RAVAN Radiometer Assessment Using Vertically Aligned Nanotubes

RAVAN: Meeting Earth science objectives with less

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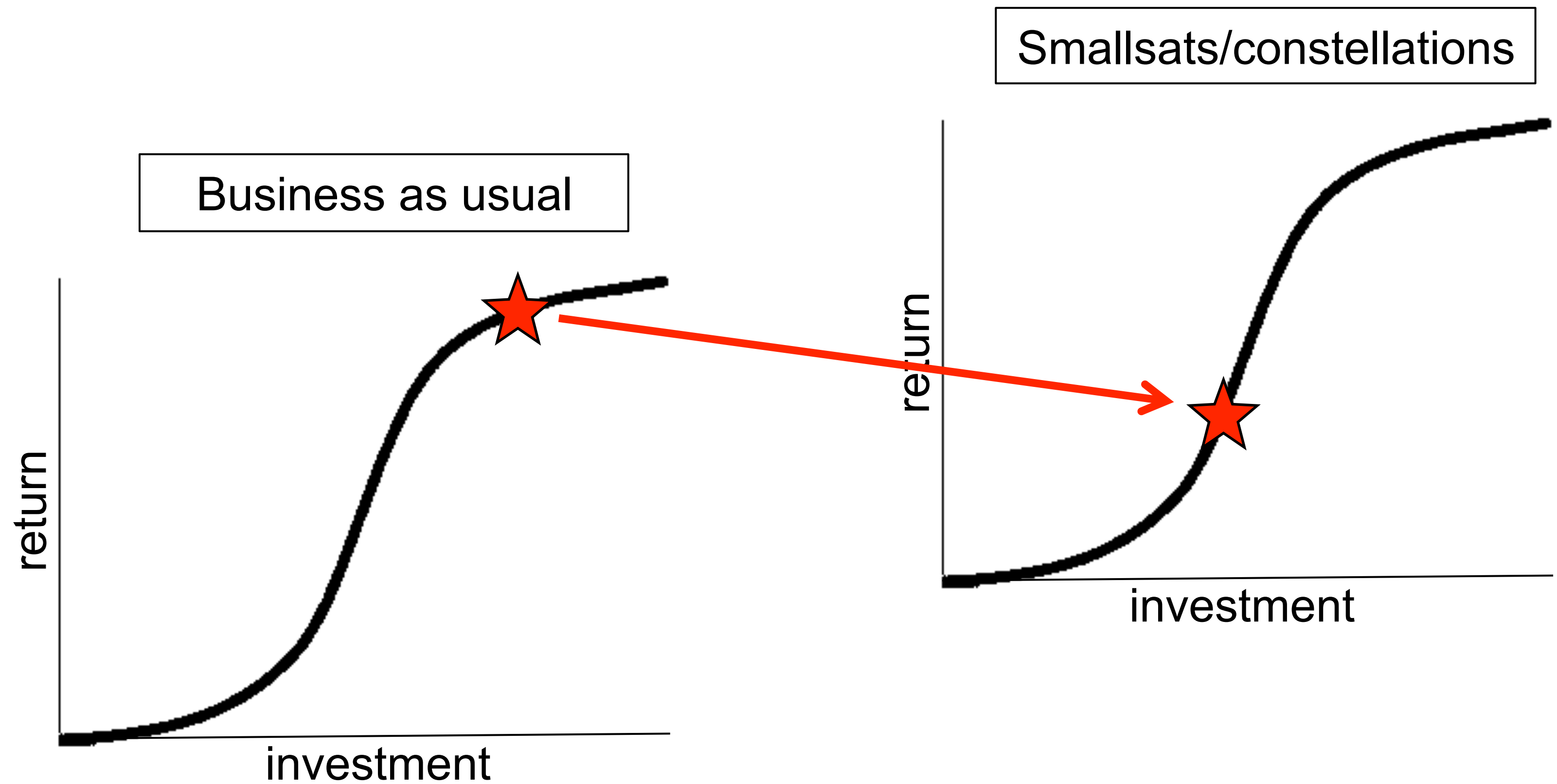
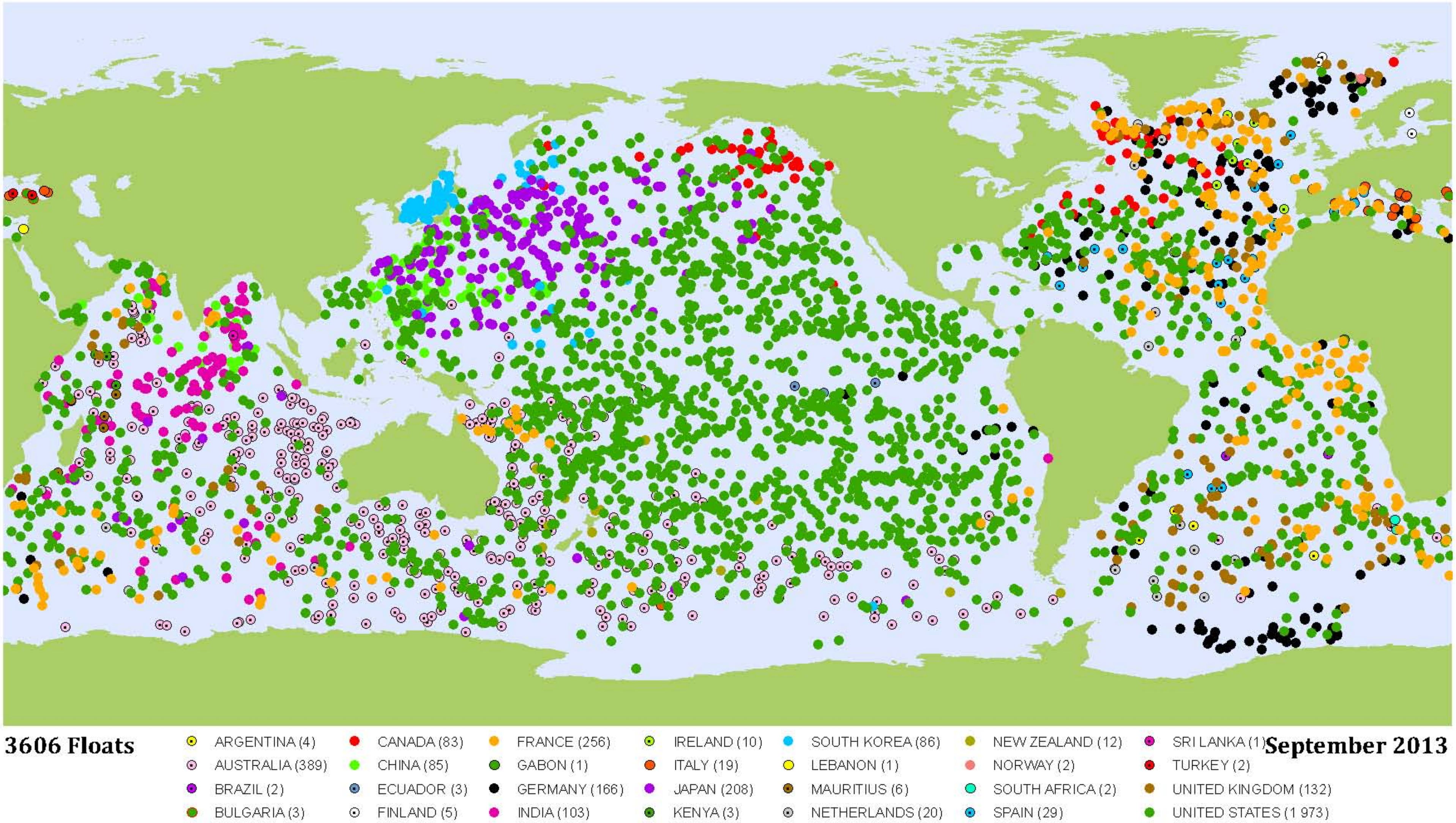
RAVAN is an example of a new approach to Earth science observations

