Latest Detector Developments in IR Carbon Nanotube Technologies – Microfabricated Bolometers – Absolute Radiometry

NIST

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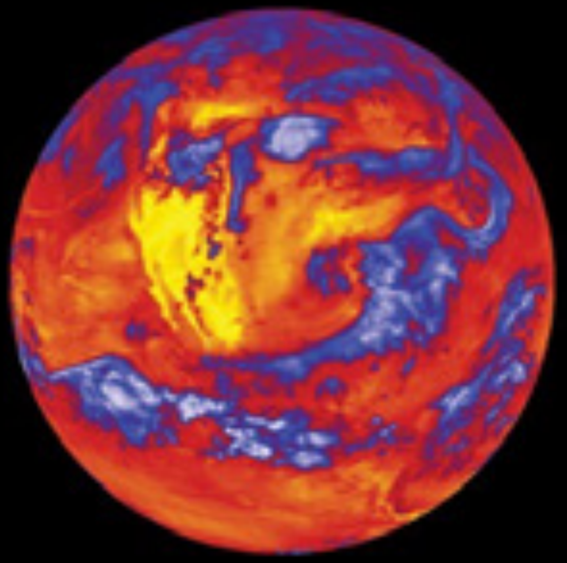
Michelle Stephens
John Lehman

LASP

Cameron Straatsma
Odele Coddington
Dave Harber
Peter Pilewski
and many others…



CERES far infrared image of the Earth taken with a scanning radiometer

Funding for CSIM, CTIM, BABAR, and BABAR-ERI provided by NASA ESTO – Parminder Ghuman (GSFC) and Keith Murray (LARC)


NIST

- Some words about nanotubes
- Some words about absolute radiometers
- The bigger picture
- Some specific examples

Modern Nanotubes

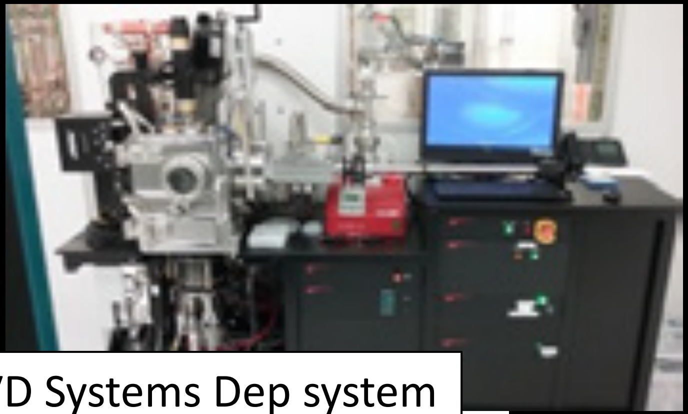
Control VACNT x-y-z on a chip

- Gold-black
- Black paint
- NiP, Black Si
- Spray on carbon nanotubes

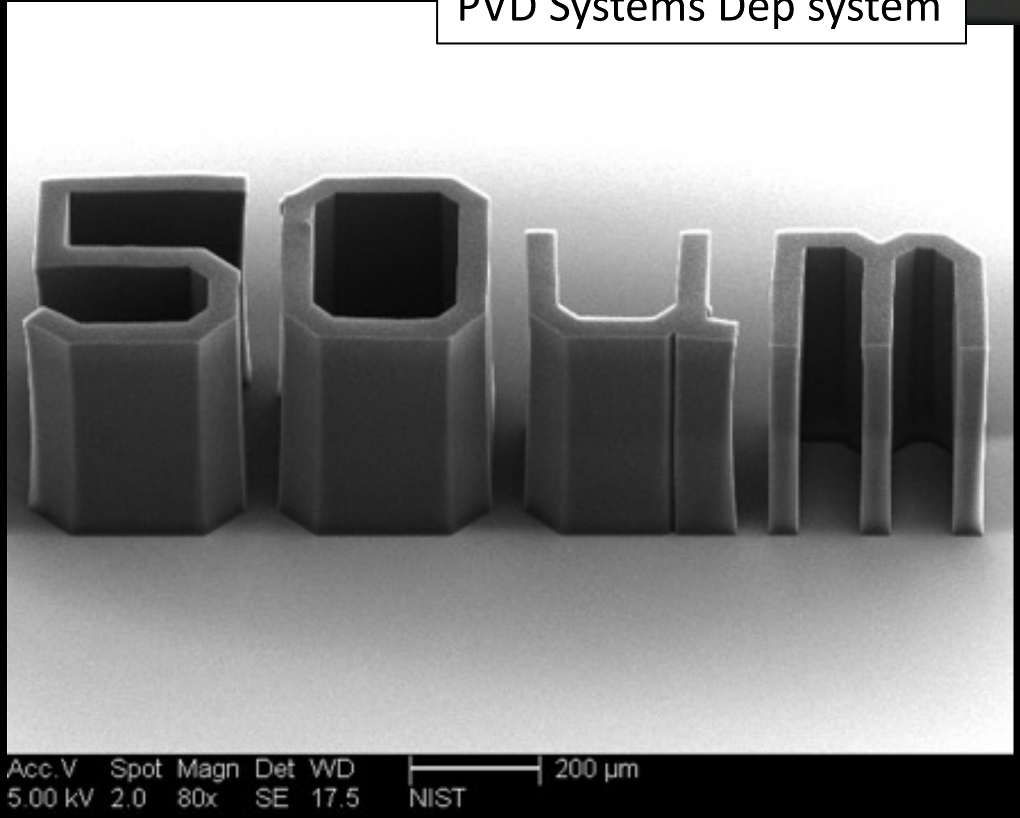
VACNTs are the darkest, broadband 2-D "coating"

Yes, they are black, but how do you know?

