Infrared radiometry for space-based Earth outgoing radiation measurements

Patrick McArdle[1], Nathan Tomlin , Chris Yung, John Lehman, Michelle Stephens

Physical Measurement Laboratory (PML), National Institute of Standards and Technology (NIST), Boulder, Co, United States

Corresponding e-mail address: patrick.mcardle@nist.gov

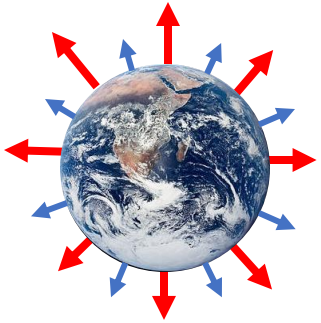
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Laboratory for Atmospheric and Space Physics
University of Colorado Boulder

Outline

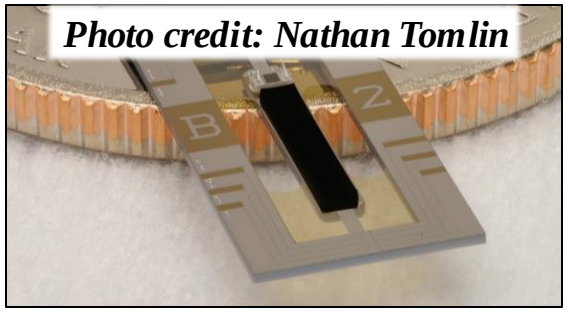
Infrared remote sensing for climate monitoring

- Earth energy imbalance
- Earth outgoing radiation
- Cloud Forcing



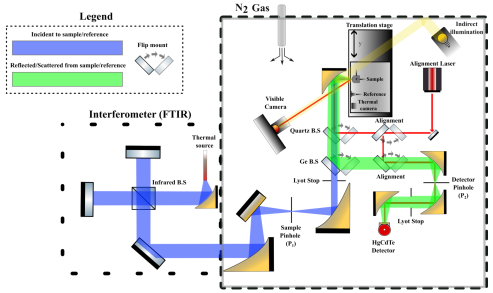
Detectors

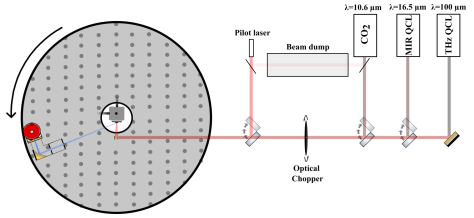
- Bolometers
- Vertically aligned carbon nanotubes (VACNT's)
- Microfabricated VACNT bolometers at NIST

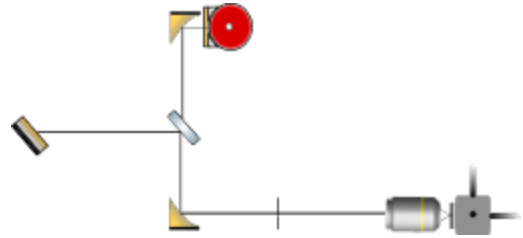


Detector Characterization

- Micro-diffuse reflectance
- Work in progress
  - Infrared μBRDF
  - 2D - Imaging







Earth Energy Imbalance (EEI)

Energy in

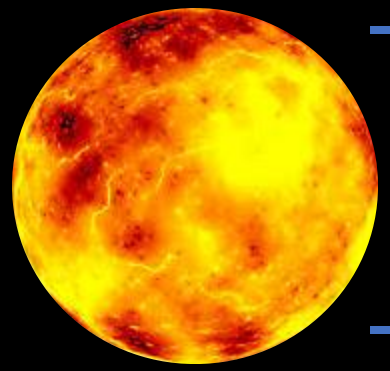
Total Solar Irradiance (TSI)

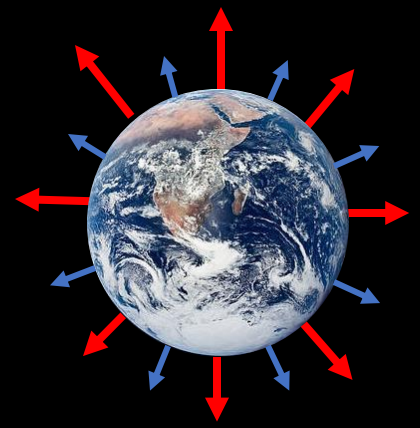
$TSI - EOR < 0$ Cooling

$TSI - EOR > 0$ Heating

Energy out

Earth outgoing radiation (EOR)





