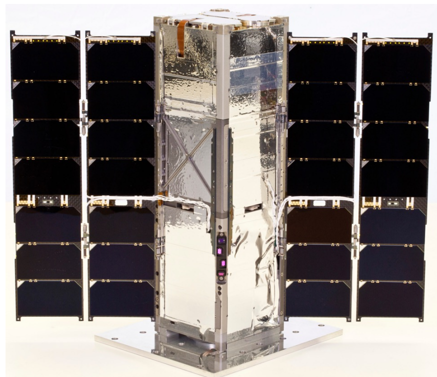
# Improvements for a future mission

- **Climate-level thermal knowledge and control are challenging in a CubeSat**
- **Significant improvements in future RAVAN-type sensors on a larger small satellite** (more volume and power)
  - Better active and passive temperature control of the electronics and the structures around the radiometers
  - Better radiometer baffles, with more space afforded by an even modestly larger small satellite bus and/or fewer radiometers in close proximity, these baffles could be made deeper, which would help to minimize the glint associated with passing out of eclipse. Radiometers built with a narrower field of view, such as CERES and scanner radiometers in general, would allow for smaller baffles and better thermal control.
  - Better gallium black bodies, with more space along the optical axis allowing the doors to accommodate a cavity emitter and a longer melting transition.
- **More frequent calibration**
  - UHF interference often limited how often we could make observations, but capturing and understanding shorter-term changes would enable us to account for more payload variability.
- **Extensive pre-launch calibration**
  - Such calibration impossible for RAVAN given compressed launch schedule

# RAVAN technology incorporated into subsequent projects




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

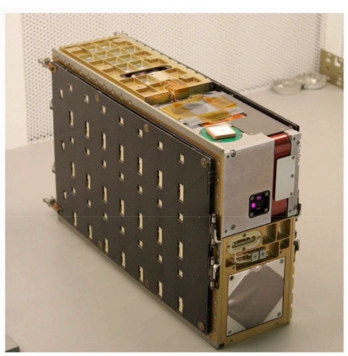


**VACNT, Ga BB demonstration**
**RAVAN (2016)**
NASA ESTO InVEST

**VACNT BB emitter; Ga BB**
**LaRC/APL Trutinor next-gen "CERES"**
LaRC IRAD (2018–2019)

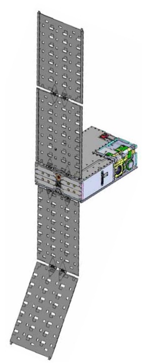
**VACNT radiometer array**
**LASP Black Array of Broadband Absolute Radiometers for Imaging Earth Radiation (BABAR)**
NASA ESTO IIP-2019

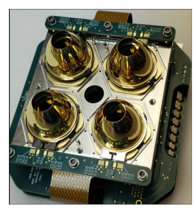
**VACNT radiometer**
**LASP Libera (2027)**
NASA EVC-1