- the blackest black isn't great if you can't measure it

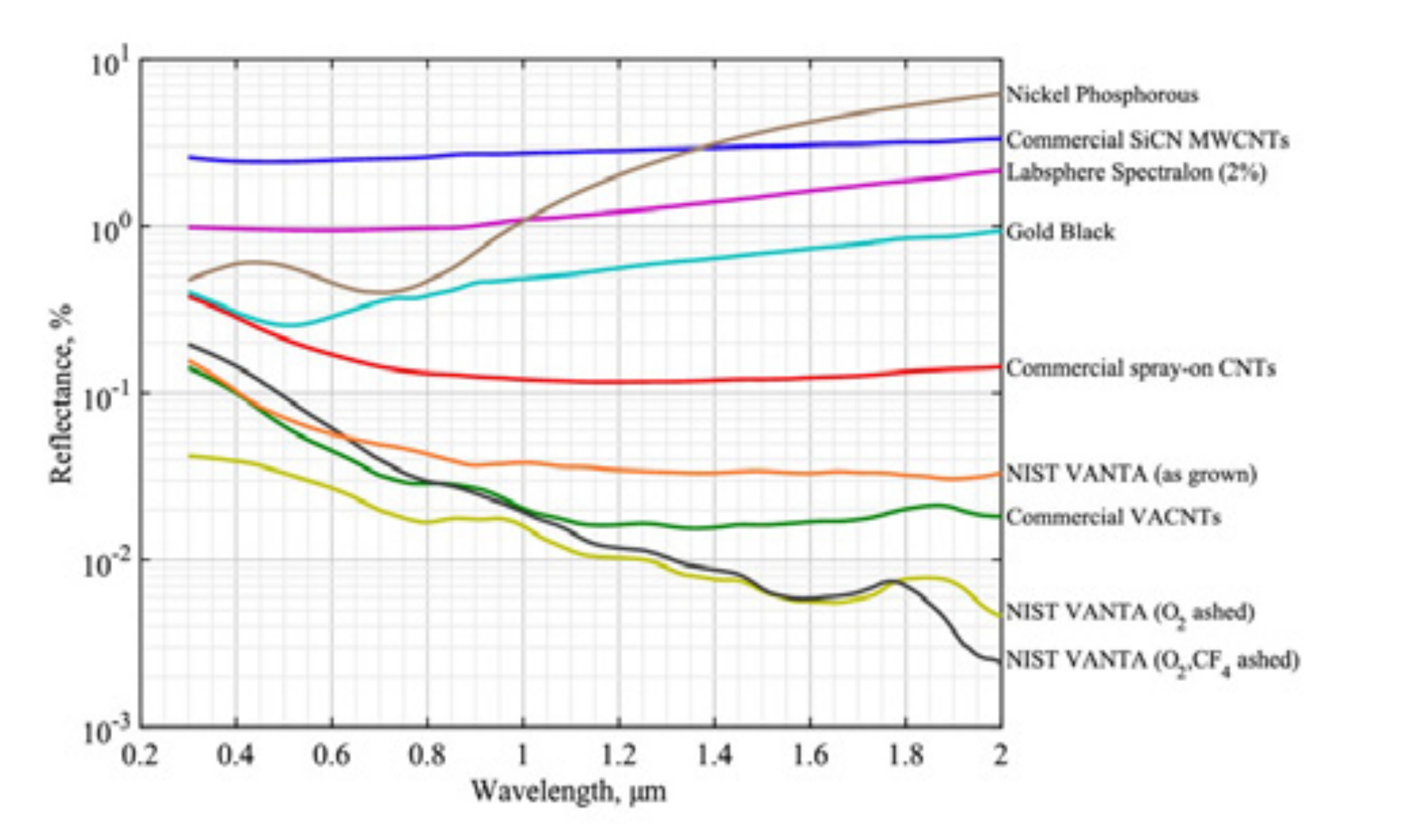


PVD Systems Dep system

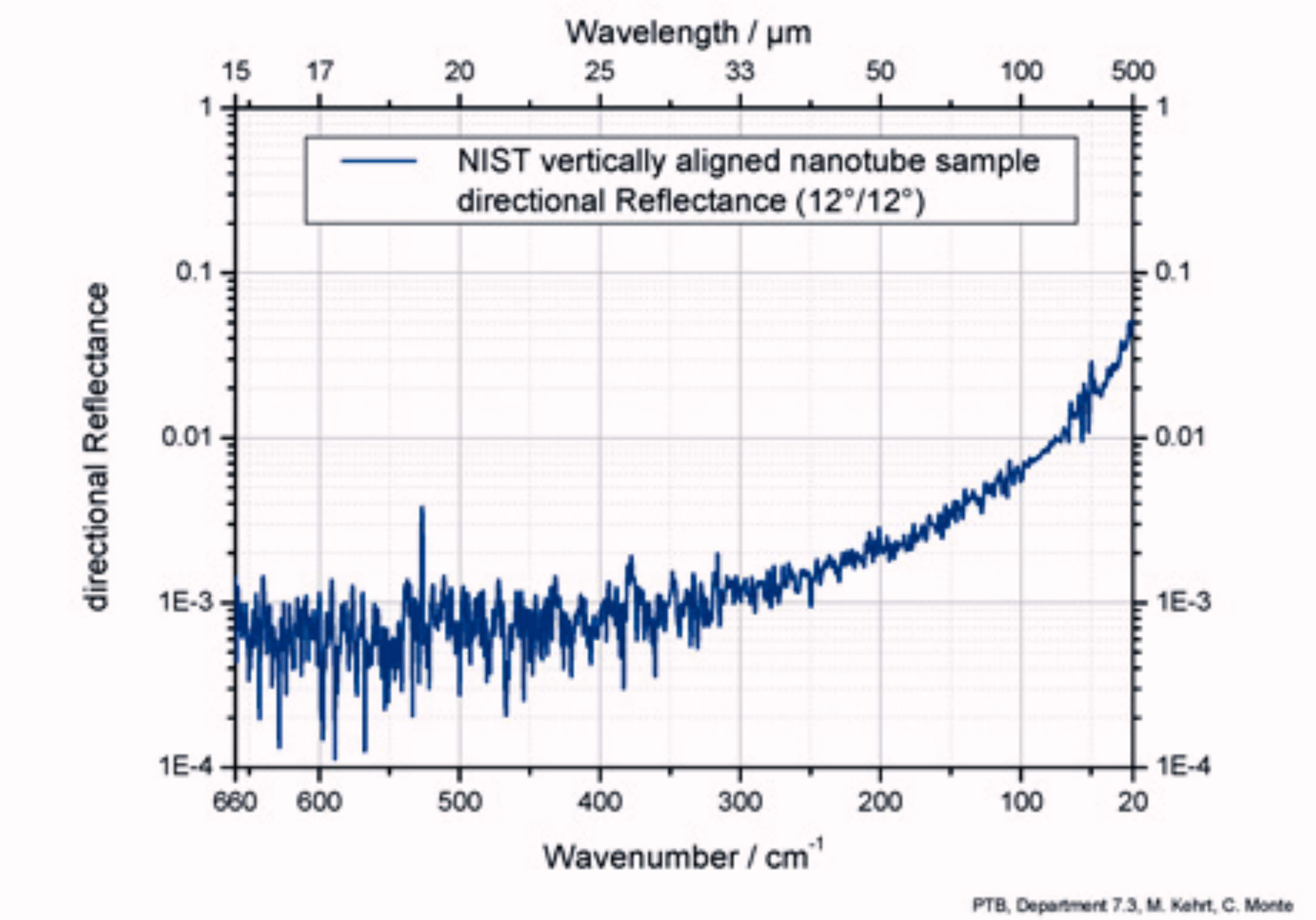


VIS/NIR reflectance

Appl. Phys. Rev. 5, 011103 (2018)



FIR reflectance ca. 2012, PTB



Thermal Properties, Black Coatings

1. index ~ air (or vacuum)

2. "Optically thick"

3. Thermal diffusivity large

$$\alpha = \frac{k}{\rho c}$$

$k \sim 400$ W/m•K (big!)
$\rho \sim 7$ kg/m^3 (small!)
$c \sim 400$ J/kgK

Lehman et al., Applied Optics, 50, 4099-4104, (2011)

Advantages

- Lithographic
- Extremely broad
- Extremely uniform
- High diffusivity
- “Space qualified”
- *we are the only Group doing this*

Disadvantages

- High temperature fab
- Some delicacy (last step)
- *we are the only Group doing this*

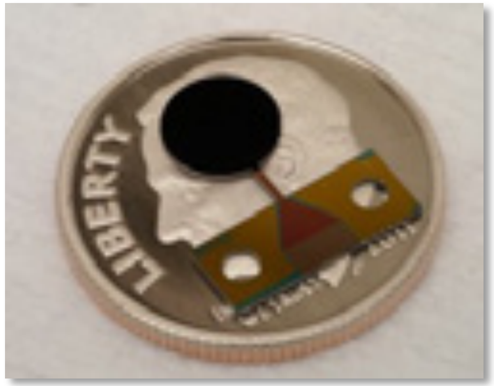
See: Appl. Phys. Rev. 5, 011103 (2018)

Review of “Carbon Nanotube Based Coatings” data and recipes, etc.

