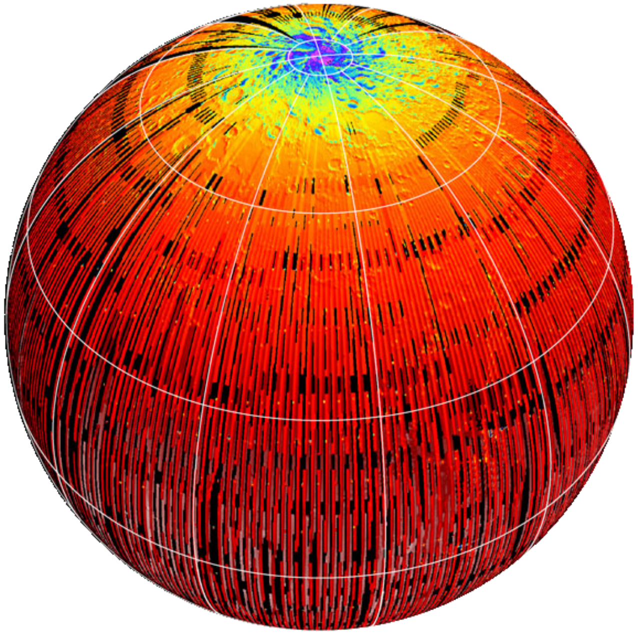

Far-Infrared Remote Sensing Enabled by Room-Temperature Thermopile Imagers

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NASA Jet Propulsion Laboratory - California Institute of Technology

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Introduction

- JPL Thermopile Technology
- Seebeck effect
- Gold Black Broadband Absorber
  - Gold Black parameters
- RBI Focal Plane Module (2-by-1 pixel format)
- Larger Arrays (64-by-16 pixel format)
- Improving Design and Performance
- Conclusions

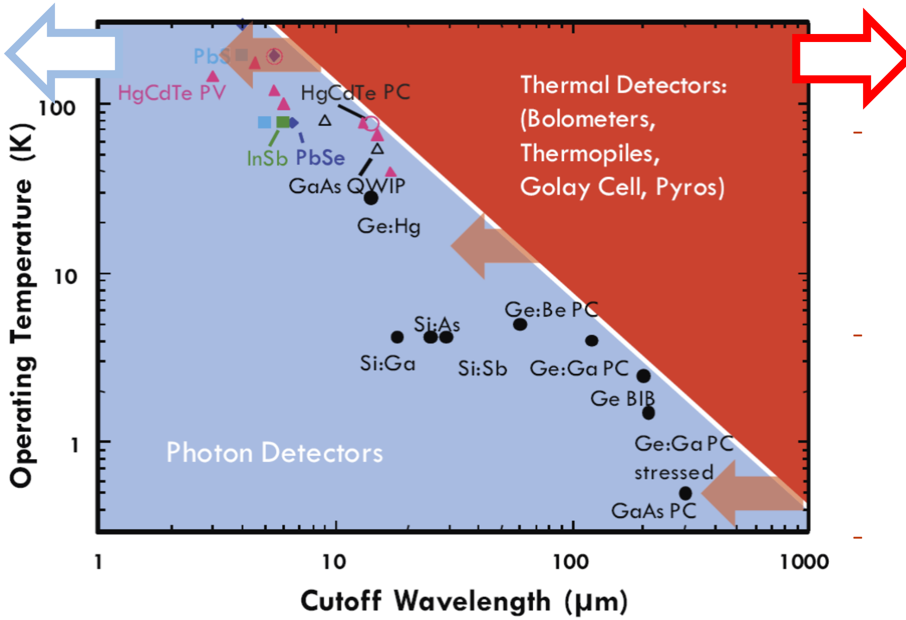
Detector Portfolio

Photon detectors

- Selective wavelength dependence of the spectral response per incident IR power

- Limited by G-R noise arising from photon exchange with a radiating background

- Need to be cooled to cryogenic temperatures



Thermal detectors

- Thermal effects are wavelength independent thus the spectral response is constant

- Limited by temperature fluctuation noise arising from radiant power exchange with a radiating background

- Thermopile architecture does not need cooling – room temperature operation

Which is the best candidate for IR sensing?