*The CSIM CubeSat*

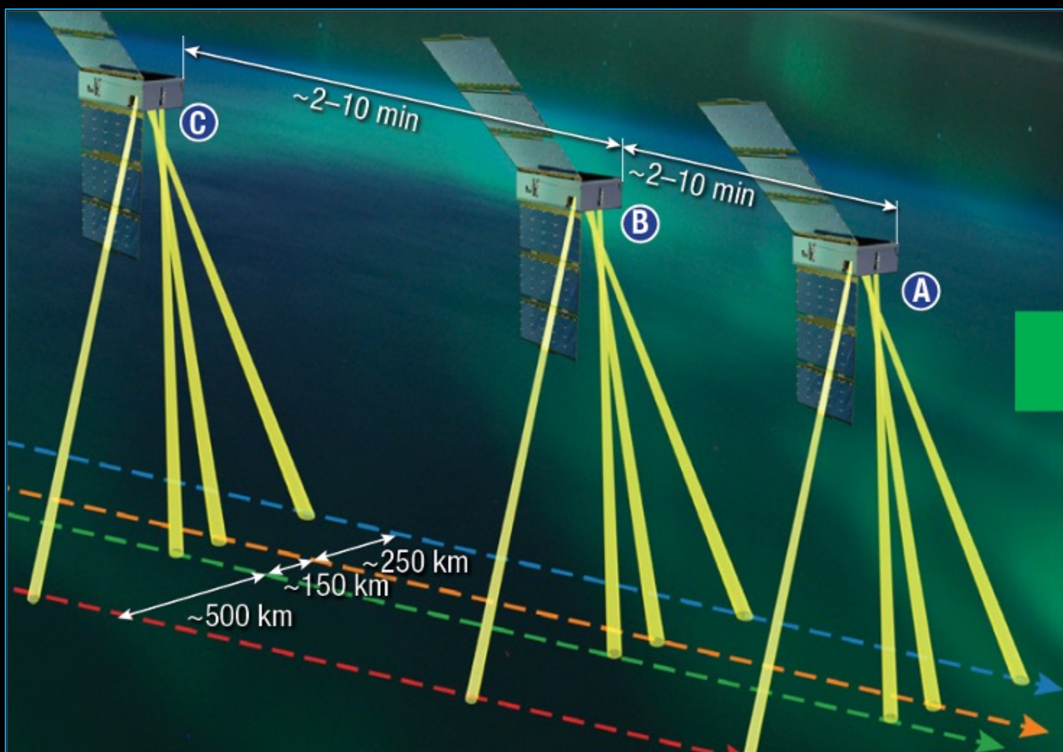
**VACNT radiometer/**
**BCT 6U bus**
**LASP CSIM (2018)**
NASA ESTO IIP, InVEST





**VACNT radiometer/**
**BCT 6U bus**
**LASP CTIM (2022)**
NASA ESTO InVEST

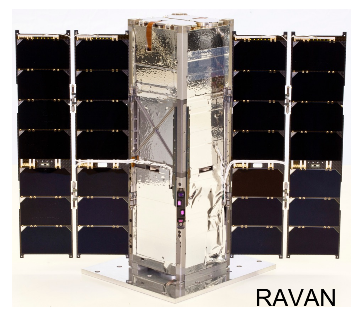
# NASA (APL) EZIE mission leverages RAVAN's bus heritage




- Electrojet Zeeman Imaging Explorer (EZIE)
- Measurement of Electrojet Temporal Evolution:
  - 3 6U CubeSat flying in a pearls-on-a-string formation with varying separation managed by differential drag.
- Measurement of Electrojet spatial structure:
  - A compact payload consisting of four identical $O_2$ 118-GHz spectropolarimeters to remotely measure and image electrojet induced magnetic fields
- Deployment orbit:
  - Circular, 525- to 625-km altitude
  - Near Sun-Sync, 09:00–11:00 or 22:30–00:30 LTAN
  - Launch Date: Late 2024 or early 2025

# Summary

- RAVAN (InVEST-2012) launched Nov 11, 2016 for 20-month mission
  - Four radiometers worked well
  - One (of two) gallium black bodies failed; the second performed throughout mission
- Primary conclusions
  - NASA ESTO technology demonstration success
  - Earth radiation budget science measurements harder problem
- The good
  - Carbon nanotubes (“VACNTs”) work in space, specifically as radiometer absorbers
  - Gallium phase-change black bodies for calibration monitoring
  - Long-term stability demonstrated
  - Qualitative (at least) agreement with reanalysis and CERES
  - Reconstruction of spatial information from WFOV “single pixels”
- The “less good”
  - Short-term fluctuations problematic (for 0.1% climate-level observations), most likely due to inadequate thermal knowledge and control
- RAVAN serves as a benchmark for future EEB science missions that use RAVAN technologies and/or smaller spacecraft


Swartz, W. H., et al. (2019), RAVAN: CubeSat demonstration for multi-point Earth radiation budget measurements, *Remote Sens.*, *11*, 796.