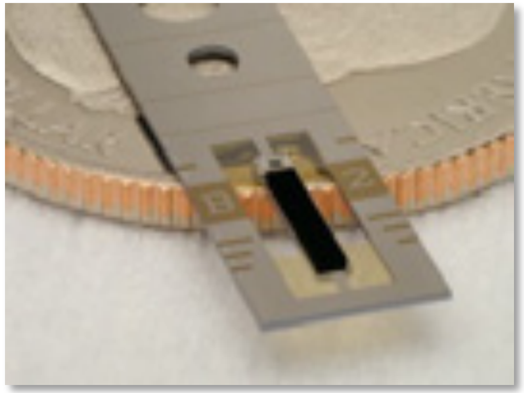
VACNT radiometers

Past 5 years, NIST/LASP have been developing a range of VACNT radiometers

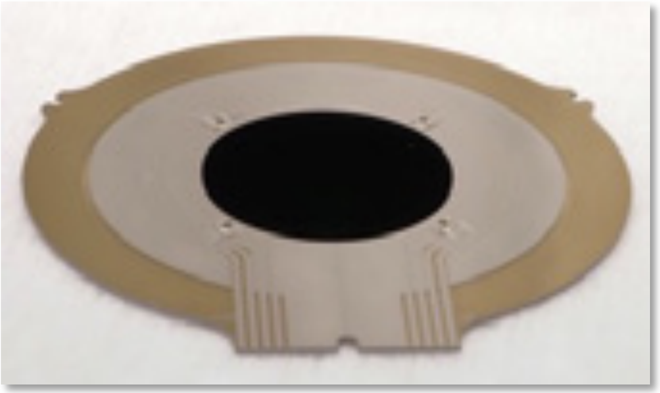
2017 → 2019



cryogenic fiber optic radiometer

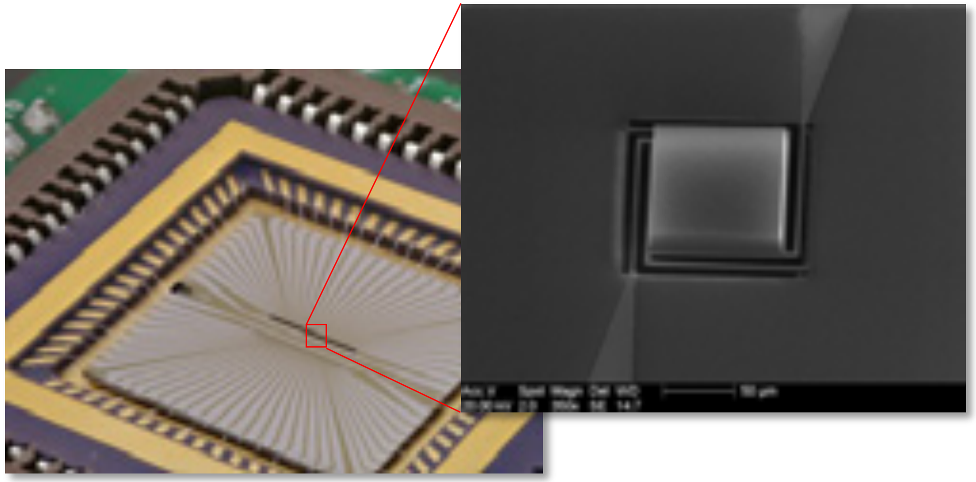


CSIM radiometer



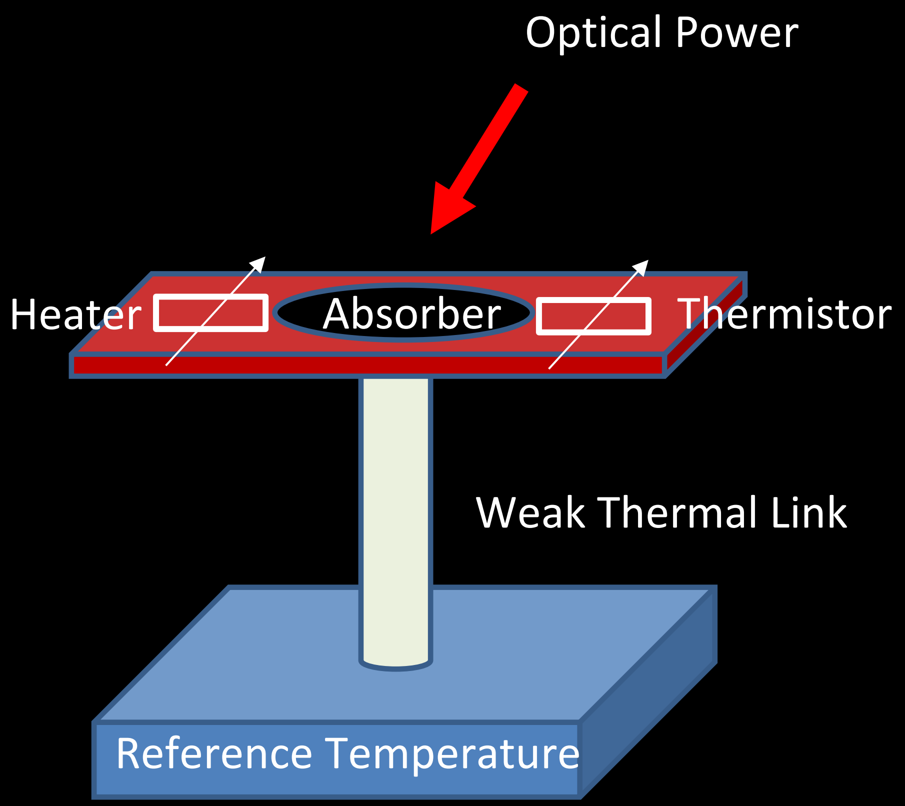
CTIM radiometer

Libera prototype



2020: BABAR-ERI packaged VACNT microbolometer array for far infrared imaging

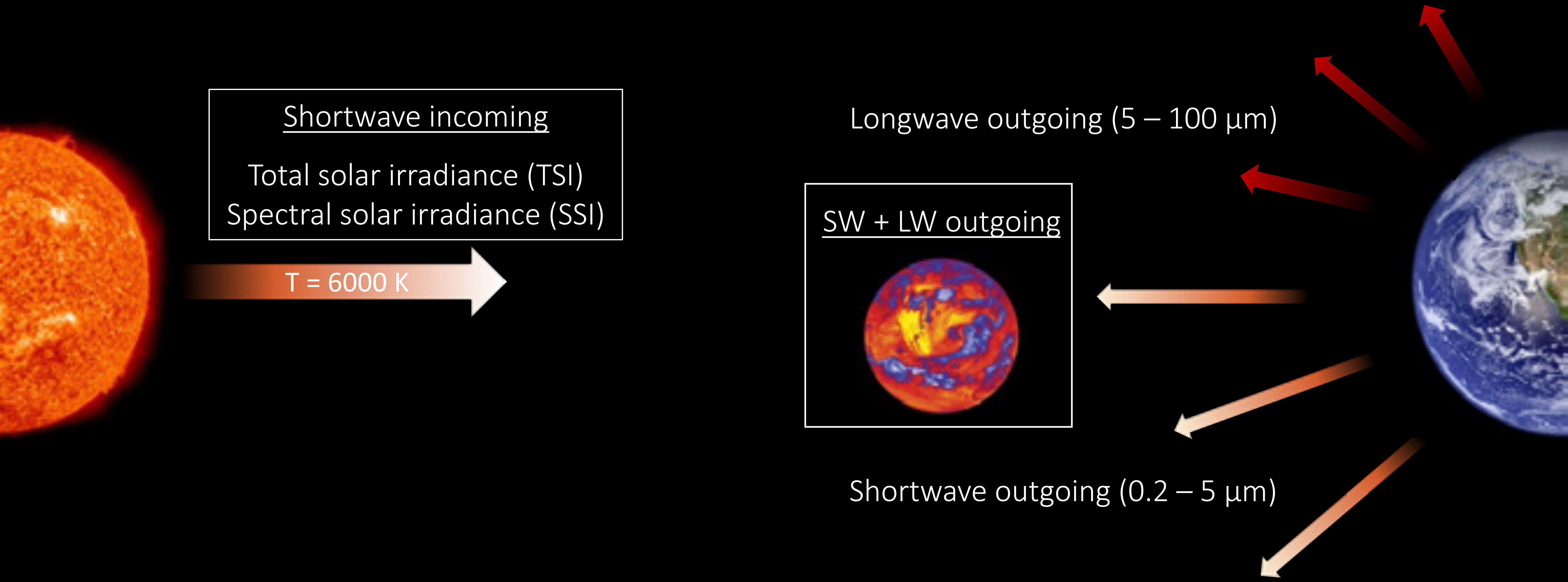
Present Primary Standardization



Optical Power Traceable to the SI by Electrical Measurements
resistance, current, voltage

Earth Radiation Budget

Earth Energy Imbalance (EEI) = $SW_{incoming} - (SW + LW)_{outgoing}$



Top of atmosphere measurement of the balance of all energy going into Earth and all energy leaving

Earth Radiation Budget

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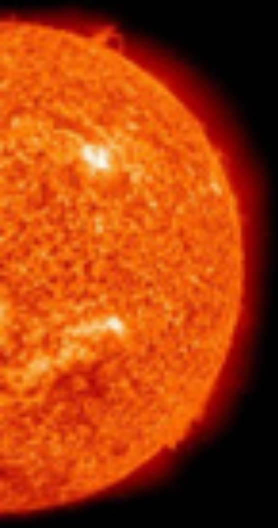
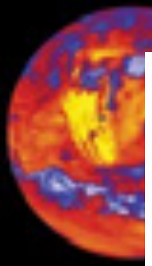