- **Traditionally Earth space observations are made with large, exquisite, expensive measurement platforms**
- **But, such point observations are limited in time and space**
  - **Often fixed local time**
  - **Sometimes with very long revisit times**
- **Space constellations provide much greater observational potential**
- **How can one reduce cost to make a constellation affordable?**
  - **Make measurements that are "good enough" (are the most exquisite measurements really necessary?)**
  - **Use new ways to get to space (e.g., smallsats, hosted payloads)**

Moving to a new "S curve" provides opportunities for better (science) return on investment



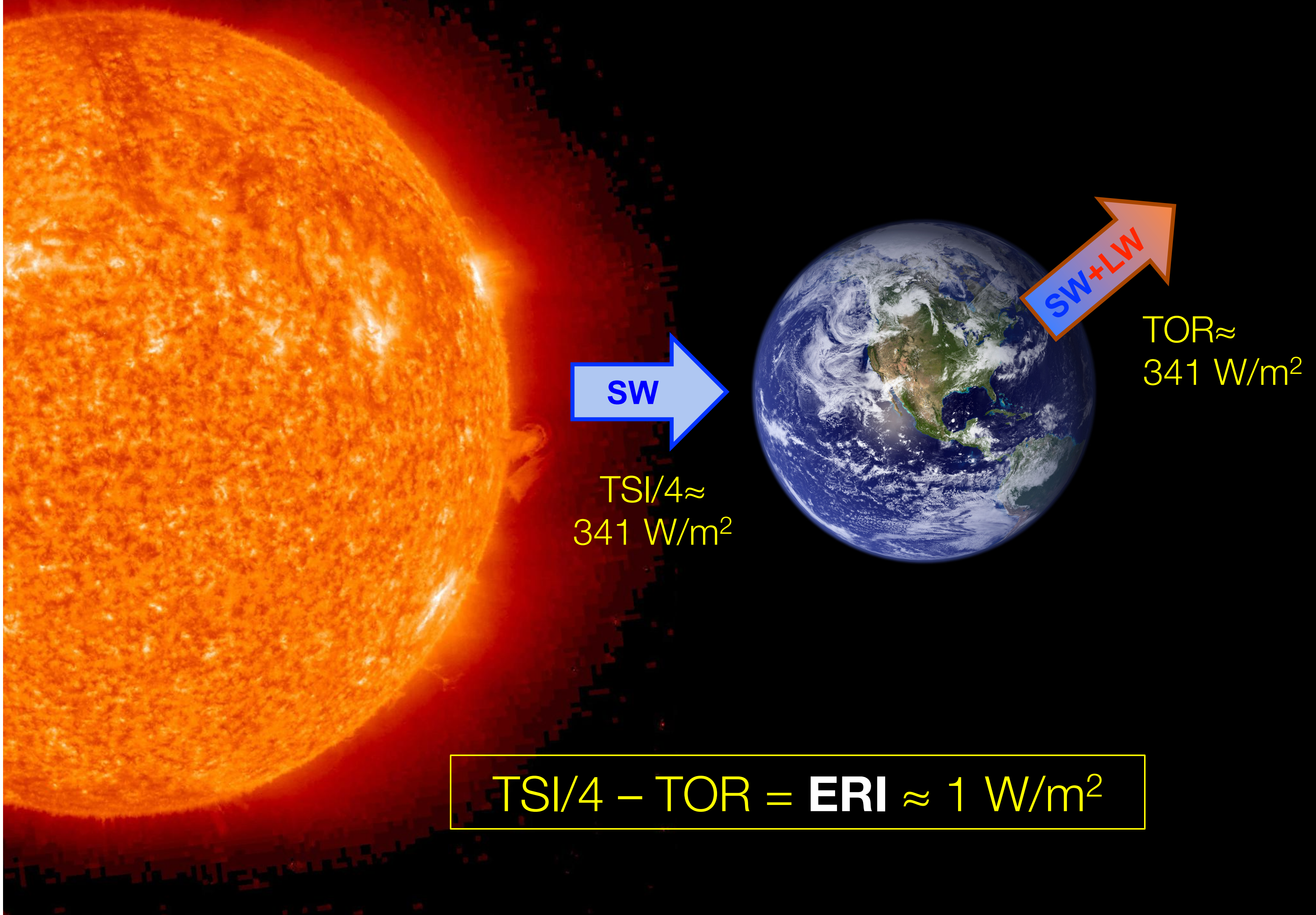
Argo network makes global ocean observations 24/7



Argo constellation in space would provide for a major advance in Earth radiation budget measurement

- **When the Argo ocean buoy array was introduced in 2004, producing a much better sampling of the upper ocean, it fundamentally changed our view of ocean heat content.**
- **The same thing is now needed in space.**
- **A constellation can provide unprecedented sampling of the Earth radiation budget (ERB).**

Future climate change driven by Earth radiation imbalance (ERI)