Sensitivity	Readouts
Speed	Radiation coupling
Scalability (Pixel count)	Wavelength Coverage

Mission-driven Technology

Jet Propulsion Laboratory
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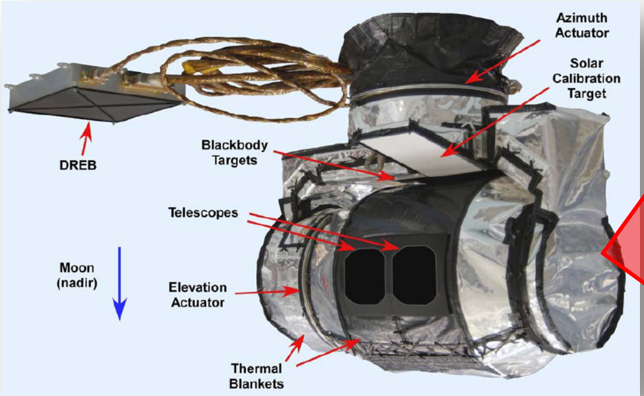
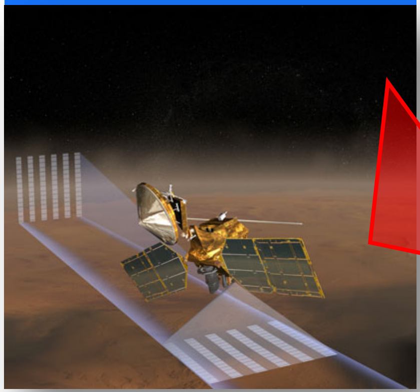
FLIGHT HERITAGE

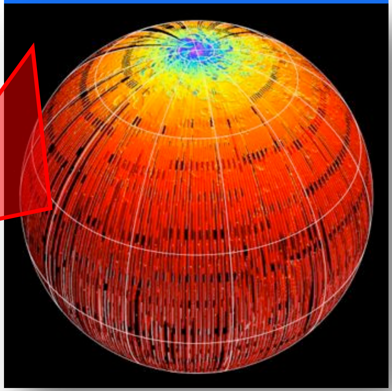
Multi-spectral, filter radiometer with thermopile arrays



Mars Climate Sounder (MCS)



Diviner Lunar Radiometer Experiment

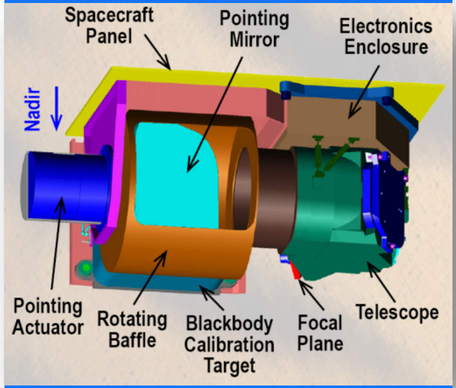


FUTURE OPPORTUNITIES

Earth

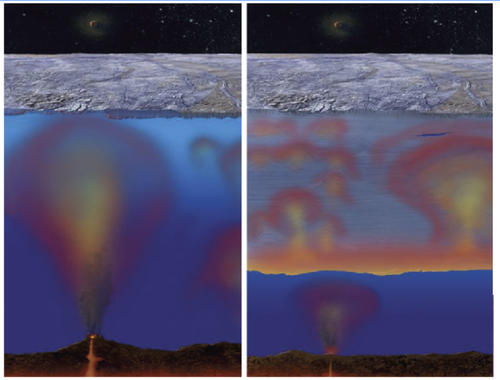
Radiation Budget Instrument, ISS, A-Train satellites