<u>Shortwave incoming</u>

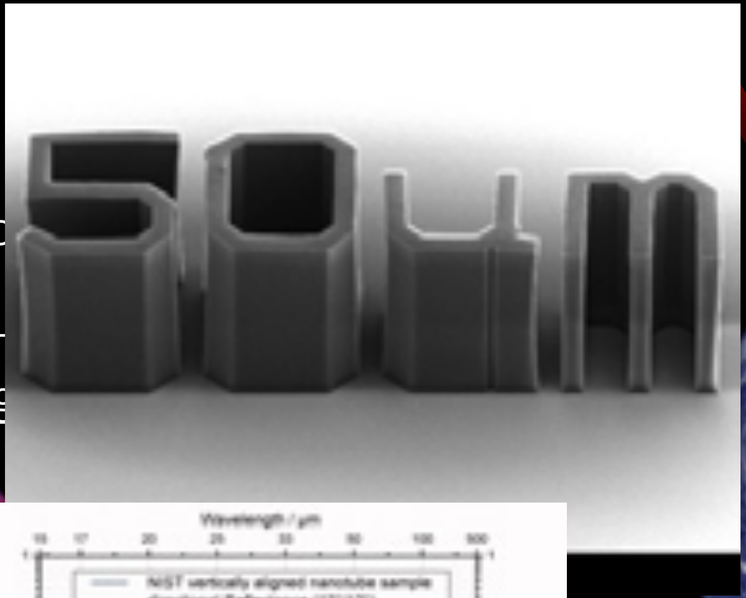
Total solar irradiance (TSI)
Spectral solar irradiance (SSI)

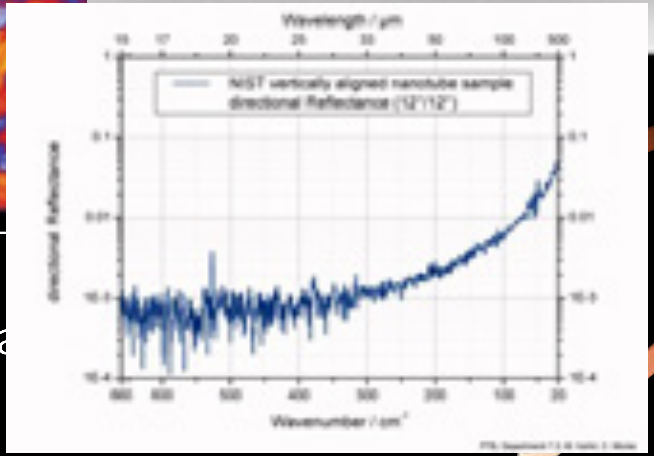
Longwave c

<u>SW + LW outg</u>



Shortwa





Top of atmosphere measurement of the balance of all energy going into Earth and all energy leaving

Earth Radiation Budget

TSI and Earth's outgoing radiation have been measured for 40 years now

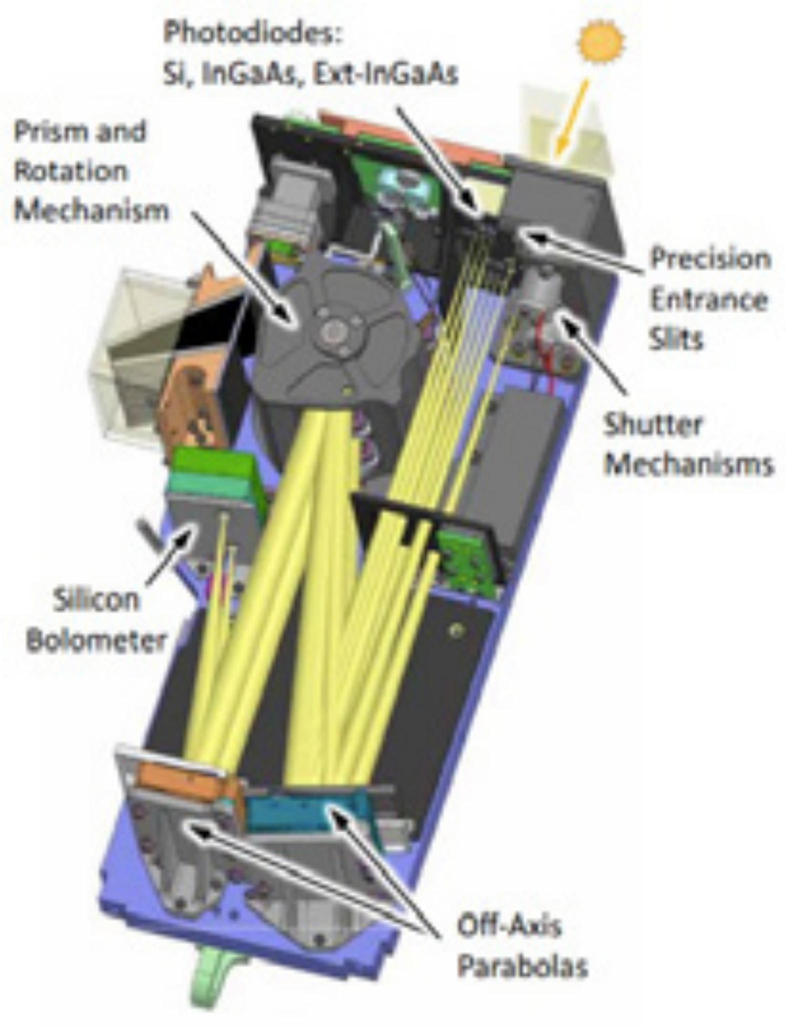
> "In the process of **modernizing**, we want to be careful that we don't have any discontinuity in the data record."
>
> Norman Loeb, CERES PI, NASA

- NASA has competing demands of modernizing instruments while maintaining data continuity.
- Discontinuity was an issue with the total solar irradiance (TSI) measurement…

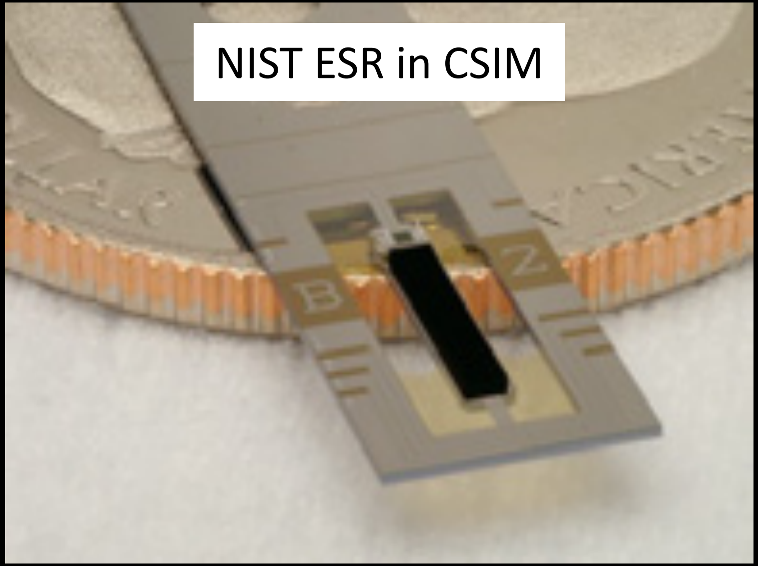
CSIM: Compact Spectral Irradiance Monitor – Spectral Solar Irradiance (SSI)

6U cubesat with an optical bench and a spectroradiometer:

- Photodiodes take the high cadence measurements
- NIST ESR provides on-board absolute calibration and tracks degradation of optics
- Took sufficient data to prove viability – SD card
- Successful spaceflight demonstration of NIST's CNT radiometer