TSI

Incident

UV – Near IR

EOR

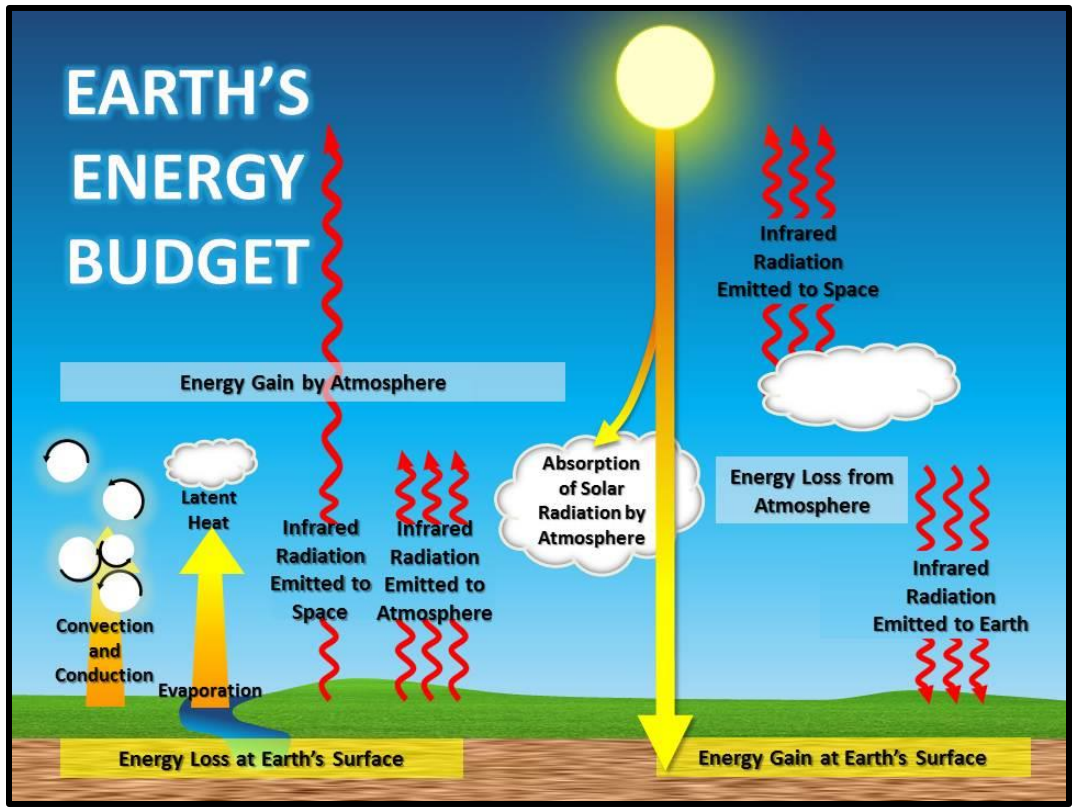
Reflected Short Wave

UV – Near IR

Emitted Long Wave

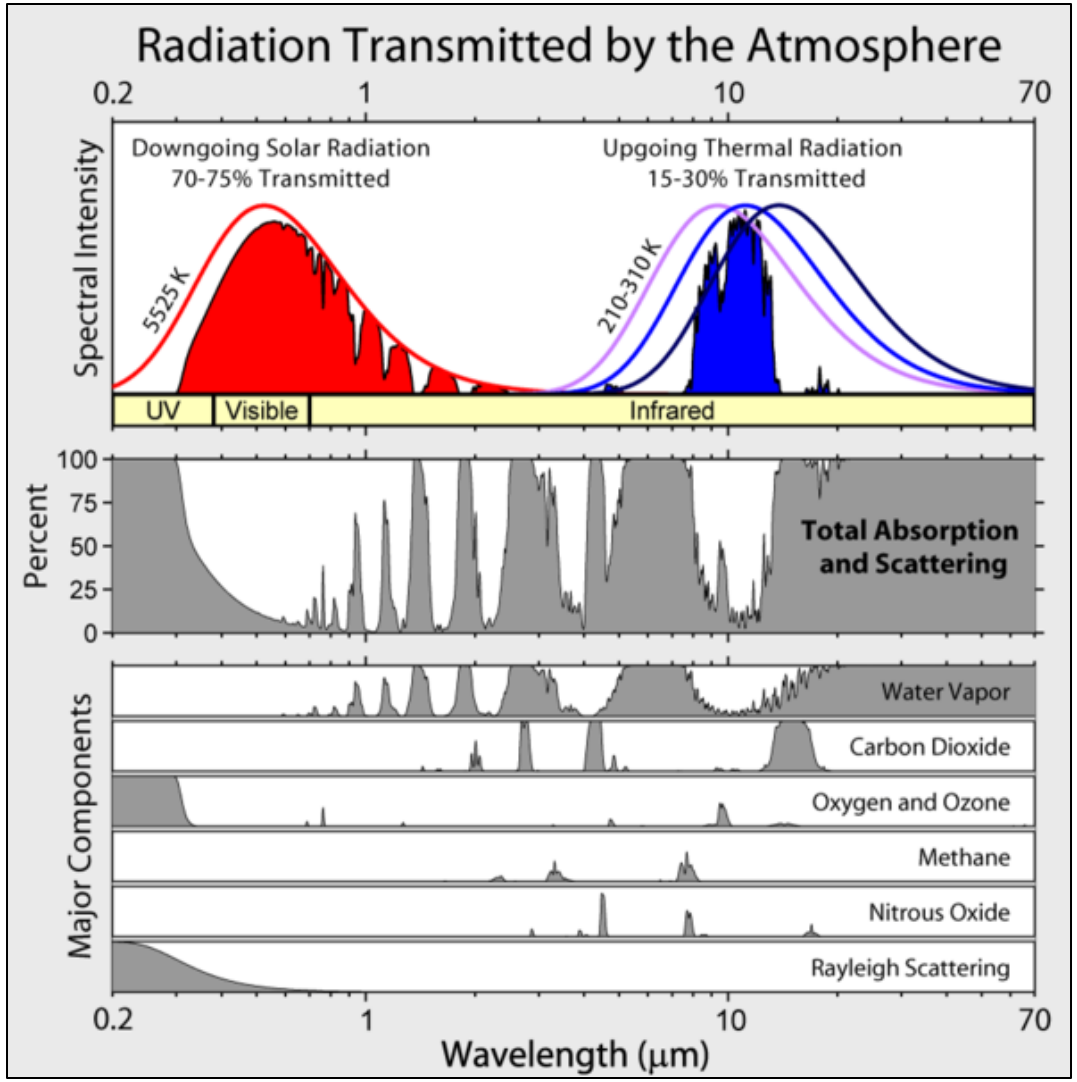
Near IR - THz

Earth outgoing radiation



https://www.ces.fau.edu/nasa/module-2/earth-energy-balance.php

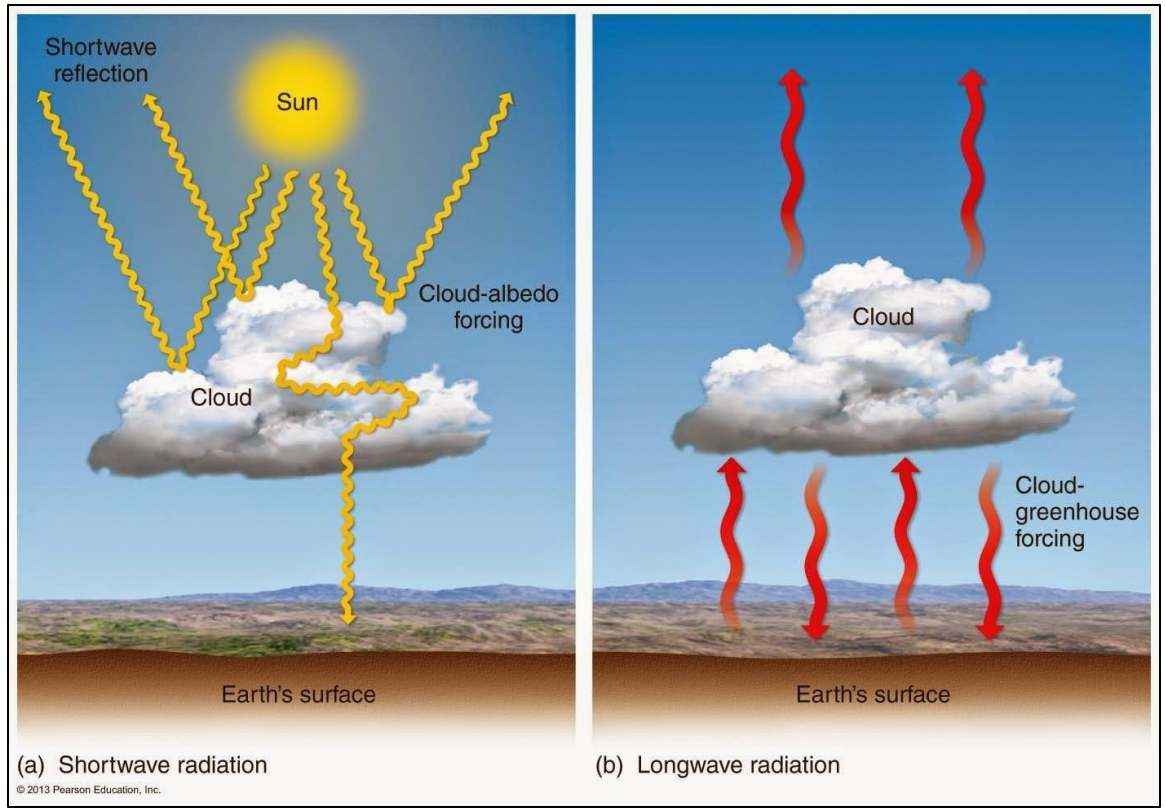
Emitted radiation predominately in the infrared



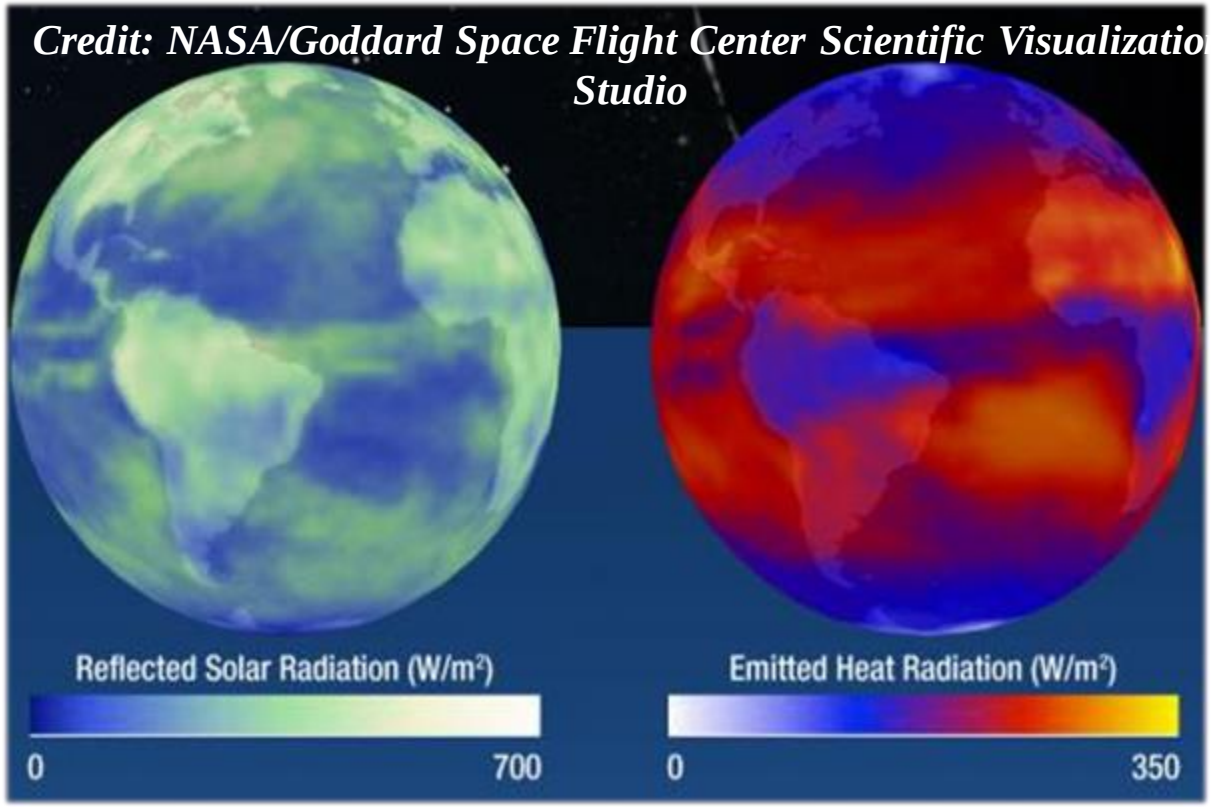
https://commons.wikimedia.org/wiki/File:Atmospheric_Transmission.png