Primitive Bodies



Trojans Tour and Rendezvous & Asteroids

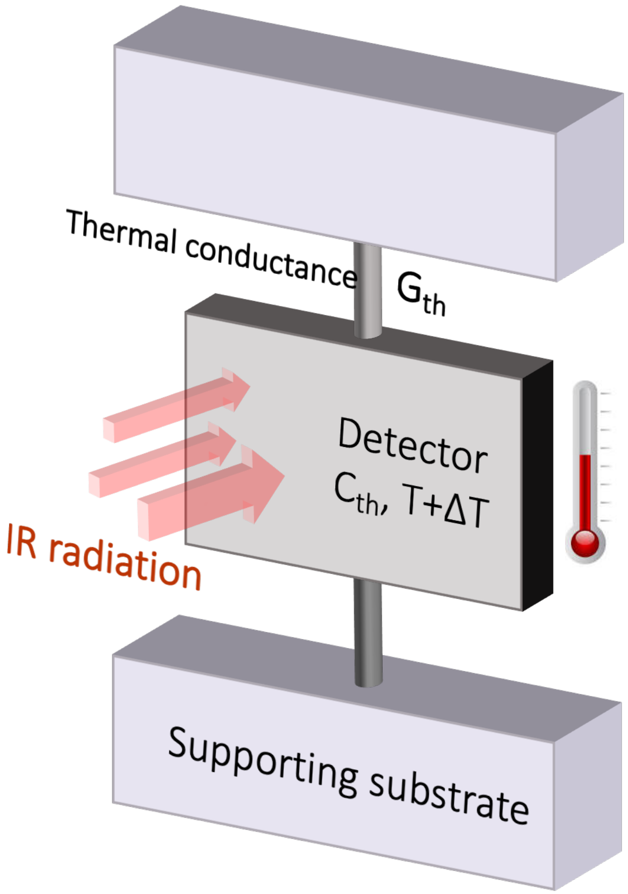
Jupiter



Reconnaissance Package on Clipper

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Operating Principle of Thermal Detectors



Noise Equivalent Power	$(4k_b G_{th} T^2)^{1/2}$
Detector Response Time	C_{th}/G_{th}

IR radiation transduction

1) Incident IR radiation is absorbed to change the temperature of the material
2) Detector suspended on legs, which are connected to a heat sink
3) Temperature change is converted into an electrical output through one of the following temperature-dependent effects:
   - Pyroelectric
   - Pyromagnetic
   - Photoelectric (e.g. bolometers)
   - Seebeck (e.g. thermopiles)

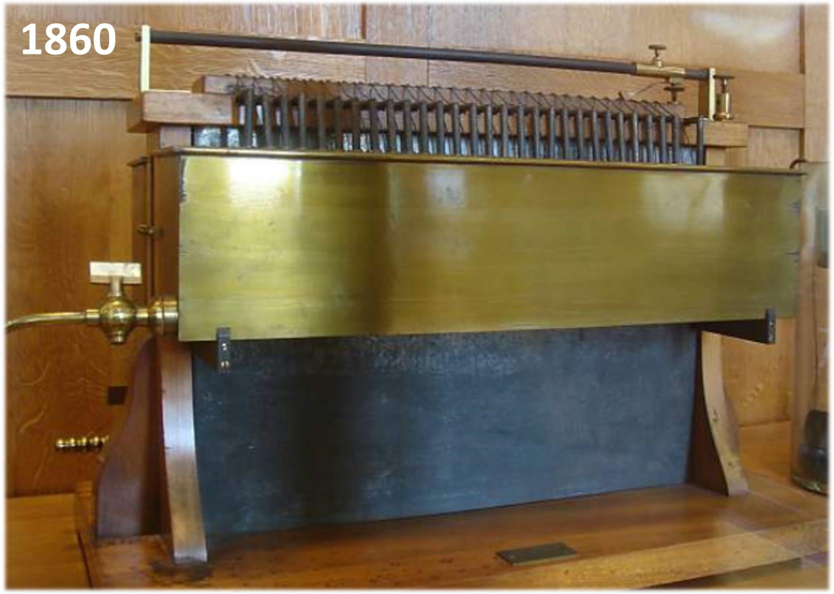
$$\Delta T = \frac{\varepsilon \Phi_o}{\left(G_{th}^2 + \omega^2 C_{th}^2\right)^{1/2}}$$

where $\Phi = \Phi_o e^{i\omega t}$ is a periodic radiant power, G_{th} is the thermal conductance w.r.t. the surroundings, C_{th} is the thermal capacitance of the detector