Inside of the CSIM cubesat


NIST ESR in CSIM

CSIM data http://lasp.colorado.edu/lisird/data/csim_ssi_l3/

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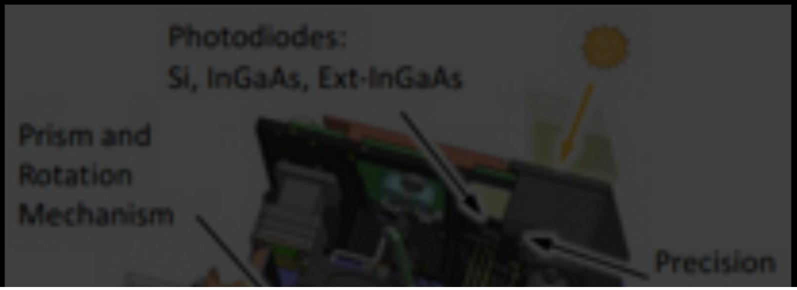
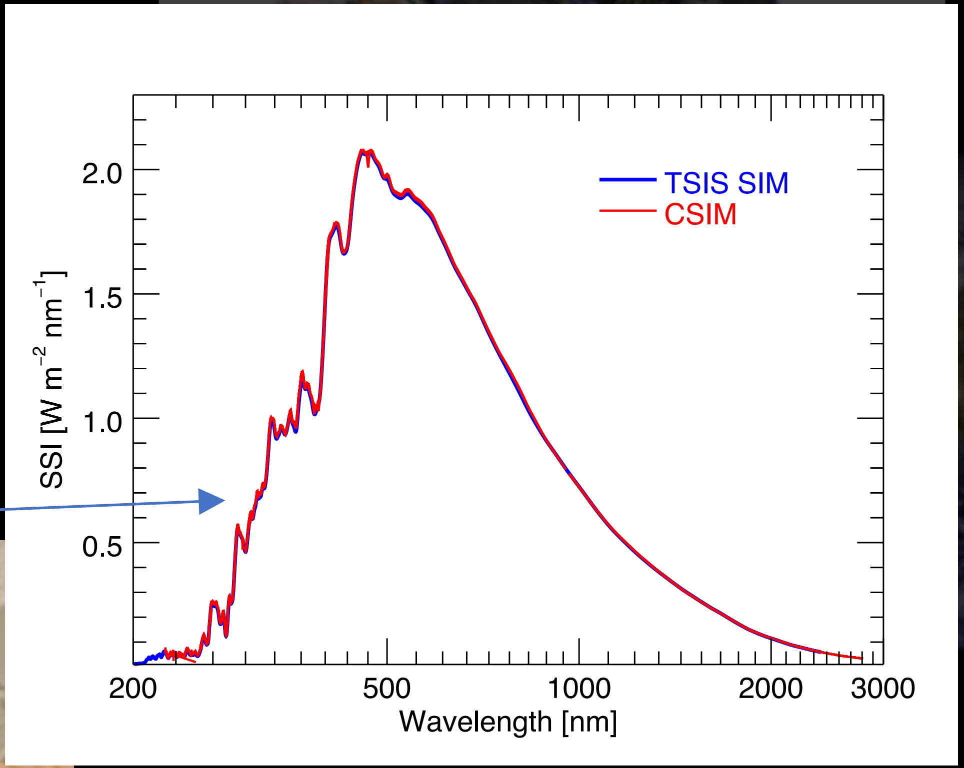
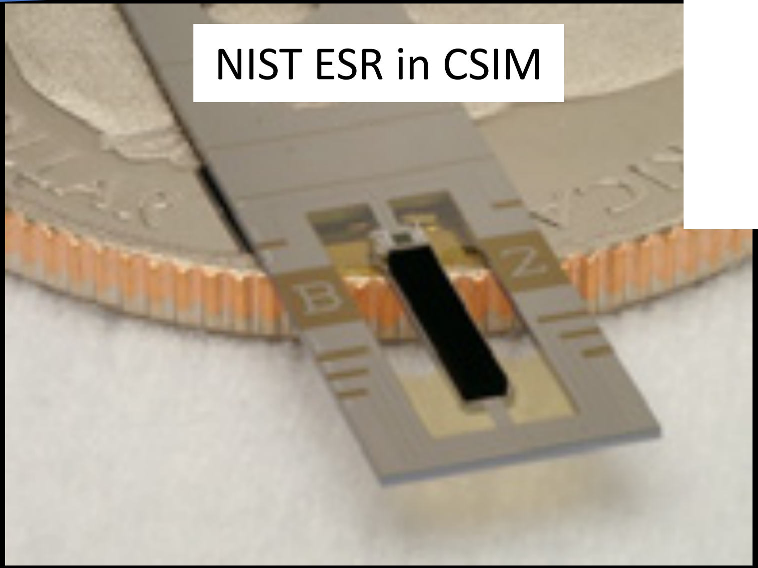
- Data agrees well with TSIS-1





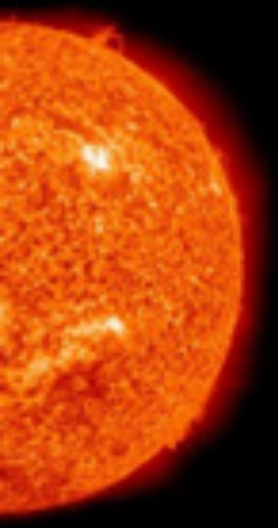
Inside of the CSIM cubesat



CSIM data http://lasp.colorado.edu/lisird/data/csim_ssi_l3/

Total Solar Irradiance (TSI) measurement

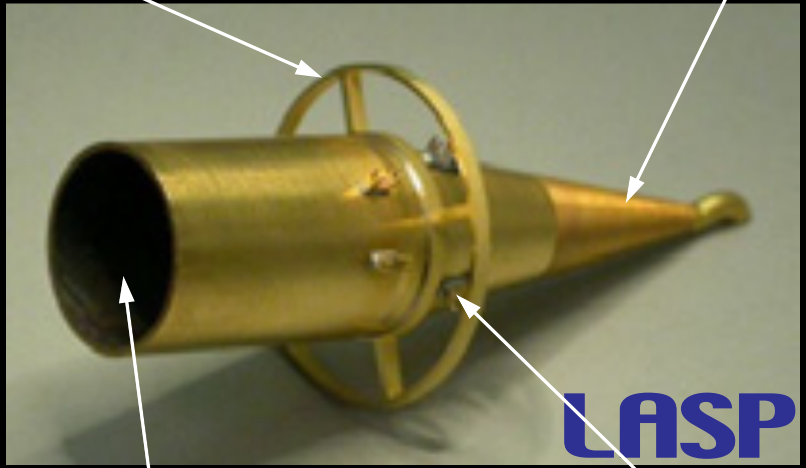
Electrical substitution radiometer (ESR)



T = 6000 K

Weak thermal link (G)

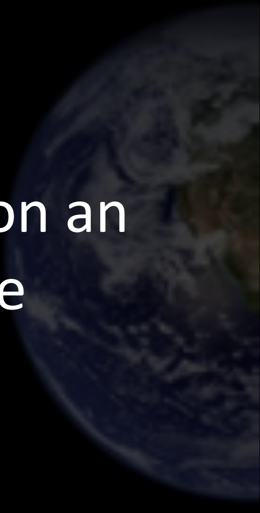
Electrical substitution heater



Blackened isothermal cavity

Thermometry

0.1 % variation on an 11-year cycle



LASP Measurement Requirements

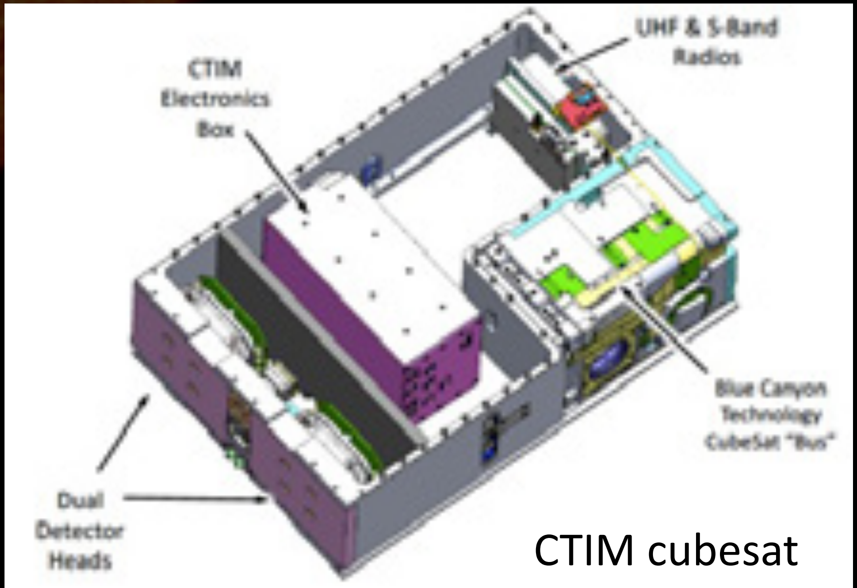
- Wavelength range: 0.1 µm – 5 µm
- Accuracy: 0.01 %
- Stability: 0.001 %/year

CTIM: Compact Total Irradiance Monitor – Total Solar Irradiance (TSI)