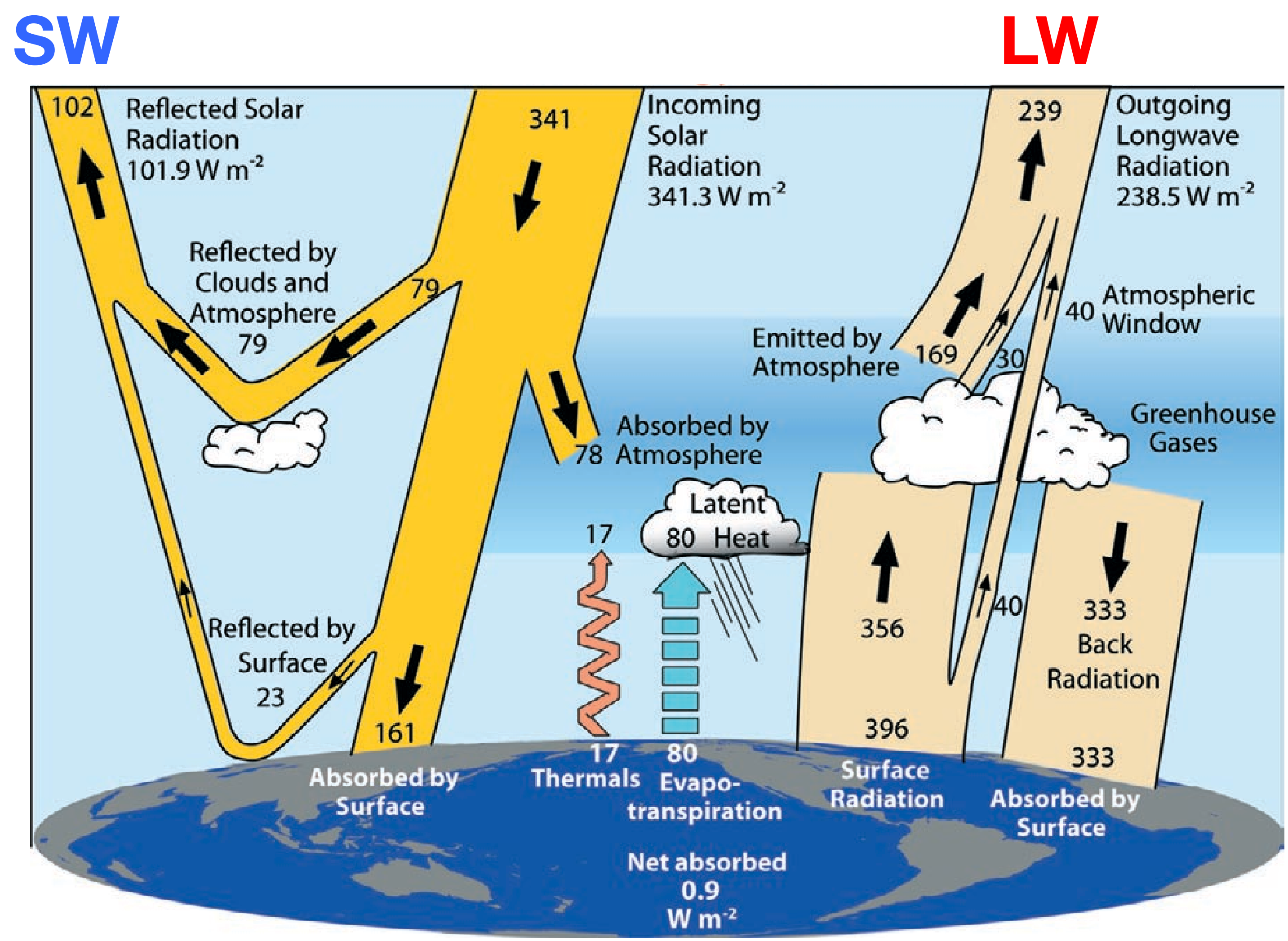


$$\mathrm{TSI}/4 - \mathrm{TOR} = \mathbf{ERI} \approx 1\ \mathrm{W/m^2}$$

ERI is the single most important number for predicting the course of climate change over the next century

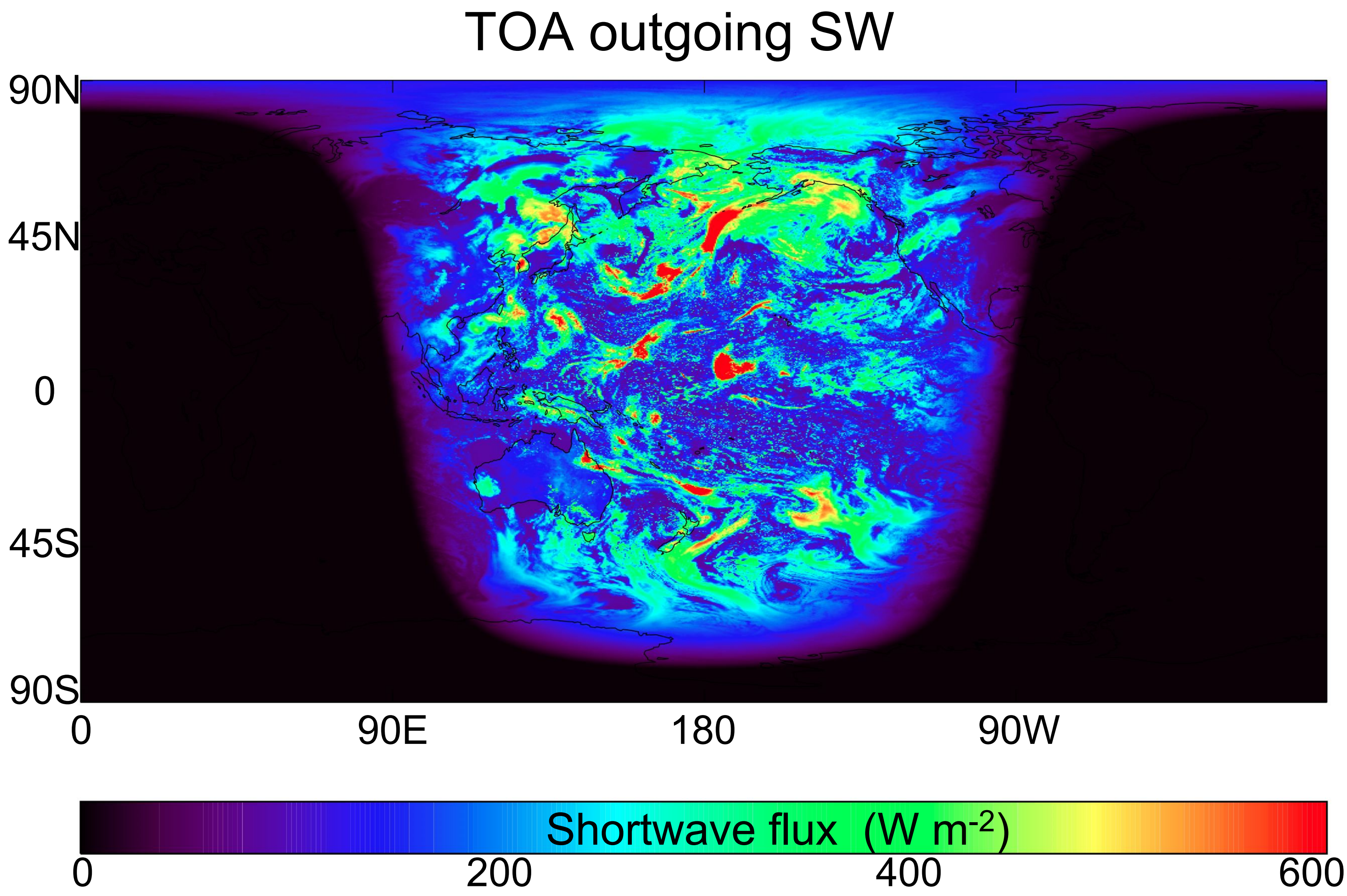
- **If ERI is negative, global warming will permanently slow down and eventually reverse. (Geo-engineering goal: make ERI negative.)**
- **If ERI is zero, global warming will coast up to a value determined by "warming in pipeline" (the ocean) – likely 2°C or less above pre-industrial.**
- **If ERI is 2 W/m^2, global warming will certainly accelerate since this dumps a huge amount of extra heat into the Earth system.**