Cloud Forcing

Cloud effect on heat transfer



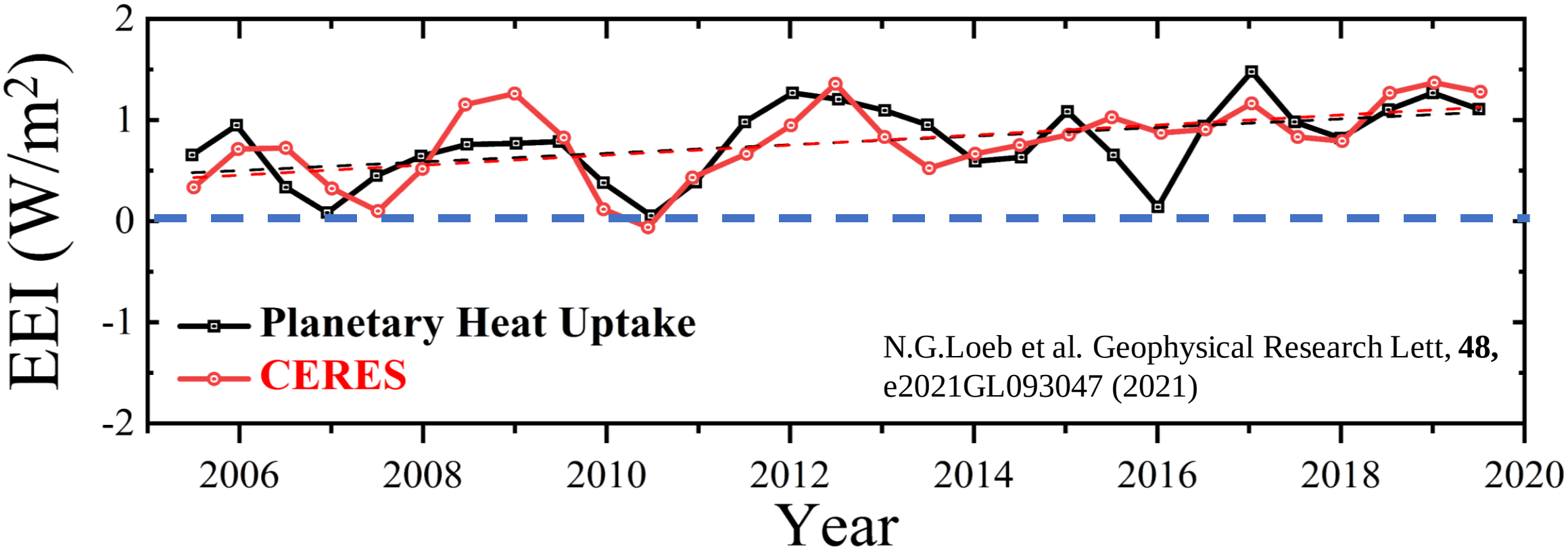
Clouds and the Earth's Radiant Energy System (CERES)



- CERES instruments have a surface resolution of ~ 20 km

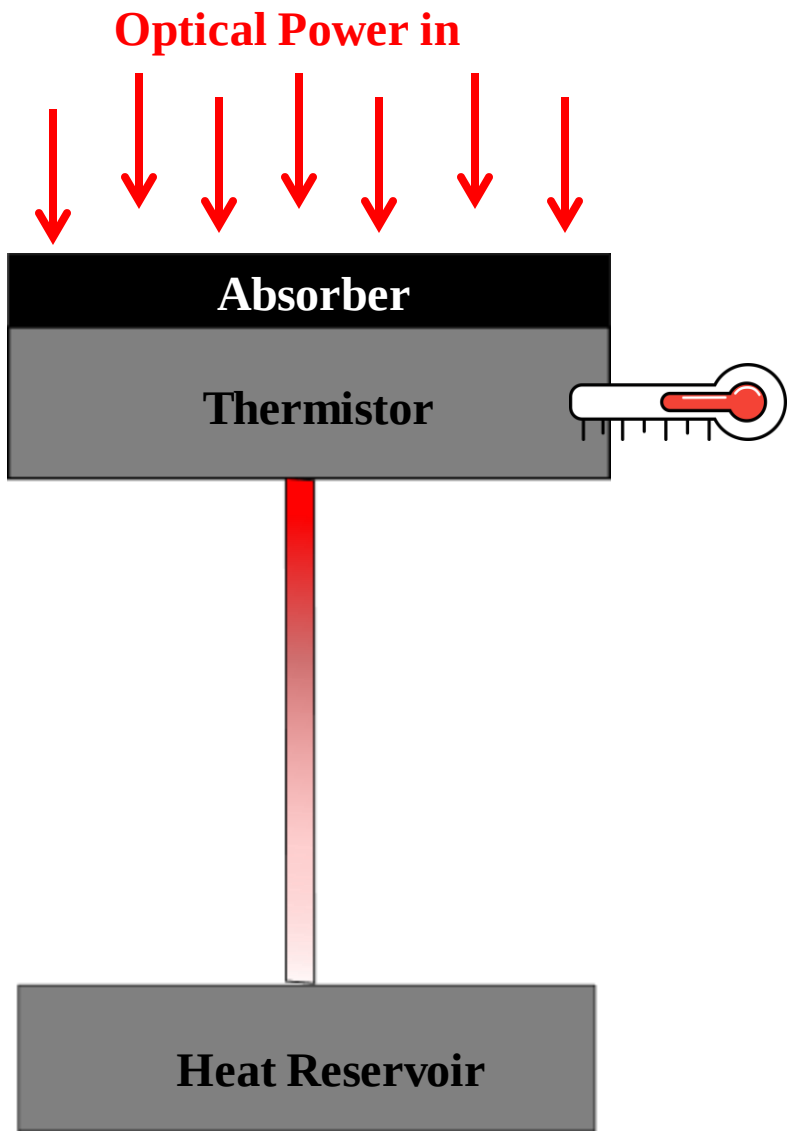
- Most clouds have horizontal length < 20 km

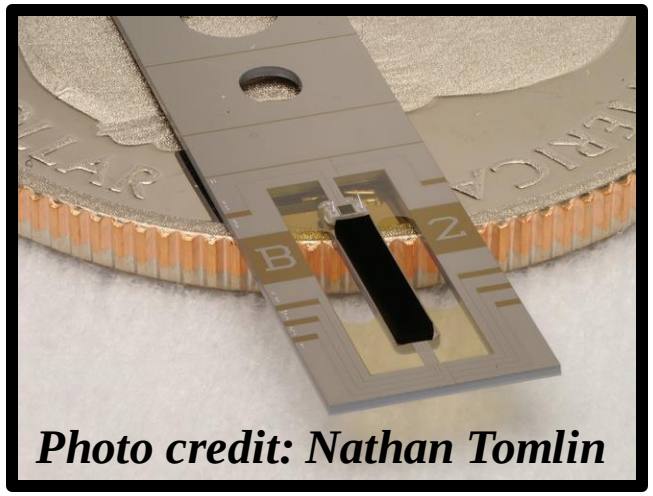
Measurements of EEI

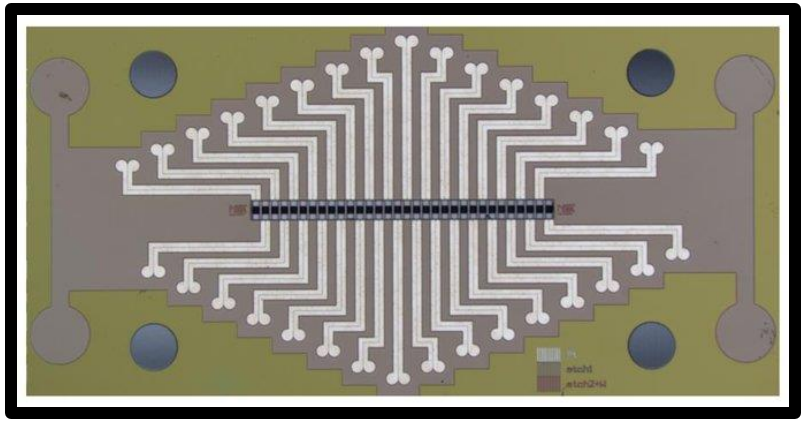


EEI ↑ $0.50 \pm \mathbf{0.47}$ W m^{-2} decade^{-1}

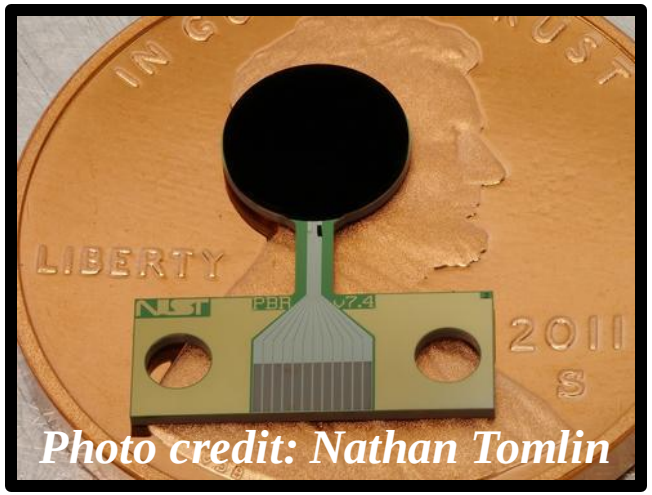
Bolometers

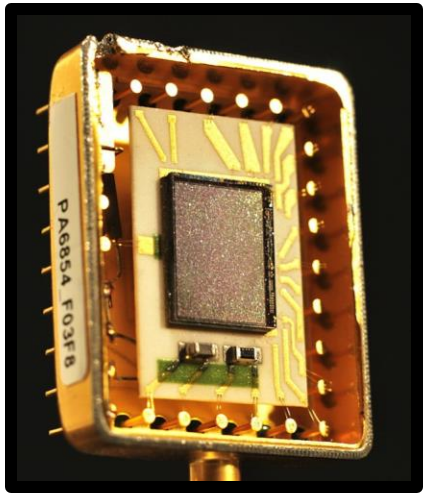






M.Stephens et al. Proc.SPIE 12234 (2022)