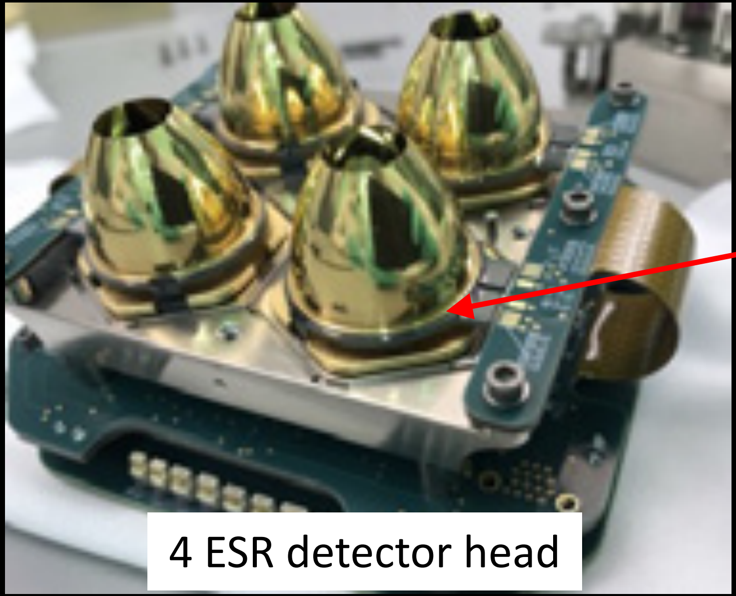
6U cubesat with dual detector heads:

- Eight radiometers in CSIM vs four in TSIS-1
- Each NIST ESR will measure the Total Solar Irradiance (TSI) directly
- Slated for launch in 2021

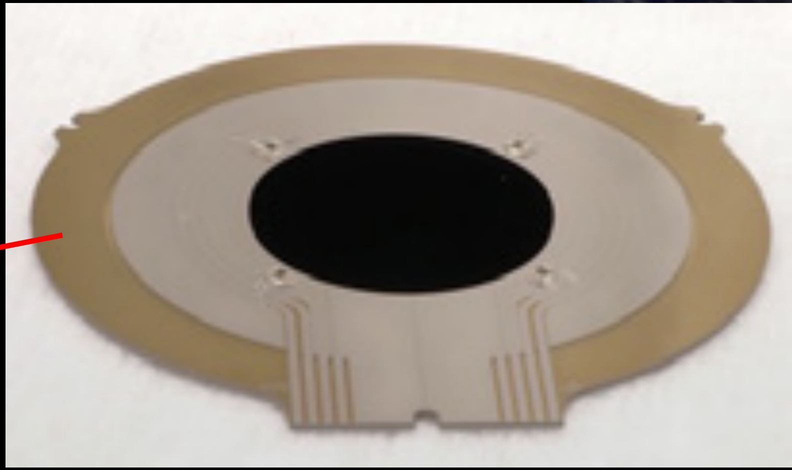
CNTs allows us to reduce to 2-D!



CTIM cubesat



4 ESR detector head



NIST ESR in CTIM

Summary: how do the platforms compare?

TSIS-1

1998 – 2010 – 2017

- Developed in ≈ 5? years
- Launched 19 years after selection
- $100 million (not including satellite and launch)
- Mounted to ISS not a satellite

CSIM

2013 - 2018

- Developed and launched in 5 years
- < $10 million to develop + launch
- ≈ $2 million to build and launch
- Agrees with TSIS-1 dataset
- New technology – NIST’s CNT radiometers with 7x lower noise survive launch

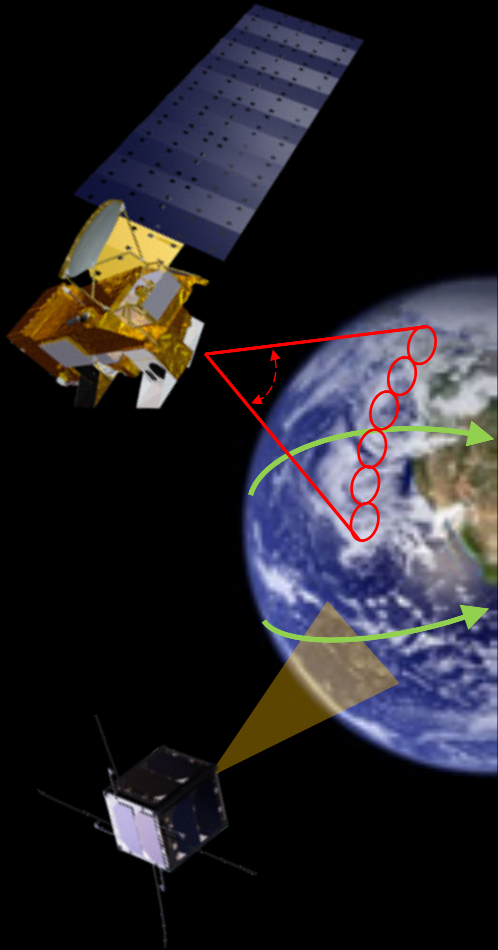
Future research at NIST: far infrared imaging

CERES on Aqua

The next five years are dedicated to detectors for sensing the outgoing radiation from Earth with Libera and BABAR-ERI:

- Libera – successor to CERES and RBI
  - Single element scanning radiometer
  - NASA willing to 'modernize' with Libera
    - Electrical substitution – first time
    - Carbon nanotube absorber

- BABAR-ERI – cubesat
  - Far infrared microbolometer linear array
  - Electrical substitution for absolute calibration
  - No scanning required – push-broom/spin