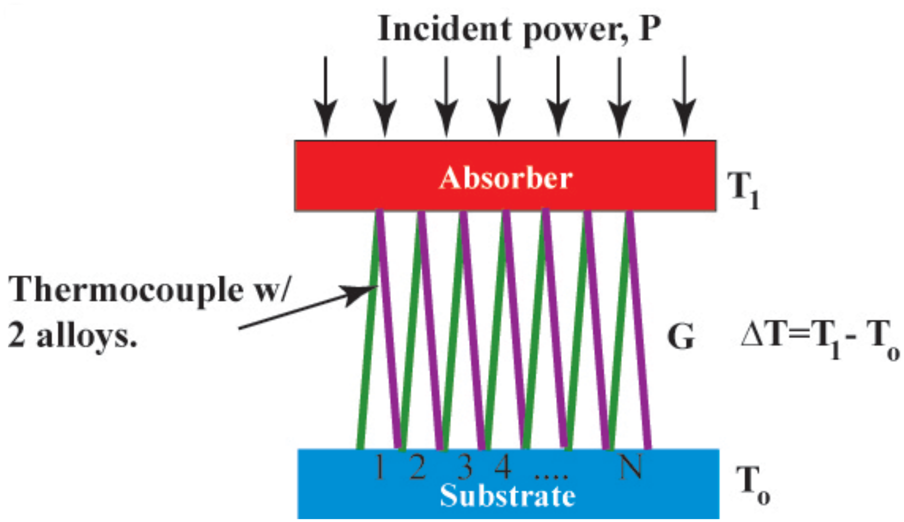
Seebeck Effect

A bit of history…

- Thermopiles have been around for a while: in *1821* Thomas Seebeck noticed that two dissimilar metals at different temperatures would deflect a compass magnet
- Below, a thermopile operated by gas burners. An interesting feature is the sliding contact at the top, to vary the number of junctions and therefore the output voltage



Seebeck Effect



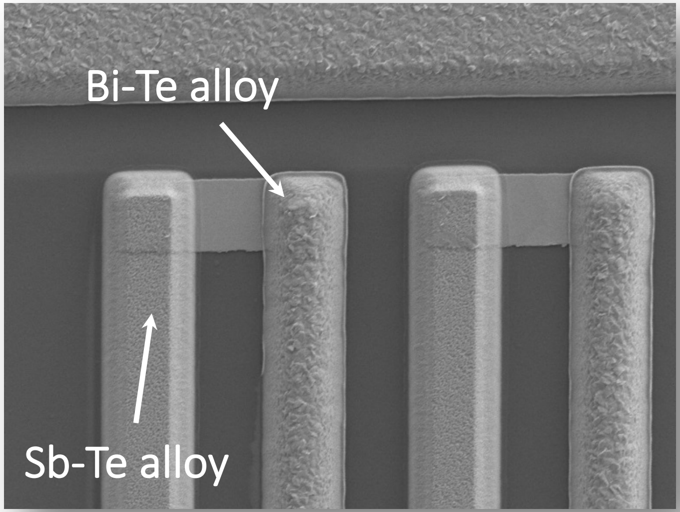
- Seebeck effect: direct conversion of temperature difference to electromotive force
- Thermopiles work by measuring the absorber-to-substrate temperature gradient → $\Delta T = P/G$
- A voltage is induced across a series of N couples, proportional to the Seebeck coefficient

$$V = N\Delta S\Delta T = N\Delta S \times P/G$$

The ***key is the thermal link G*** – Can we design a thermopile so G is dominated by gas between absorber and substrate?

Thermometer: Radiation-to-Heat Converter

Thermocouple Junction



Properties	$Bi_1Te_{1.9}$ (n-type)	$Sb_1Te_{1.7}$ (p-type)
S: Seebeck Coefficient (uV/K)	-150	120
r: Resisitivity (mOhm x cm)	1.0	3