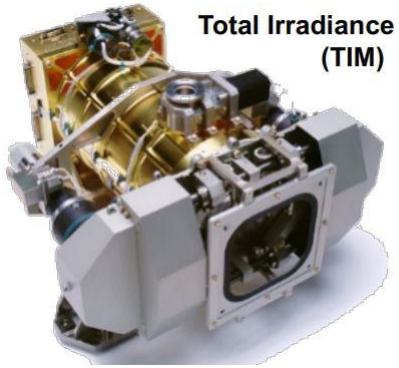




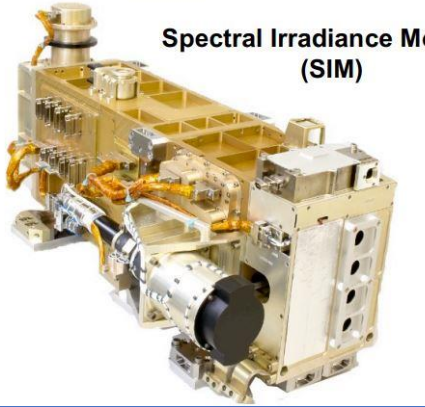
Fluke camera

Bolometry for EEI measurements

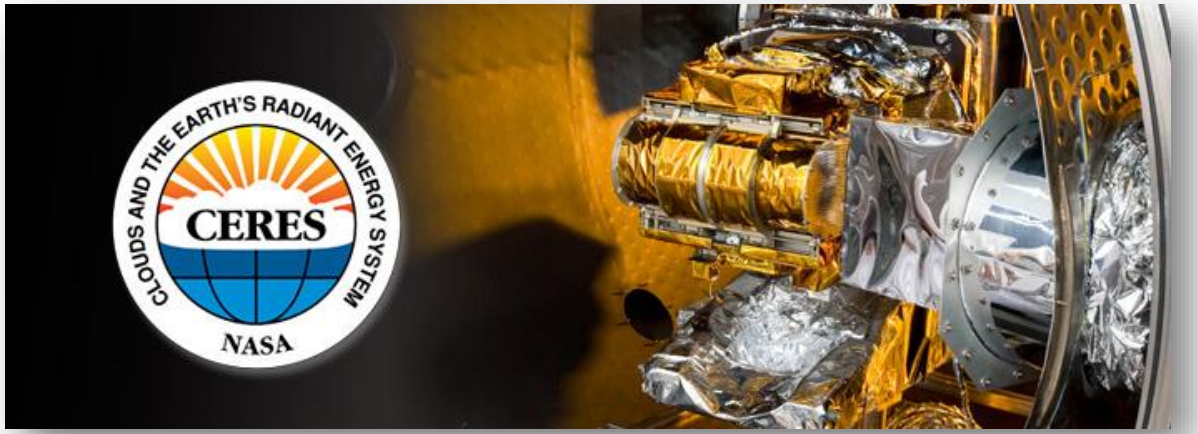
Total and Spectral Solar Irradiance Sensor (TSIS)



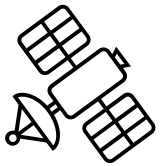
Irradiance
W/m^2



Earth Outgoing Radiation Measurements (CERES)

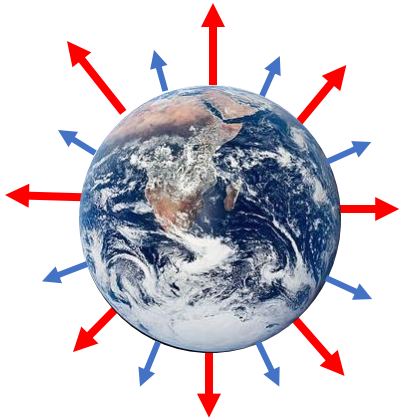


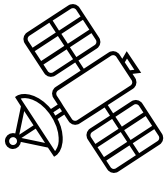
TSI



Energy In

EOR





Energy Out

Vertically Aligned Carbon Nanotubes (VACNTs)

Photo by Surrey Nanosystems

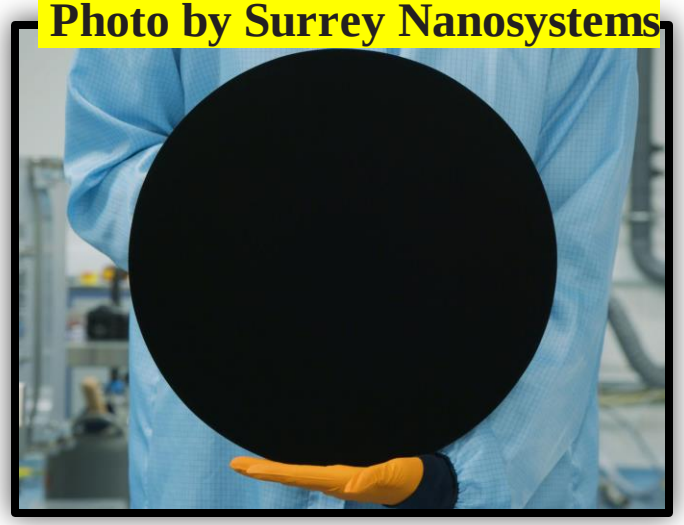
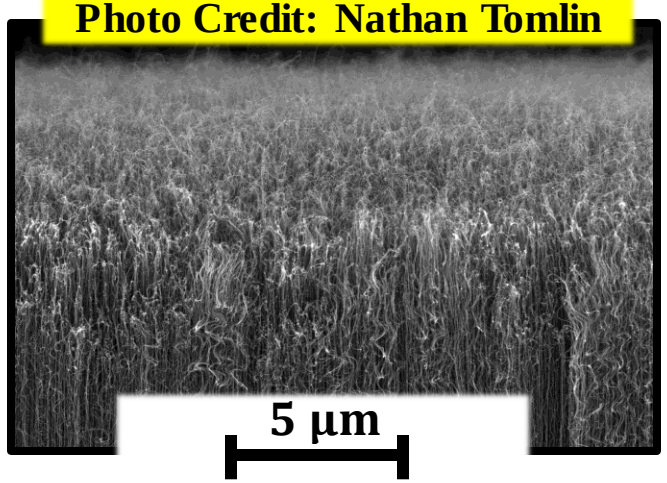
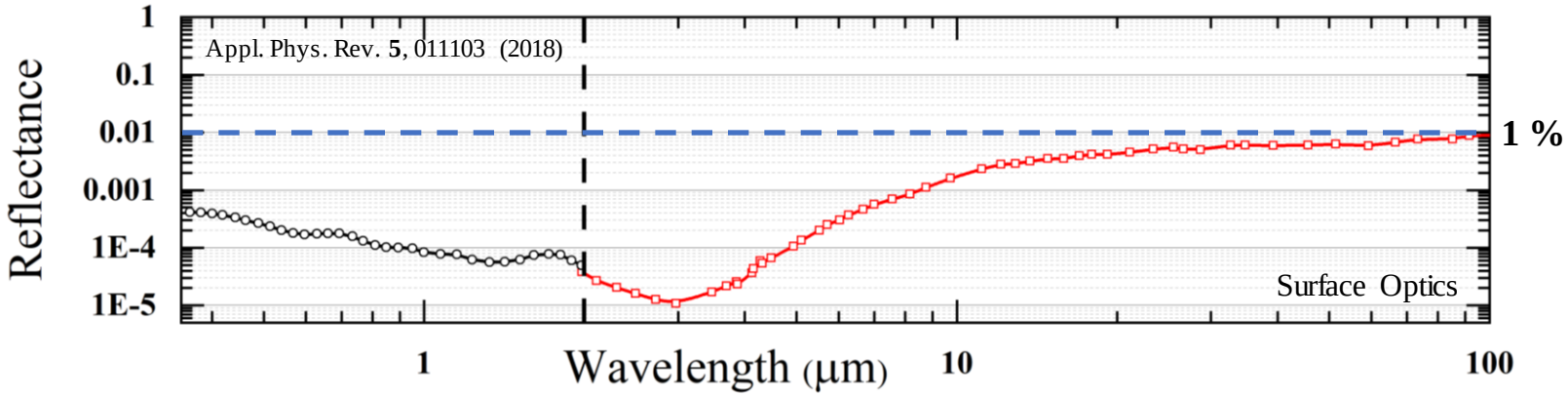