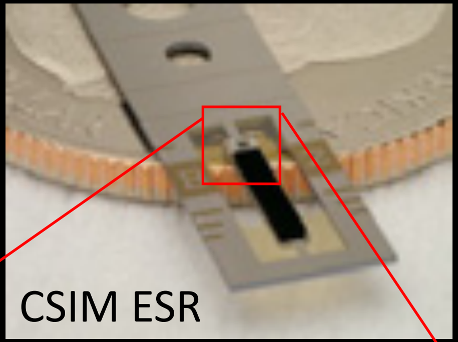
BABAR-ERI CubeSat

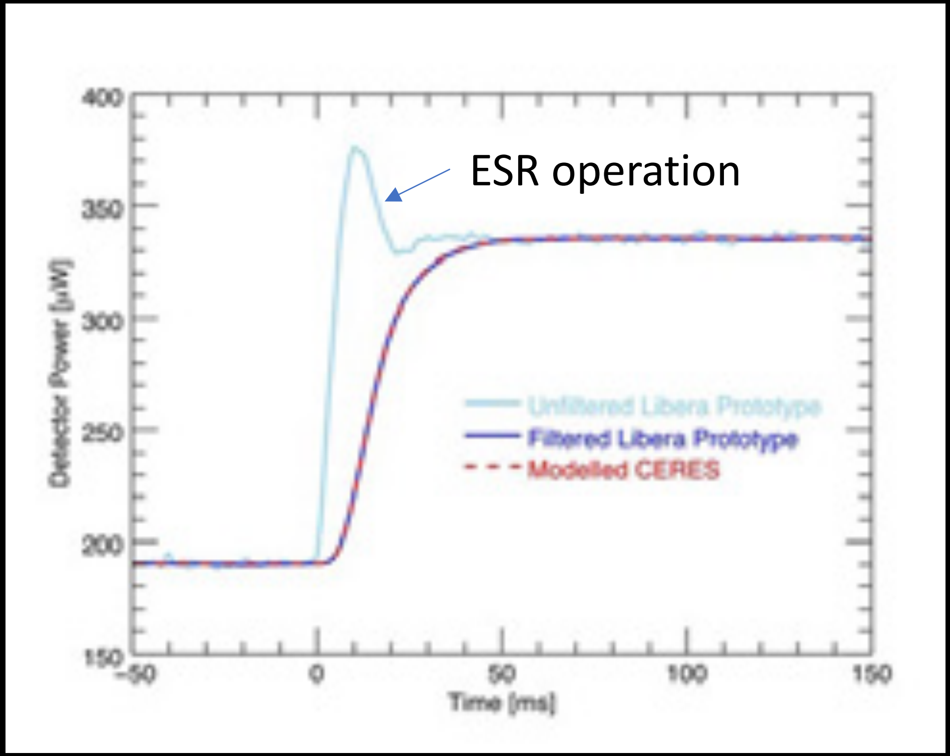
2013 → 2027 - imaging

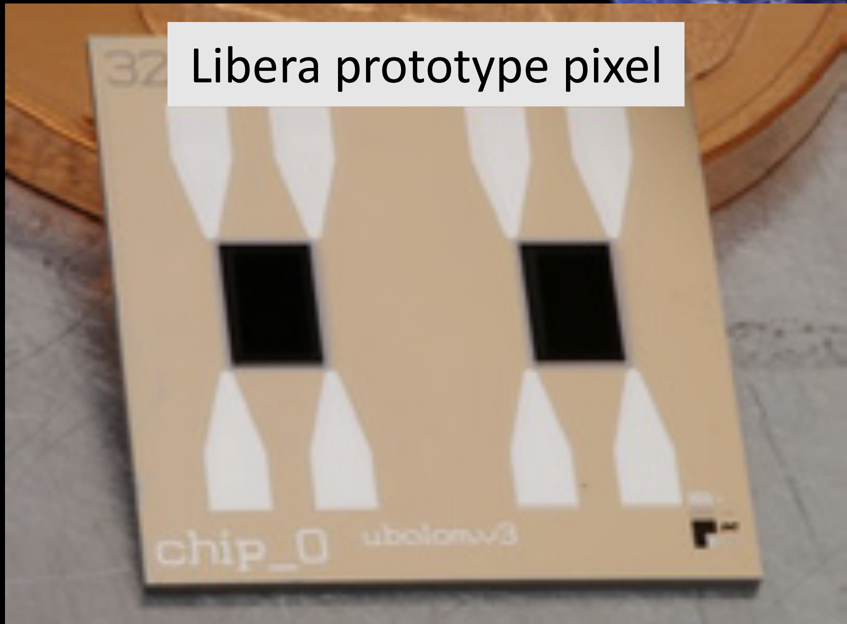
Libera – prototype detector

Earth Venture Continuity (EVC-1) proposal (2019):

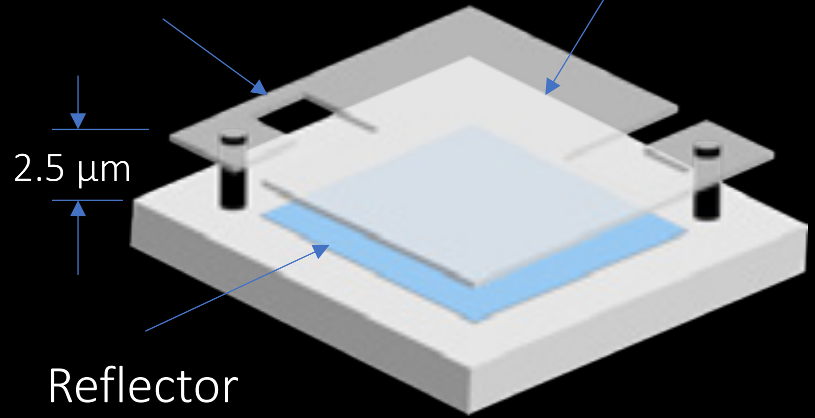
- Microbolometer technology developed in BABAR used to make a prototype detector for EVC-1 – similar performance to CERES
- LASP is awarded the $150 million contract (2020)

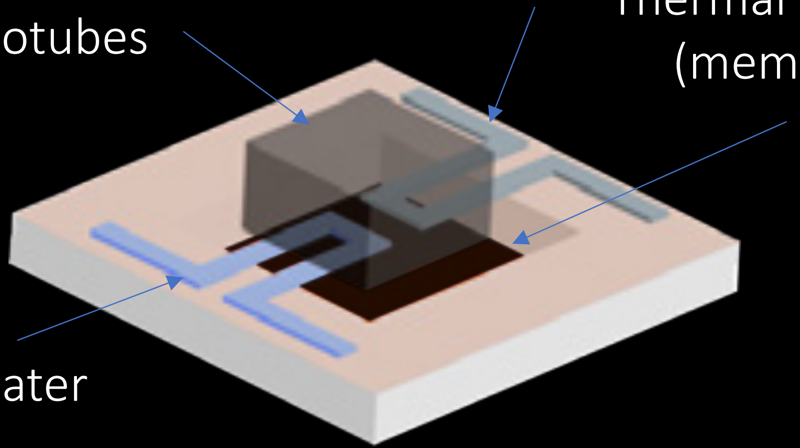






BABAR (2018) – Black Array Broadband Absolute Radiometers





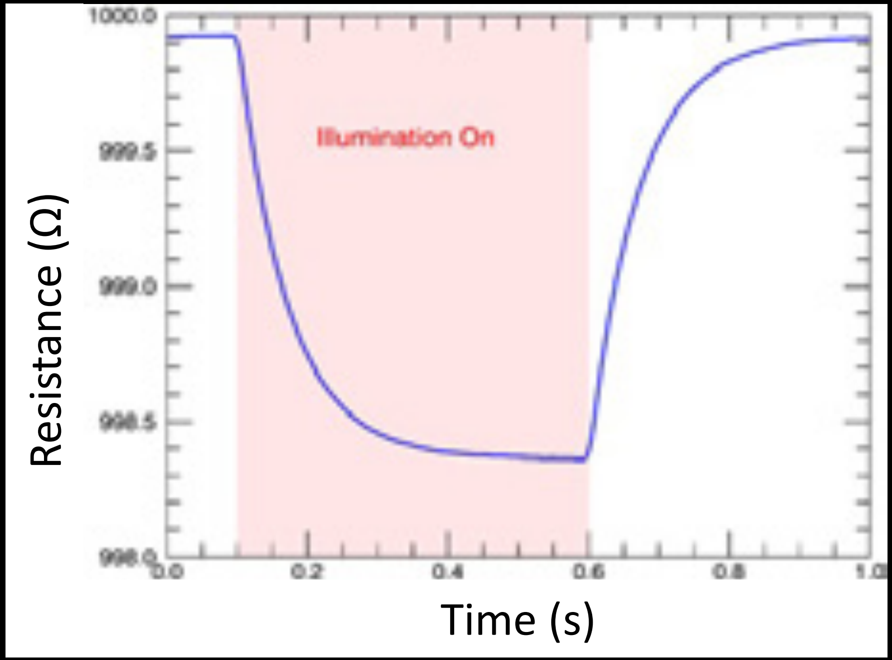
Conventional microbolometer

- Narrow band 8-16 µm (λ/4 cavity)
- Open loop operation
  - read out resistance change
- Requires extensive calibration
  - Black body calibration
  - Software lookup - nonlinear thermistor

BABAR microbolometer

- Far infrared 0.2 – 100 µm
- Electrical substitution radiometer
  - Read out incident power directly
  - Closed-loop operation
  - Faster

BABAR – microbolometer operation



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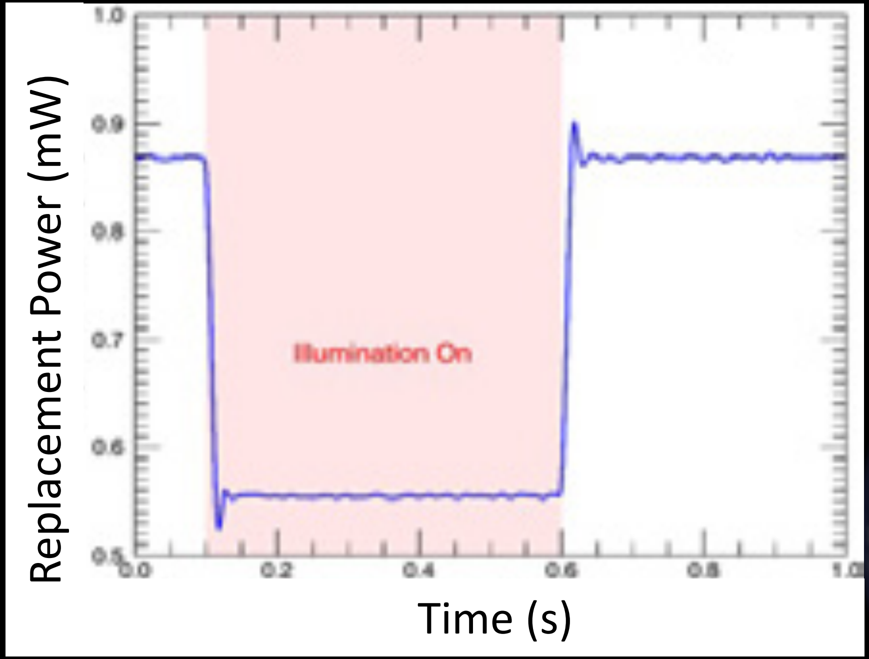