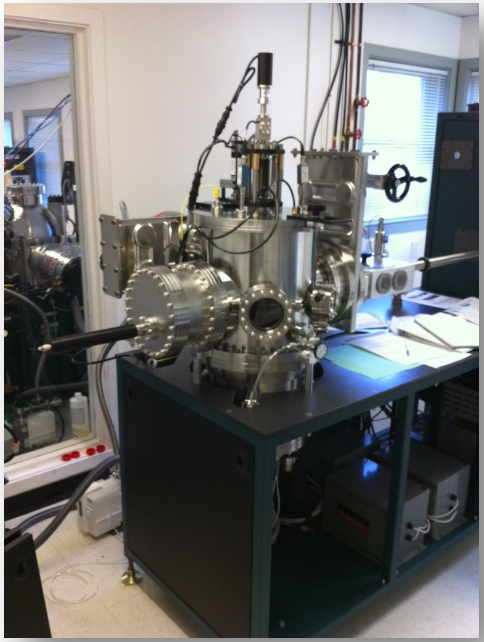
$$SNR \propto \frac{(S_{p-type} - S_{n-type})}{\rho_{p-type} + \rho_{n-type}}$$

Key Fabrication and Test Facilities

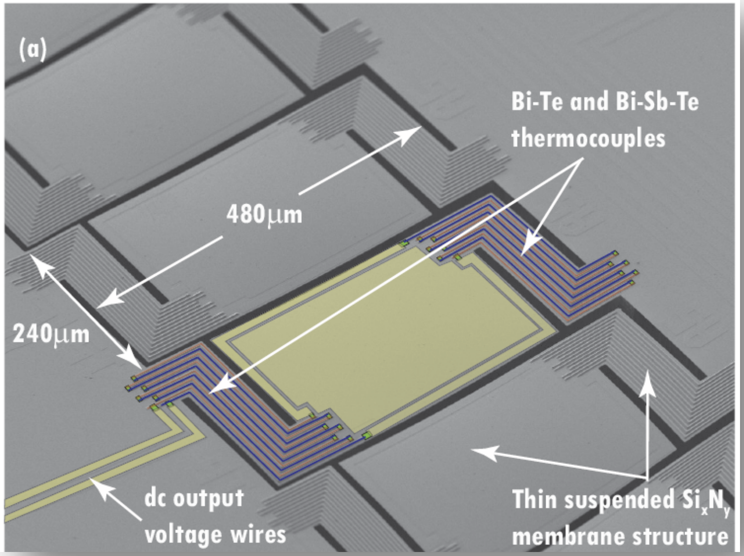
-Custom Bi-Sb-Te co-evaporator to deposit high quality films