Want to measure TOR to "climate sensitivity"



[*Trenberth et al.*, 2009]

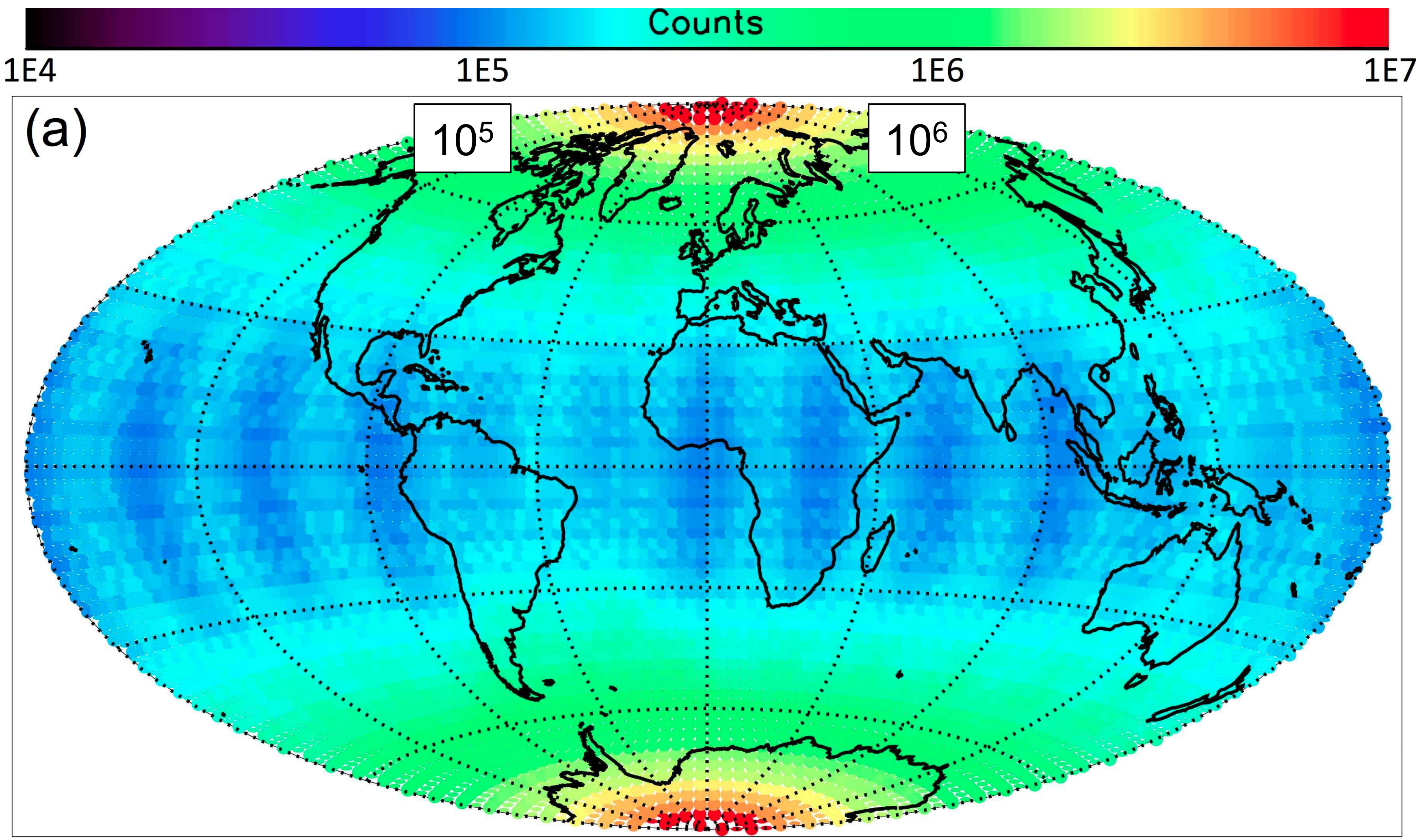
Outgoing radiation field has significant temporal and spatial variability



Simulation: Met Office global forecast model

courtesy Richard Allan

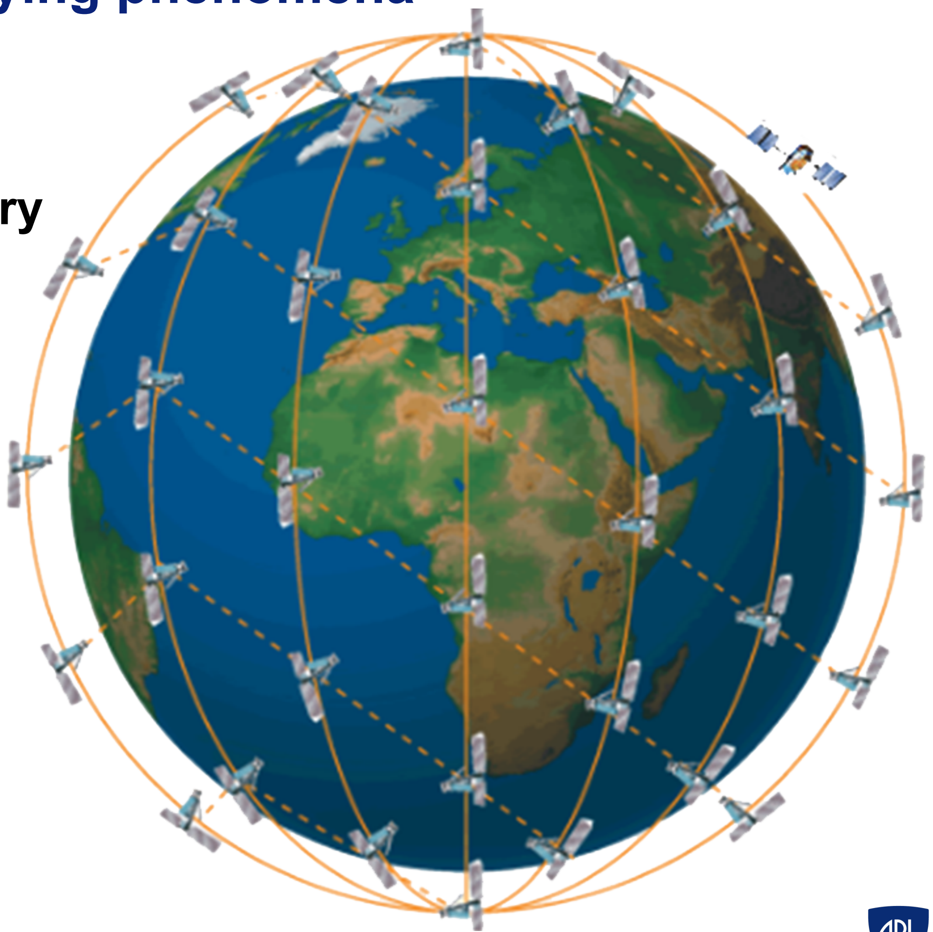
A constellation could provide global sampling throughout the day



For a 66-sat constellation, number of samples in each 250-km ISCCP pixel in 1 hr (5-s sampling).