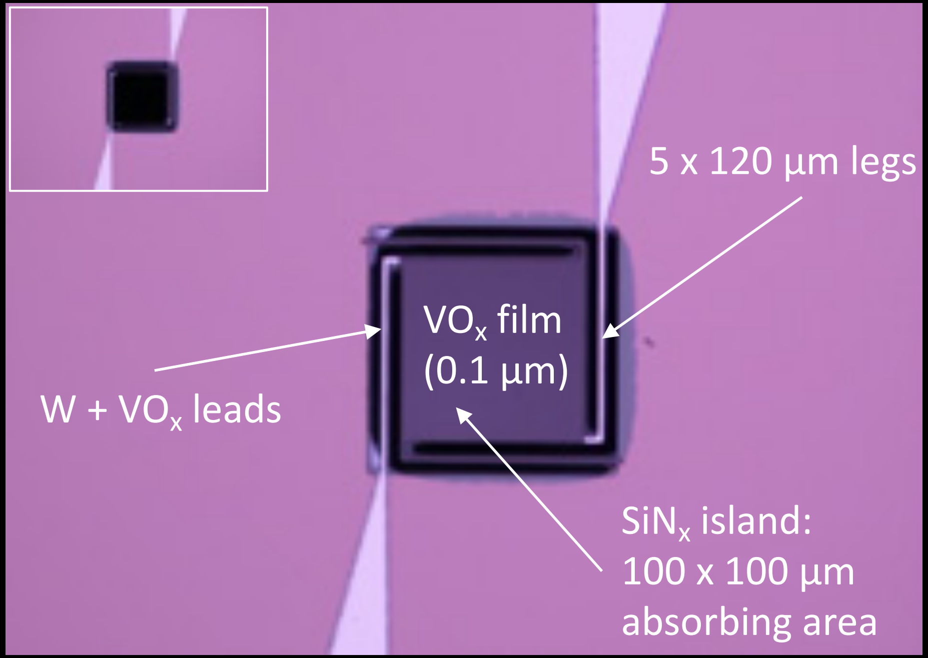
BABAR microbolometer

- Resistance to power calibration is required.
- Time constant depends on heat capacity and thermal conductance (τ = C/G)
- Open-loop time constant = 70 ms

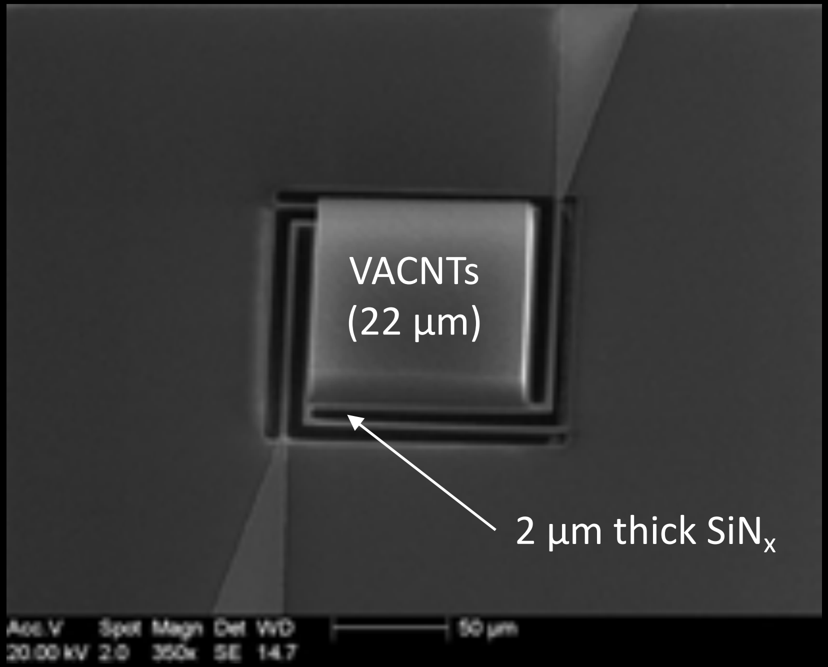
- Change in incident power is readout as a change in replacement power.
- For thin films, e^--p relaxation time < 1 ns
- Thermistor self-heating -> ESR
- Closed-loop time constant = 2.4 ms

BABAR – prototype pixel development with VO_x

Optical microscope



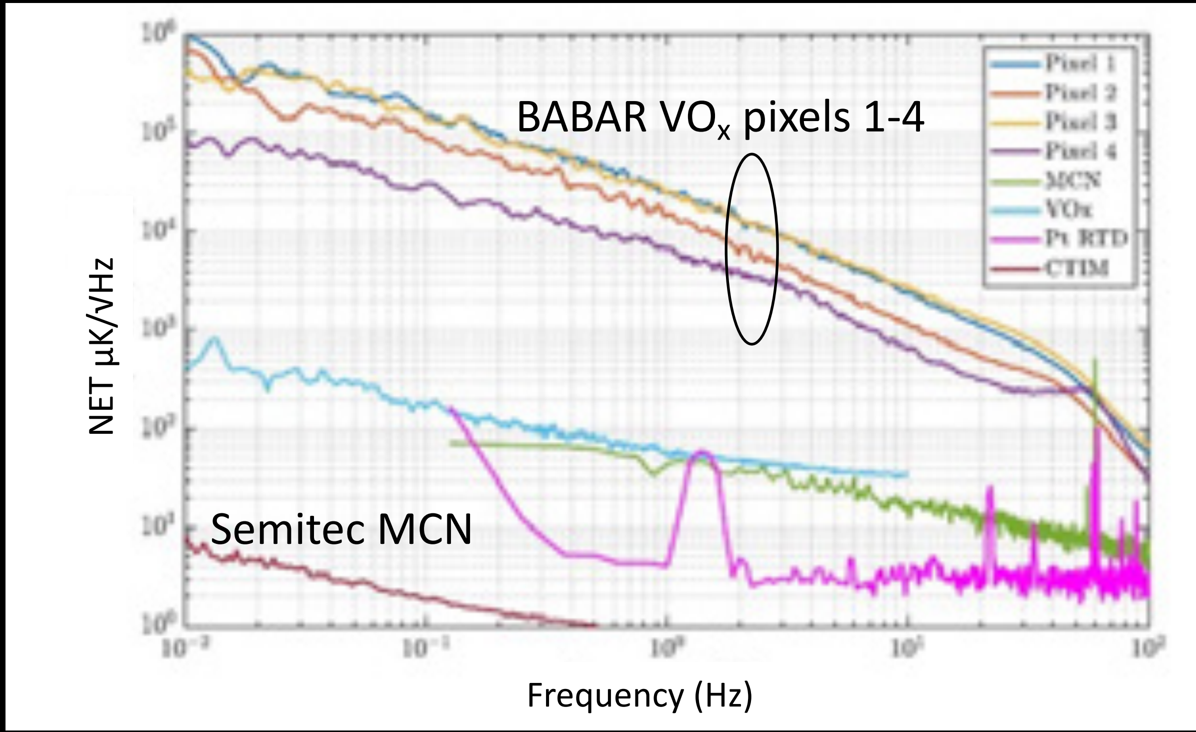
Scanning electron microscope



- Sputtered VO_x film for thermistor
- 1 %/K TCR after CNT growth (industry VO_x > 3 %/K)
- High 1/f noise (1/f noise is problematic for industry as well)

BABAR-ERI – how can BABAR be improved?

Array, pixel architecture, closed loop ESR operation – everything is working well but thermistor



Power spectral density of 1/f noise (V^2/Hz)

$$S_V = \frac{\alpha_H V^2}{\Omega\, n\, f}$$

Hooge parameter (α_H), Voltage bias (V), volume (Ω), charge carrier density (n), Frequency (f)

- VO_x displays excess 1/f noise
- VO_x $\alpha_H/n = 10^{-28}$ m^3, TCR = 1 %/K
- Published single crystal LSMO $\alpha_H/n = 10^{-32} – 10^{-30}$ m^3, TCR = 4 %/K

Single crystal thermistor is needed

Summary

- Carbon nanotubes are unique and advantageous
- Far infrared imaging requires a single crystal thermistor - microbolometer
  - Libera –NIST until 2024
  - BABAR-ERI ACT/IIP –NIST until 2018 - 2023
  - BABAR INVEST? – follow on funding for BABAR IIP
- The technology is powerful and we would like to disseminate it