-Testbed to measure *n*- and *p*-type Seebeck coefficients

-Optical setup to measure detector responsivity and response time



Thermopile pixel

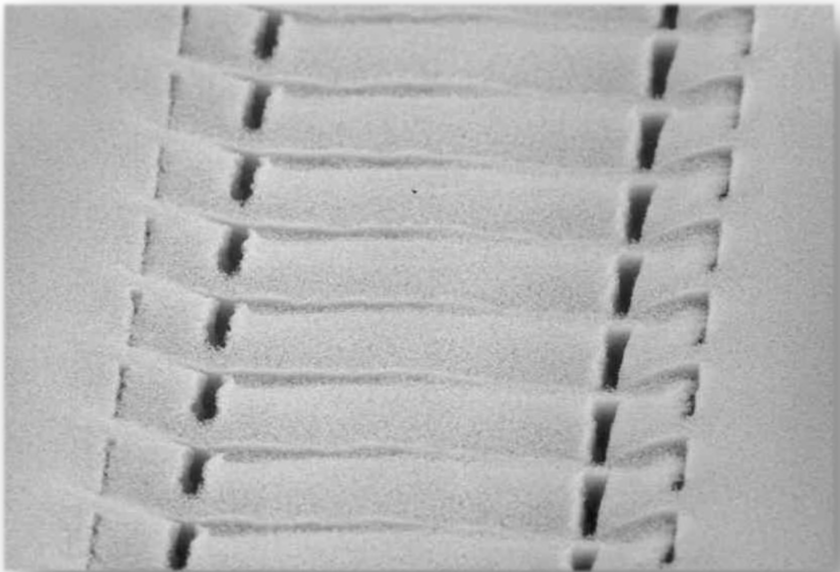


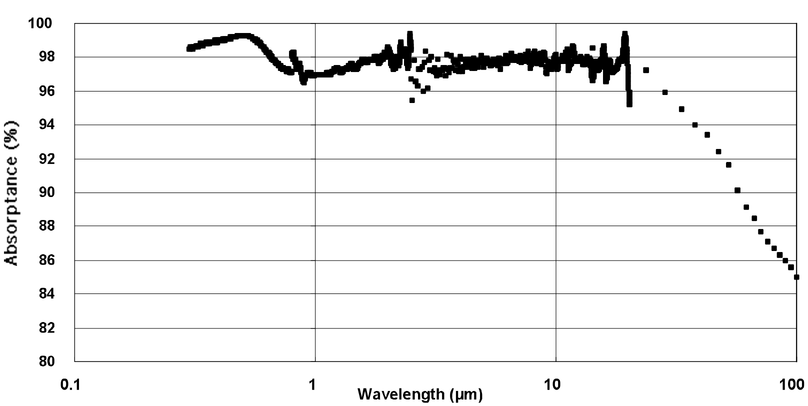
- Room-temperature operation, no need for cryogenic refrigeration
- Mass is a prime concern in space missions: lighter and exceptionally compact instrument
- No electrical bias required
- Broadband range 0.3µm to >200µm
- Negligible excess 1/f noise (long integration time)
- Detectors consist of a SiN membrane, thermally isolated from the Si substrate. Bi-Te and Bi-Sb-Te TE lines connect the thermally isolated membranes to the substrate
- Thermal radiation causes the membrane to heat up (or cool) w.r.t. the substrate, generating a voltage

Gold Black Parameters

Jet Propulsion Laboratory
California Institute of Technology

Thermopile Array with Gold Black





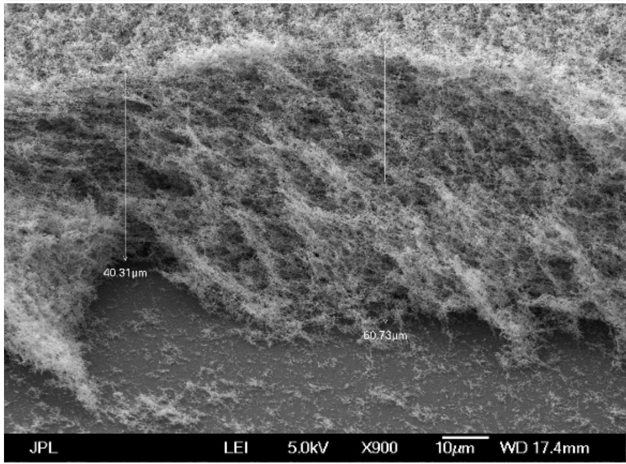
Electrical and Thermal Properties

RES Part No.	GB Thickness (um)	Resistance	Anneal Temperature (C)	Resisitivity (Ohm-m)	Thermal Conductivity (mW/mK)
K151117.3	40	62.7	200	8.4E-04	8.8
K151207.4	41	60.9	200	8.3E-04	8.8
K151207.5	39	60.5	200	7.9E-04	9.3
K151207.6	41	58.4	200	8.0E-04	9.2
K151207.8	41	57.4	200	7.8E-04	9.3
K151217.5	40	60.3	200	8.0E-04	9.1
K151217.6	40	60.6	200	8.1E-04	9.1
K151217.7	42	60.7	200	8.5E-04	8.6
K151217.8	40	59.8	200	8.0E-04	9.2