An ERB constellation would quantify ERI <u>and</u> elucidate processes and forcings

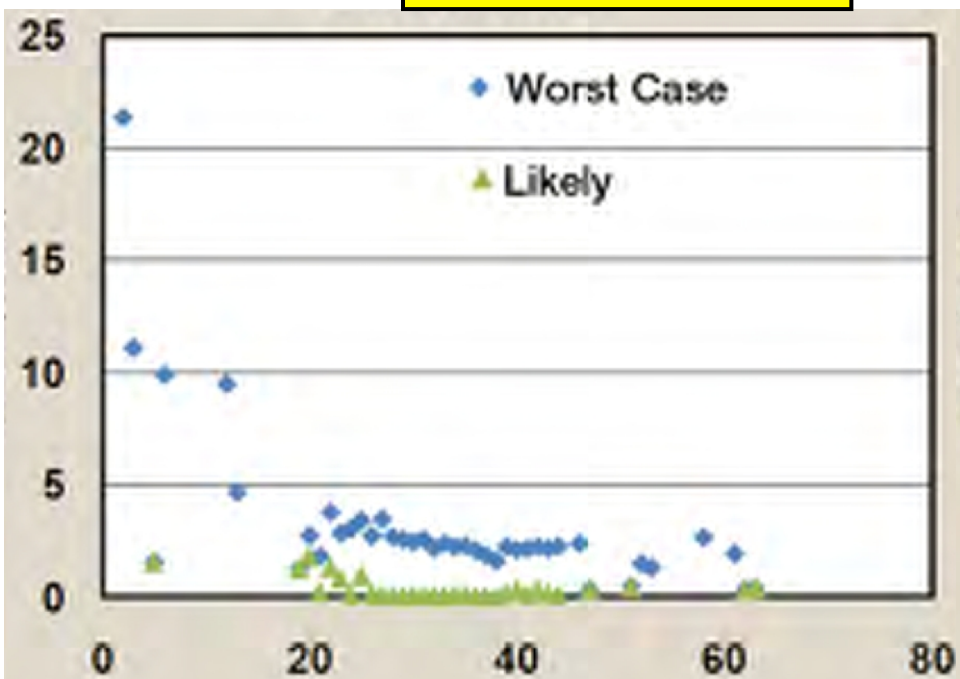
- **Accurate, un-tuned measurements of TOR**
- **Global, simultaneous, 24/7 coverage**
- **Diurnal sampling of rapidly varying phenomena**
  - **Clouds (really important!)**
  - **Plants (plankton to trees)**
  - **Ozone and other photochemistry**
  - **Aerosols**



The maturation of smallsat/hosted payload and constellation technology provides a unique opportunity for making the next great leap in ERB.

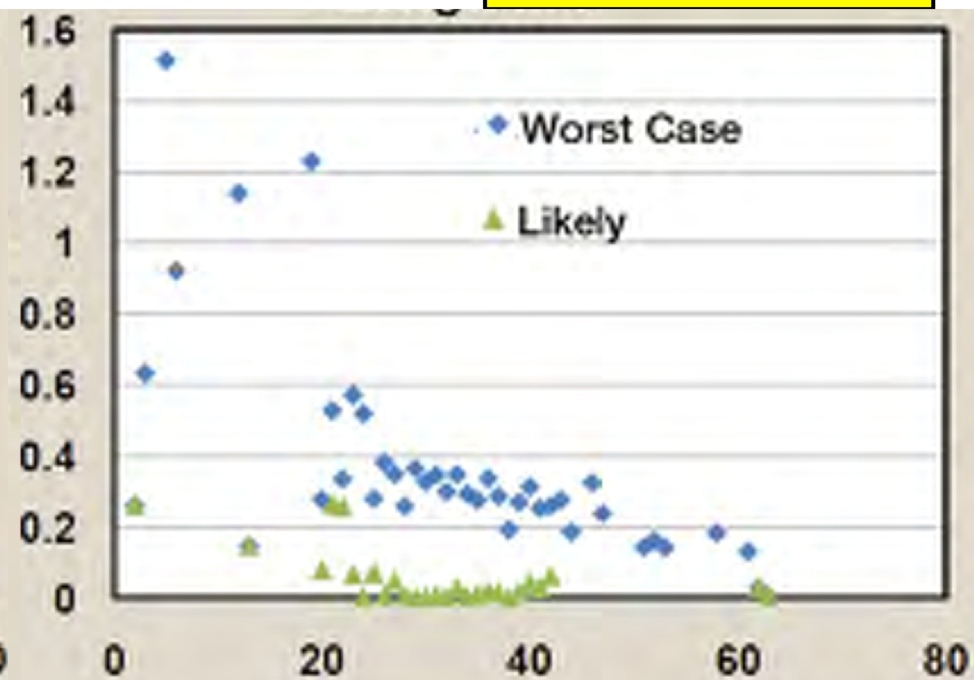
It would take a constellation of 30–40 sensors

error (W/m²) **Shortwave**



number of satellites

error (W/m²) **Longwave**



number of satellites

(Example based on Iridium NEXT constellation)

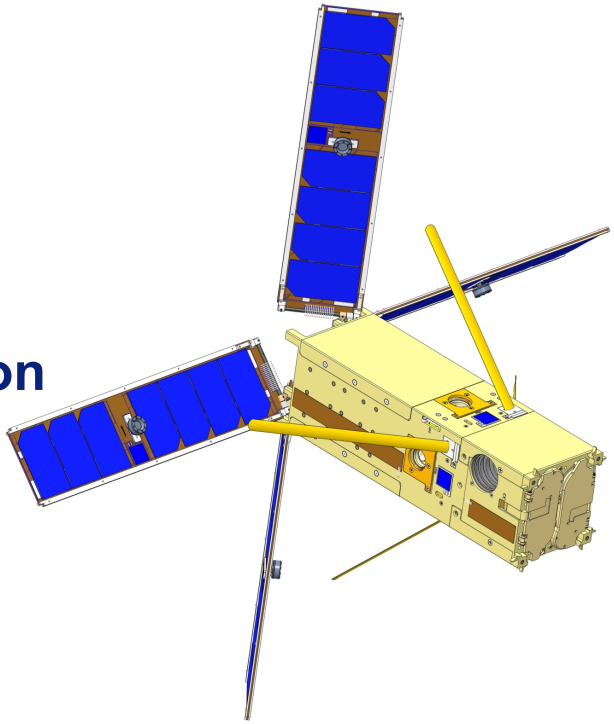
What are some other benefits of a constellation?