Photo Credit: Nathan Tomlin



Typical VACNT Reflectance



Advantages

- High thermal diffusivity
- Broadband absorbance (0.3 µm – 100 µm)
- Planar geometry
- Lithographic patterning
- ~ 4-week fabrication cycle
- Space-qualified

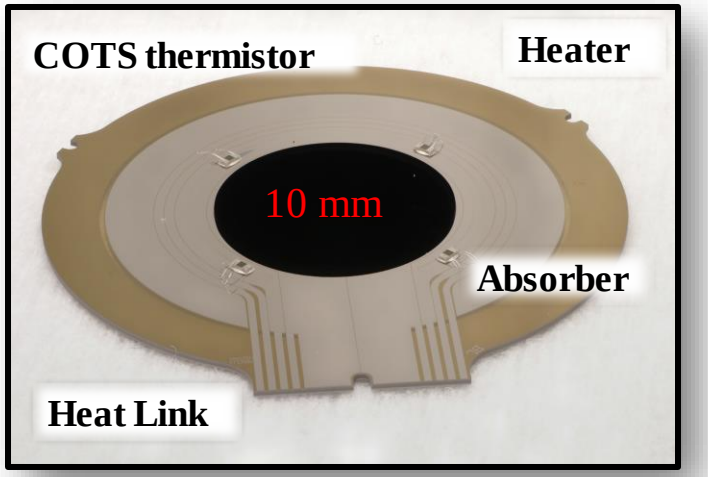
Disadvantages

- High temperature fab
- Grows differently on different surfaces
- VACNTs are damaged by touch, wet processes
- Additional heat capacity

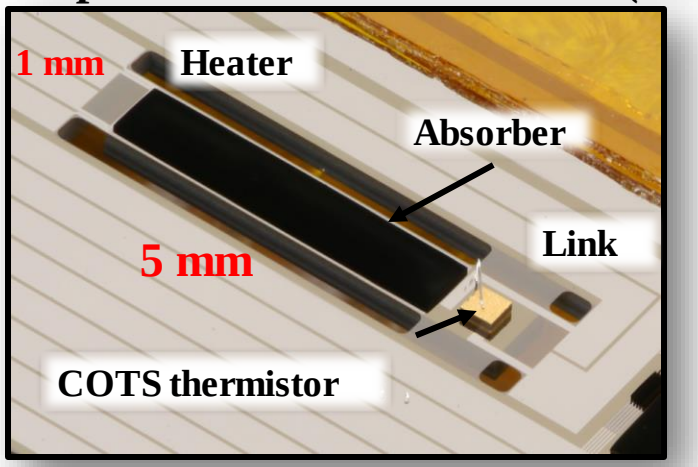
Microfabricated Electrical Substitution Bolometers

Total Solar Irradiance (In orbit currently)

Compact Total Irradiance Monitor (CTIM)



Compact Spectral Irradiance Monitor (CSIM)



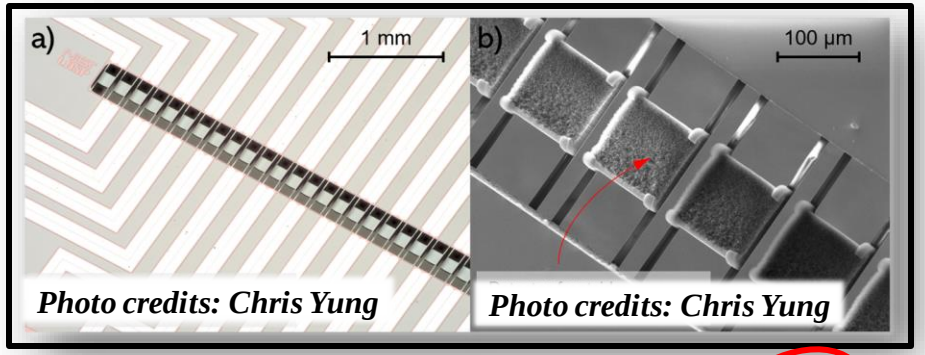
Measurement range: 0.2 μm – 2.6 μm

Earth outgoing radiation (In development)

Libera mission (prototype)

Channels
- **Short Wave:0.3 μm - 5 μm**
- **Long Wave:5 μm - 50 μm**
- **Total: 0.3 μm - 100 μm**

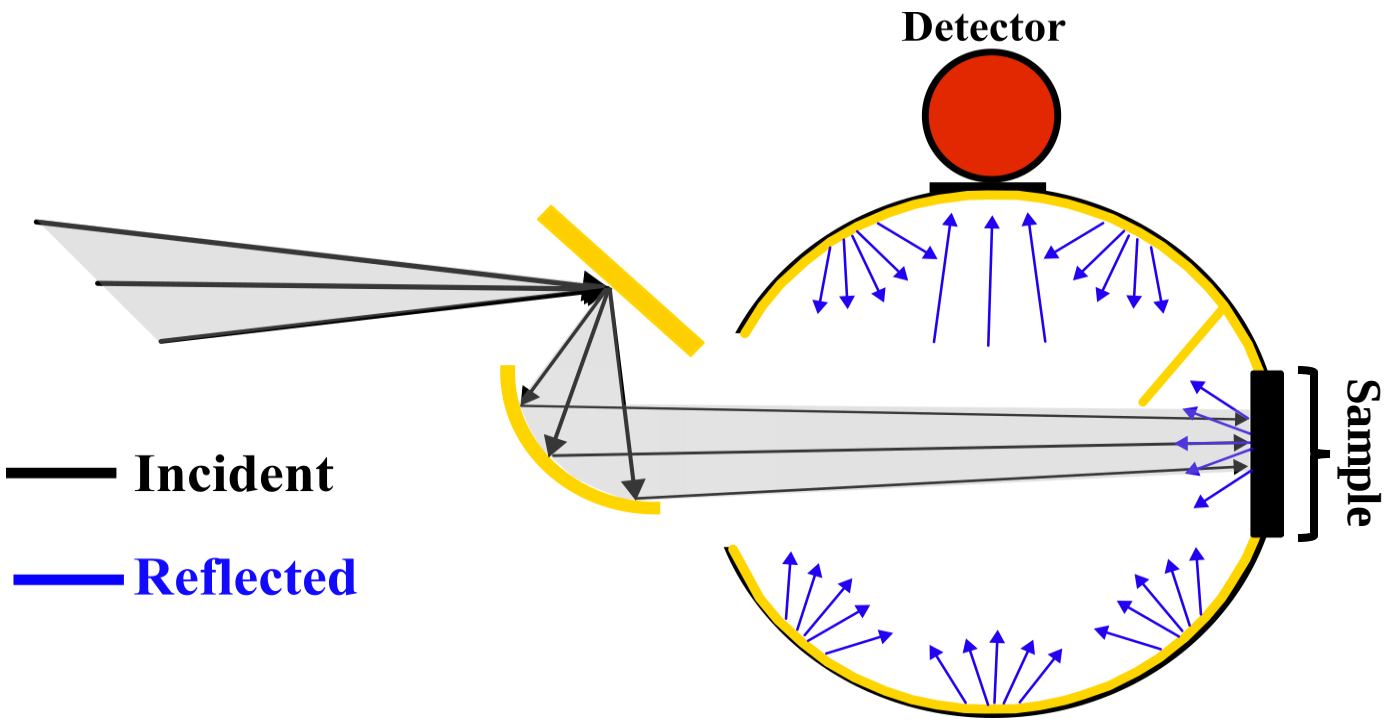
Black Array of Broadband Absolute Radiometers



Channels
- **Short Wave:0.2 μm - 4 μm**
- **Long Wave:4 μm - 100 μm**
- **Total: 0.2 μm - 100 μm**

Directional-Hemispherical Reflectance (DHR)

Integrating Sphere

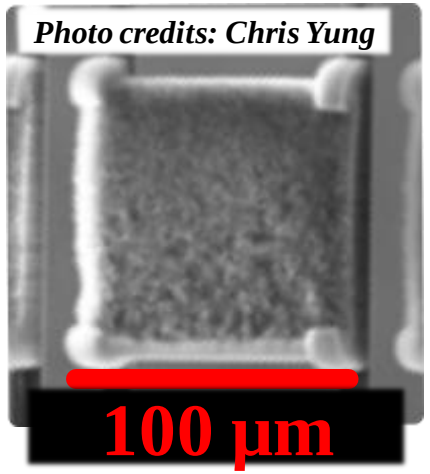


Limitation: Sample size > 25 mm

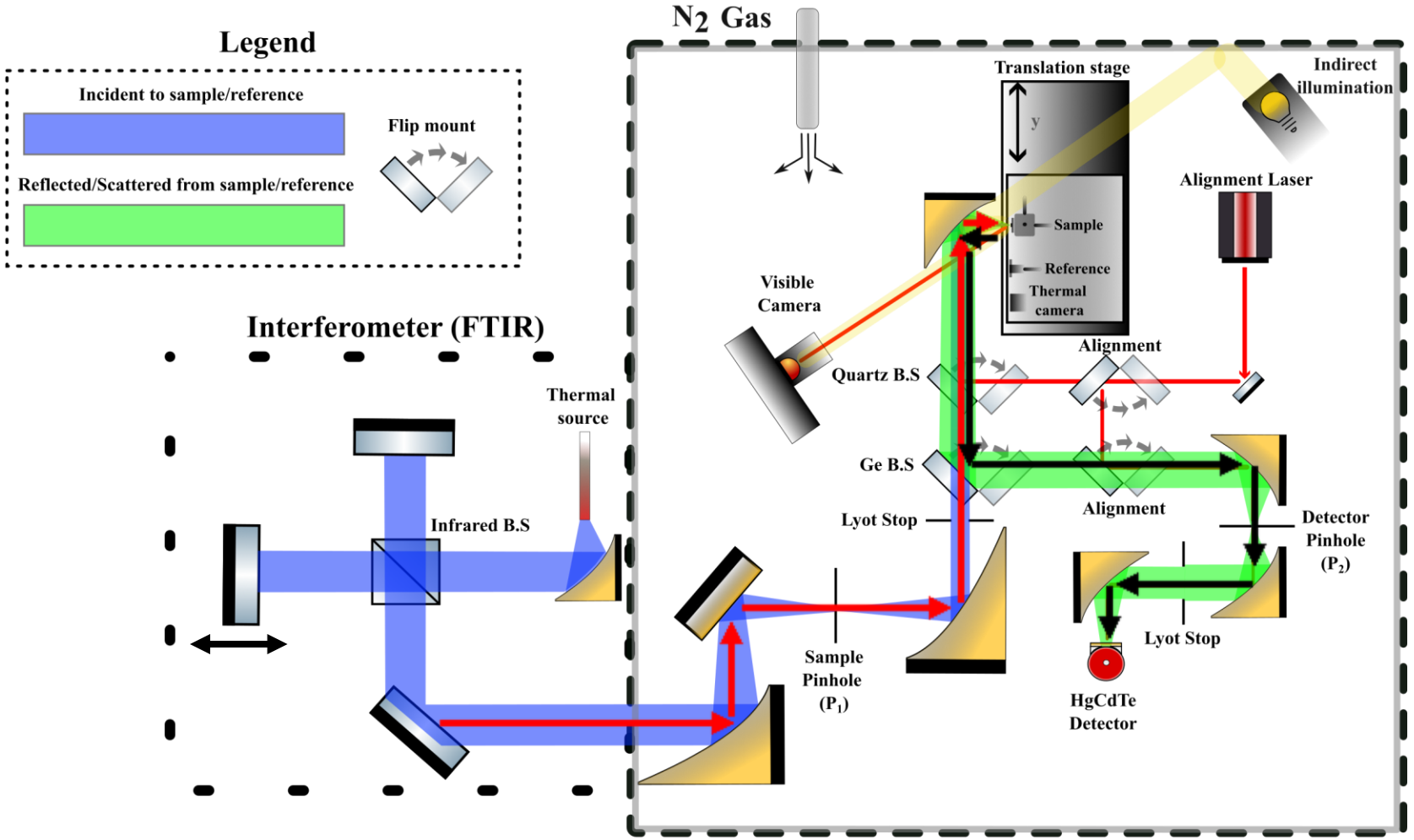
Libera Prototype Detector

Size << 25 mm

BABAR Prototype Detector

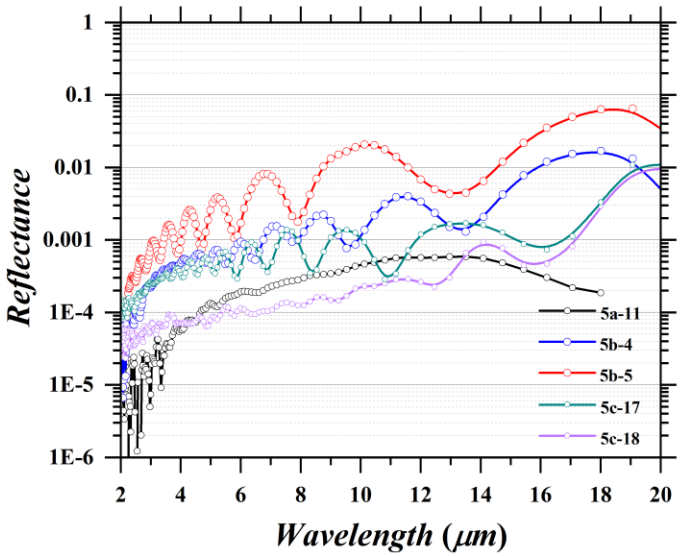


Micro-Diffuse Reflectance



Spatial resolution: ~ 140 µm resolution
Wavelength range: 2 µm < λ< 18 µm
Sensitivity: ~ 50 ppm
NA (calculated) ~ 0.3

Libera prototype Reflectance

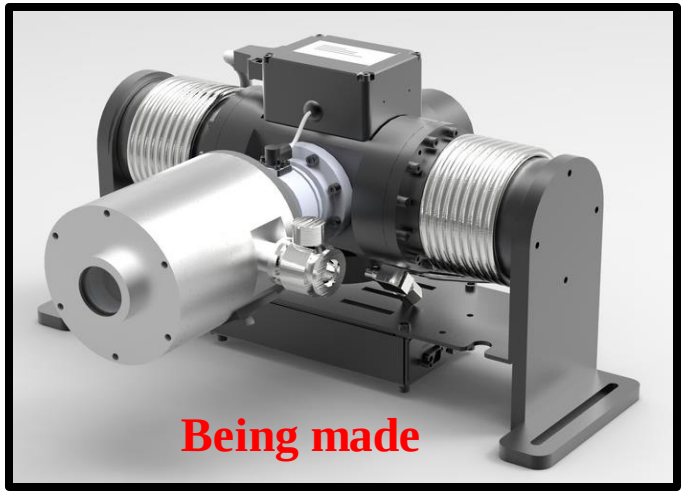


P.McArdle et al, Optics Express (In Review)