- **Expanded range of uses for ERB—e.g., making it a synoptic variable to be assimilated in weather and climate models**
- **ERB once again a dynamic research area with lots of non-incremental unsolved problems**
- **Eliminate single-point-of-failure threat**
- **Economies of scale**
- **Continuous improvement**
- **No gaps due to satellite replacement**

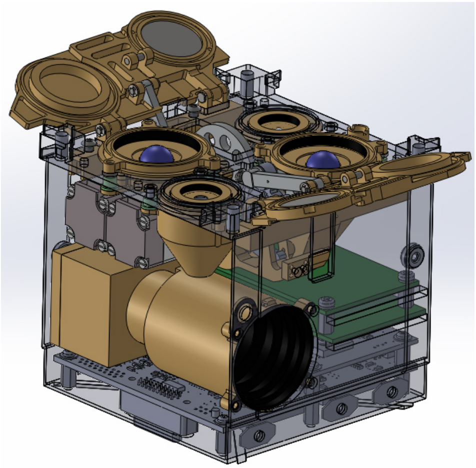
But we have to start with one….

RAVAN demonstrates key technologies

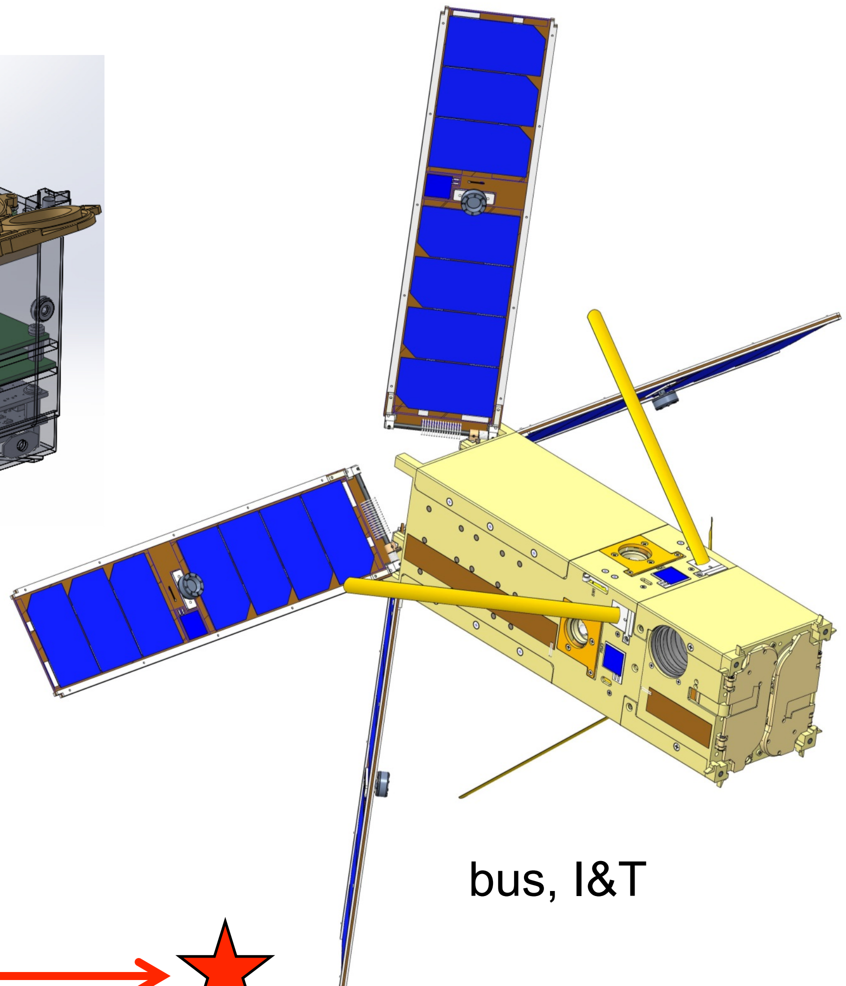
- RAVAN: Radiometer Assessment using Vertically Aligned Nanotubes
- CubeSat mission funded through NASA ESTO's InVEST program
- Combines
  - Compact, low-cost radiometer that is absolutely accurate to NIST-traceable standards (L-1)
  - VACNT absorber (APL)
  - Heritage 3U CubeSat bus (APL)
  - Process engineering analysis (Draper)
- Launch possible in early 2016
- Stepping stone toward ERB constellation



RAVAN payload development well underway

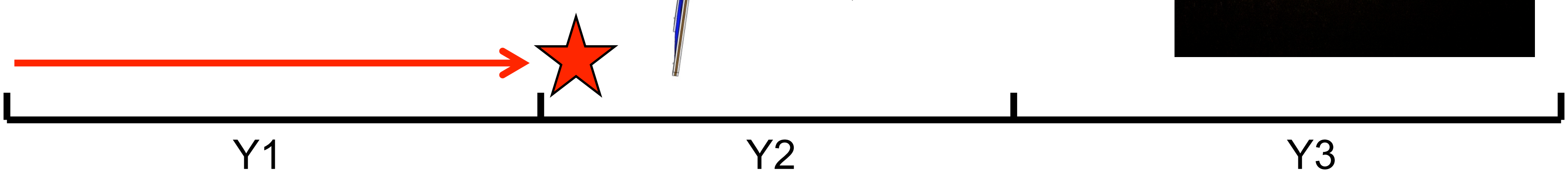


payload



bus, I&T

launch, operations



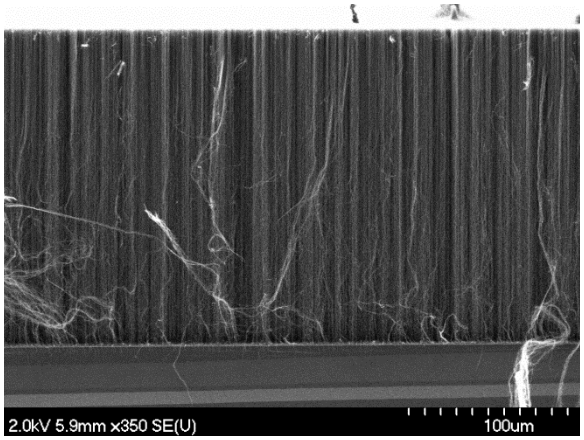
Primary mission objectives focus on technology

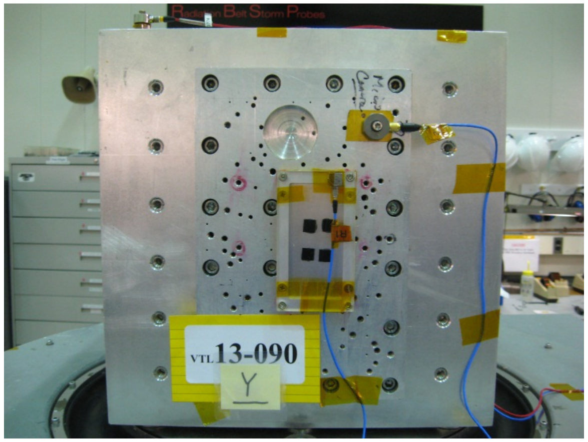
- **TECH 1: Demonstrate the use of a vertically aligned carbon nanotube (VACNT) absorber within a radiometer for high-accuracy on-orbit measurements**
- **TECH 2: Demonstrate the use of a gallium closed cell source for calibration of absolute radiometry (for transfer to orbit of ground calibration)**
- **CAP 1: Provide better than 0.3 W/m^2 (climate accuracy) absolute Earth total outgoing radiation (TOR) measurements**
- **CAP 2: Establish an accuracy standard that remains stable over time on orbit (5-month prime mission*)**
- **CAP 3: Provide radiometer units that are manufacturable and calibratable at low cost so that the required constellation remains affordable**