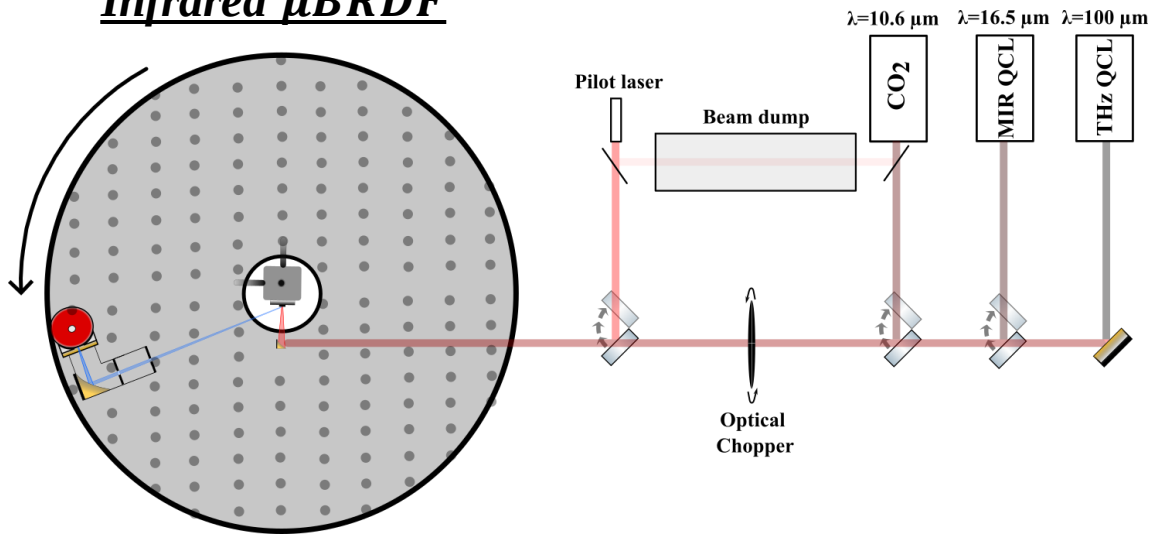
Current work

DFB QCL, $\lambda = 16.5\ \mu m$ @ 1.5 mW

DFB QCL, $\lambda = 60 - 150\ \mu m$ @ ~ 1 mW



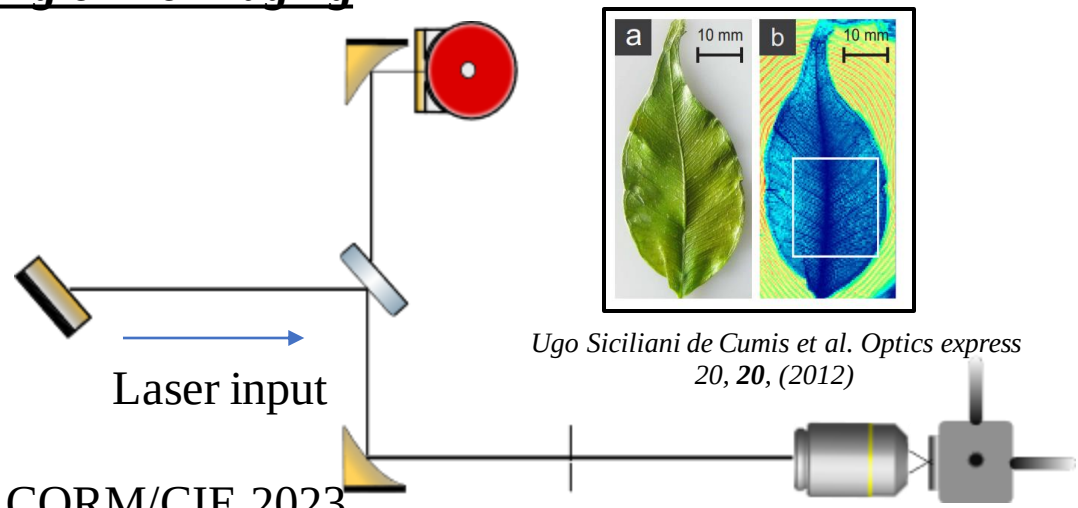
Infrared μBRDF



- Angle dependent reflectance
- DHR tie points

Single line imaging

THz imaging at $\lambda = 103\ \mu m$



*Ugo Siciliani de Cumis et al. Optics express 20, **20**, (2012)*

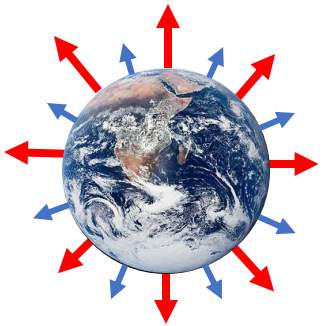
- 2-D imaging of CNT detectors
- Calibrate images to a DHR?

Conclusion

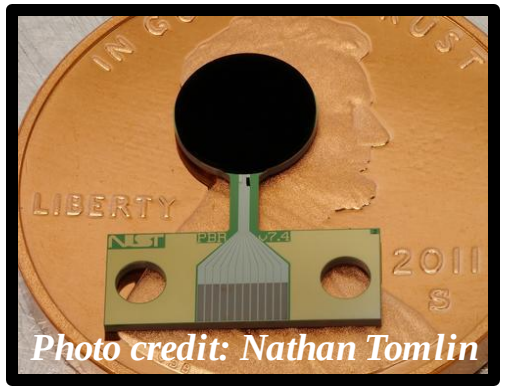
Earth energy imbalance

Earth outgoing radiation

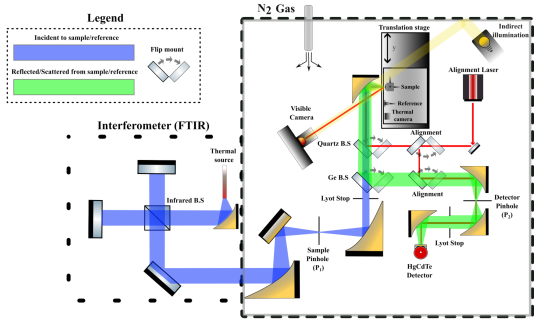
Cloud Forcing

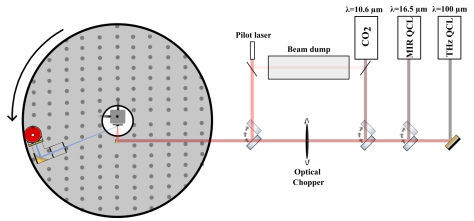


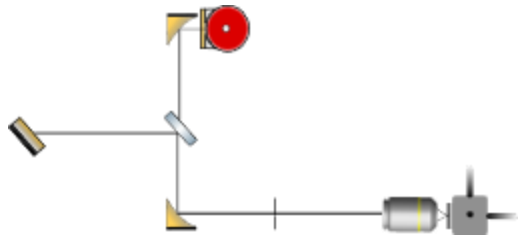
Microfabricated VACNT bolometers at NIST