*Desirement: >1 year operation desired (allows for more TOR data for comparison with CERES and other instruments)

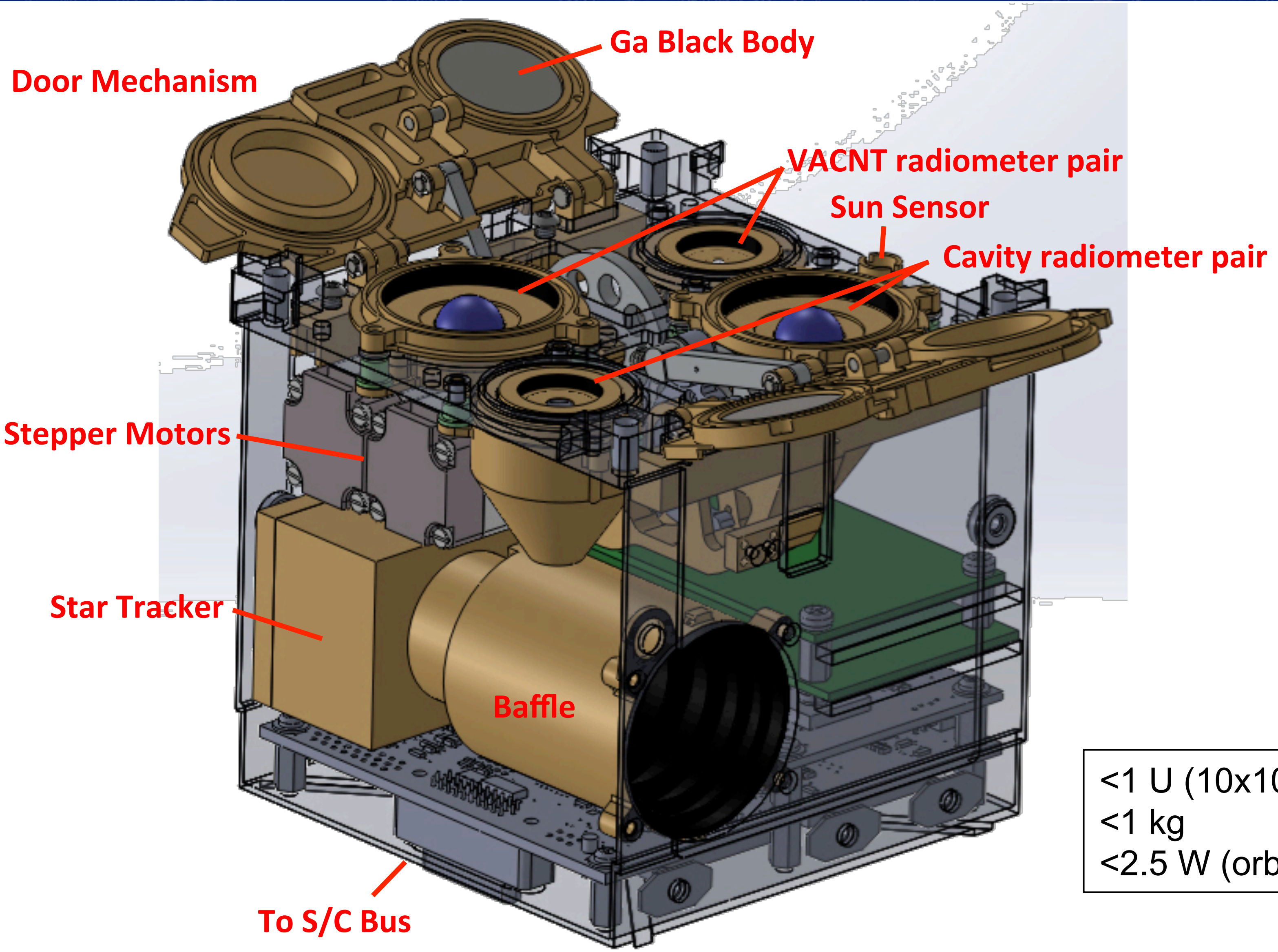
VACNTs are a key technology, grown at APL

- **Chemical vapor deposition on silicon wafer; post-growth modification**
- **Pre-screen library at APL for IR reflectivity to 16 µm**
- **Characterization (likely at NIST) to 100 µm**
- **3-axis vibe testing was performed on samples**
- **Overall the samples showed no gross change or irregularity that indicates they would be damaged past use by the launch (i.e., <u>VACNTs passed vibe test</u>)**



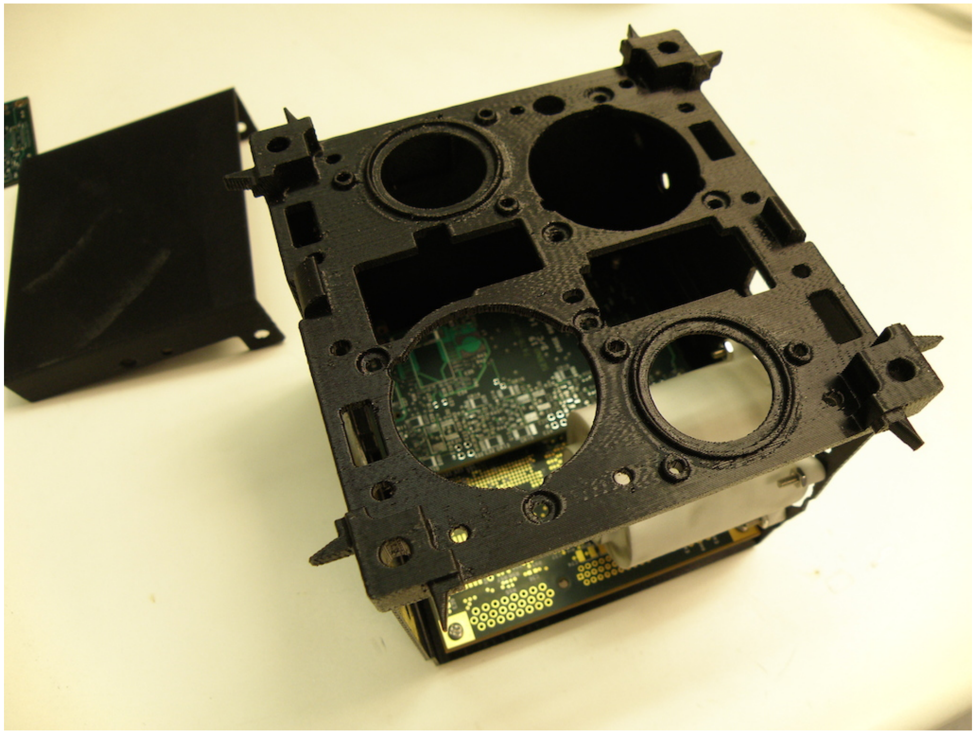


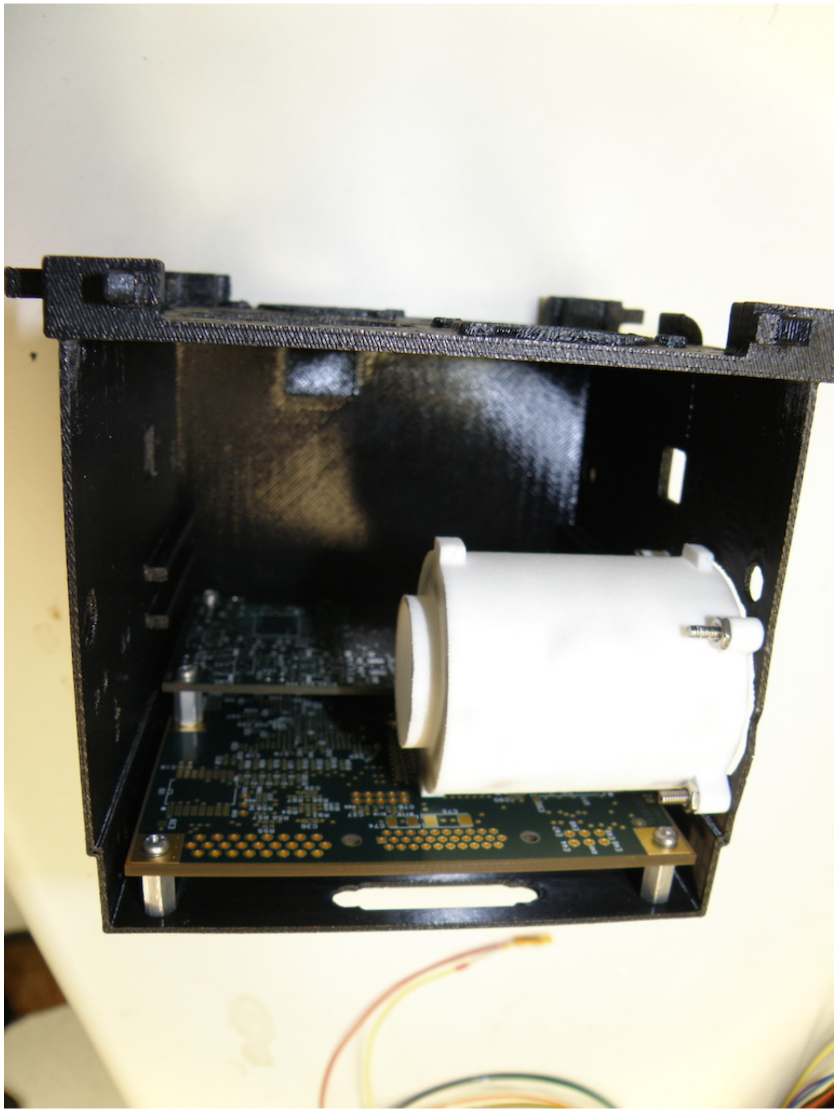
RAVAN payload comprises both new and old tech



<1 U (10x10x10 cm^3)
<1 kg
<2.5 W (orbit average)

Payload EM unit nearing completion





Housing mock-up shown here, partially populated.

Design concept: New vs. old tech

- Treat TOR as simple irradiance measurement
  - Thermal detectors with spectrally flat black absorber and precision aperture
- Redundant Total and SW channels
- Shortwave filter is a sapphire dome
- Primary Radiometers: VACNT on Si
  - Compact radiometer with better sensitivity for a given time constant
  - Characterization much more involved
  - Great, but not perfect absorber (>99%)
- Secondary Radiometers: Cavity (“old” tech)
  - Black painted conical Cu cavity
  - Better than 99.95% absorbing
  - Less subject to contamination
  - Simpler characterization and calibration
  - Degradation monitor for primary radiometers
  - Proves performance of primary
  - Risk mitigation
  - Provides redundancy

Getting to climate accuracy

- **Ga black body emitter**
  - Transfer standard for Total channels
  - Degradation monitor of both primary and secondary Total channels
  - Ga BB coupled with solar and space looks gives offset and degradation monitoring
- **Adequate resolution and absolute scale to determine outgoing radiation to 0.3 W/m^2**
  - Radiometric design must be adequate to achieve this (thermal, scattered light, polarization, aperture definition, electrical scale)
- **Modes of operation/calibration**
  - Nadir–primary radiometers
  - Internal calibration (doors closed; Ga BB)
  - Solar calibration
  - Space calibration
  - Inter-calibration (primary and secondary radiometers)

Mechanical design for a very small form factor

- **Payload volume is small (<1 U) but must contain:**
  - **4 radiometers: Primary (VANCT) Shortwave and Total channels plus a secondary (cavity) pair of detectors**
  - **2 motorized covers with integrated gallium reference sources for Total channel stability monitoring**
  - **Star tracker and fine (0.1°) sun sensor**
  - **Control Electronics**
- **Reusable doors must open to clear radiometer 135° FOV and passively lock tightly for launch**
- **Radiometers actively temperature controlled and thermally isolated from spacecraft**

RAVAN leverages APL's 3U CubeSat experience

- Two APL 3U CubeSats launched Nov. 19, 2013 from Wallops
- Radiometer payload is accommodated in current payload volume (<10×10×10 cm^3)
- Sensor is nadir-pointing (most of the time)
- GPS navigation
- <1° pointing knowledge (accomplished by use of star tracker)

RAVAN will fly as early as 2016

- Proposed to CubeSat Launch Initiative, 11/23/13
- RAVAN selected and ranked #2 (of 16)
- Recent discussion with CSLI suggests earliest possible launches in 2016, possibly 2017

CubeSat Mission Parameters								
Mission Name	Mass	Cube Size	Desired Orbit*		Acceptable Orbit Range	325 km @ 51.6 degree incl Acceptable – Yes or No	Readiness Date	Desired Mission Life
RAVAN	5.5 kg	3U	Altitude	600–700 km	550–700 km	No**	1 Sep 2015	2 years
			Inclination	80°–95°	> 40°			

* non sun-synchronous ** 325 km too low

CubeSat Project Details						
Focus Area	Student Involvement	NASA Funding		Sponsor	Proposal Collaboration	
		Yes or No	Organization		Yes or No	Int'l – Yes or No
1. Technology – VACNT-Based Bolometer Demo 2. Science – Climate Observation	Yes	Yes	ESTO	NASA	Yes	No

Conclusions: Small package(s), new science

- **Space constellations provide an opportunity for new kinds of Earth science observations**
  - **Simultaneous global measurements at high temporal cadence**
- **Earth radiation budget constellation would provide**
  - **Quantification of Earth radiation imbalance (local and global)**
  - **Smaller-scale processes associated with climate forcing**
- **RAVAN CubeSat mission demonstrates**
  - **One element of ERB constellation**
  - **New ERB measurement technologies: VACNTs, Ga BB**
  - **Low-cost stepping-stone to new observations strategies**

Funding: NASA Earth Science Technology Office