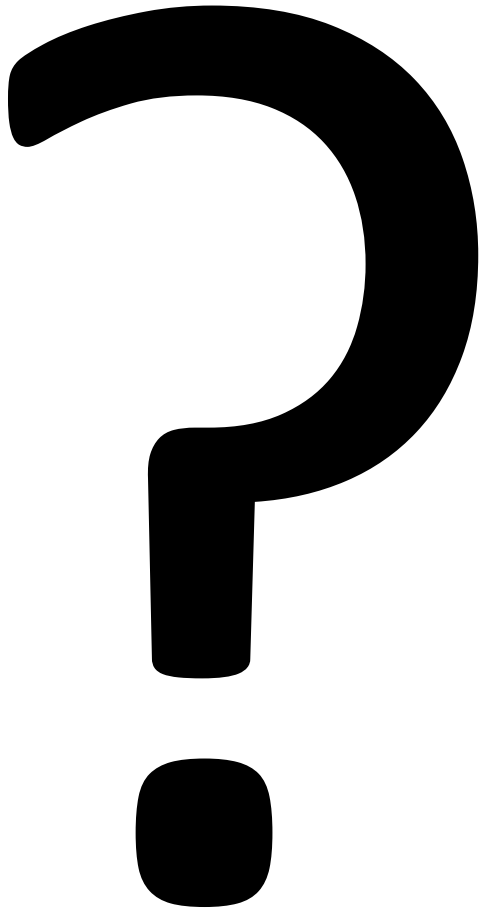


Detector Infrared characterization





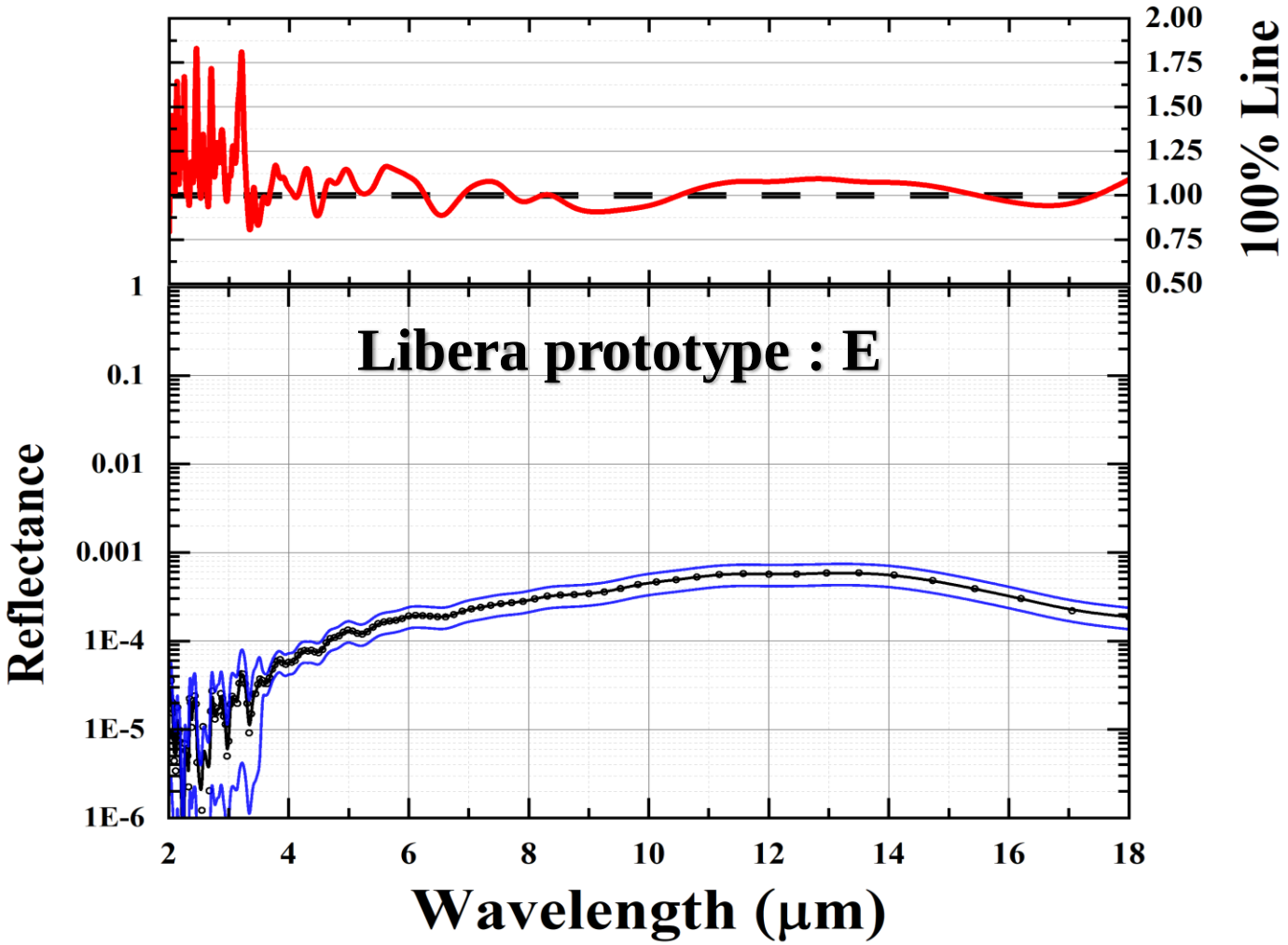




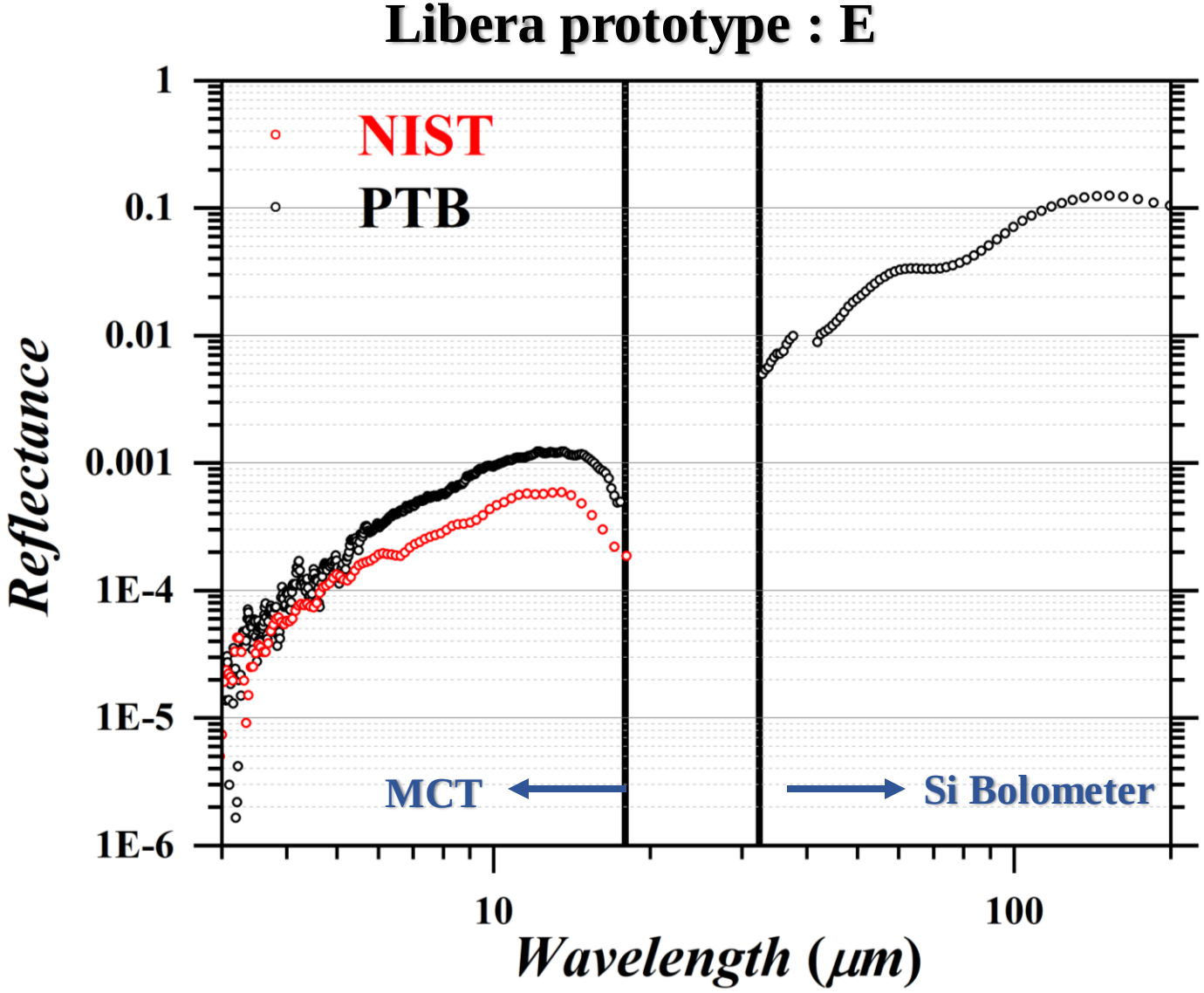
Backup Slides

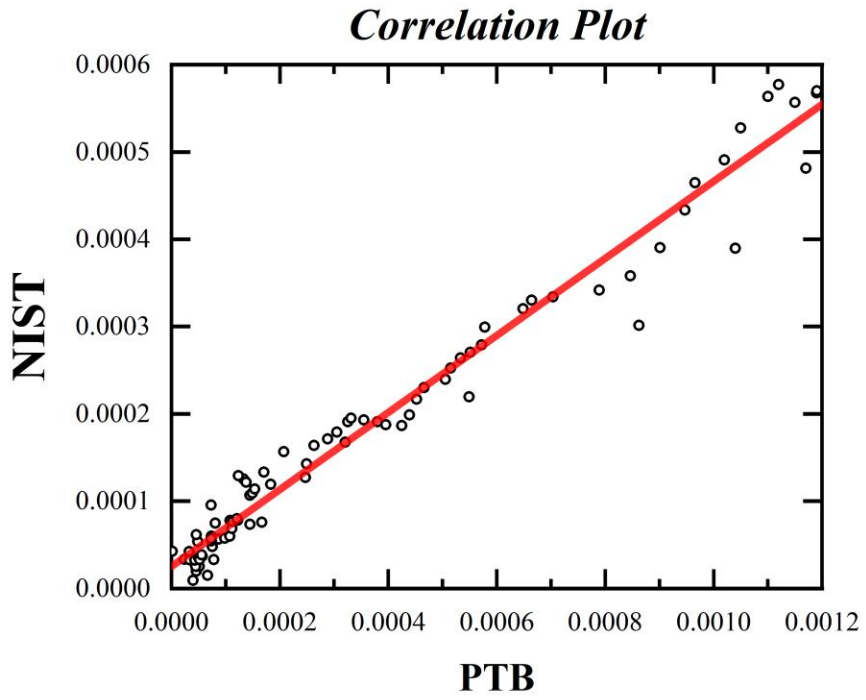
Uncertainty Budget

Sources of uncertainty (x_i)	Relative standard uncertainty ($\delta(x_i)$)	Probability distribution	Uncertainty type
Signal to noise (SNR)	0.01-0.5	Rectangular	B
Reference Reflectance	0.02	Rectangular	B
Reference Alignment	0.025	Rectangular	B
Focus Alignment	0.05	Rectangular	B
Source instability	0.01	Rectangular	B
Background	0.025	Rectangular	B
Atmosphere	0.01	Rectangular	B
Total relative standard uncertainty ($\sum\delta(x_i)$)	0.15-0.69		



PTB vs NIST





- Linear correlation indicative of Lambertian behavior

Bidirectional Reflectance Distribution Function (BRDF)

$$\rho_{DHR}(\theta_i, \phi_i, \lambda) = \int f_r(\theta_i, \phi_i; \theta_r, \phi_r; \lambda) \cos(\theta_r) d\Omega_r$$

Reasonably assume Lambertian reflectance ($I \propto \cos\theta$) and reference to PTB

NIST: NA=0.3 **PTB: NA=0.4**

$$\frac{\text{Partial Hemisphere}}{\text{Full Hemisphere}} = \frac{1}{\gamma}$$

$$\text{DHR} = \gamma * \text{Reflectance}$$