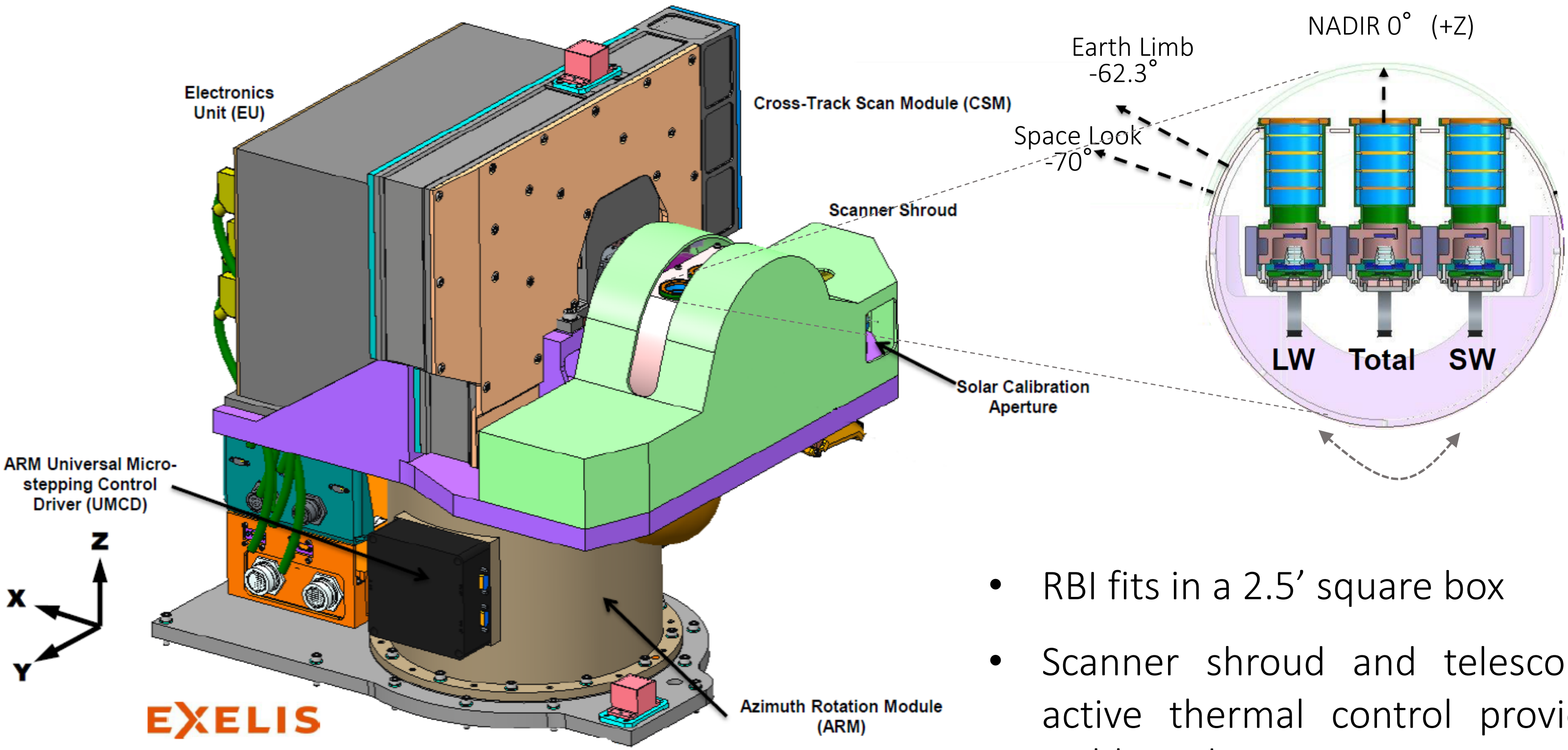
†Using Wiedemann-Franz to determine the thermal conductivity.

Measured density of gold black is 0.5% of gold.

Thermal Cond. AVG (mW/mK) 200C	9.0
Thermal Cond. STD (mW/mK) 200C	0.26
% STD	2.9%
Resistance AVG (kohm) 200C	60.1
Resistance STD (kohm) 200C	1.4
% STD	2.4%



RBI - Instrument

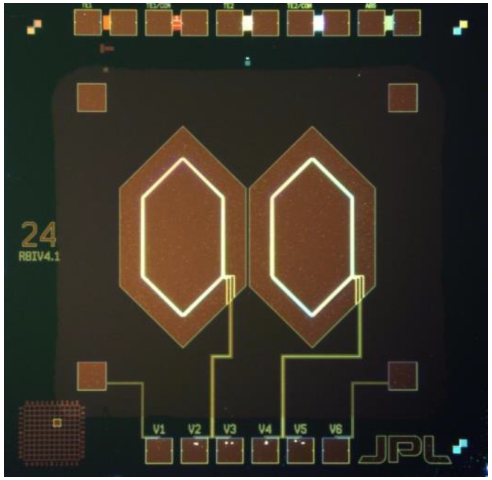


EXELIS

- RBI fits in a 2.5' square box
- Scanner shroud and telescope active thermal control provide stable detector temperature environment

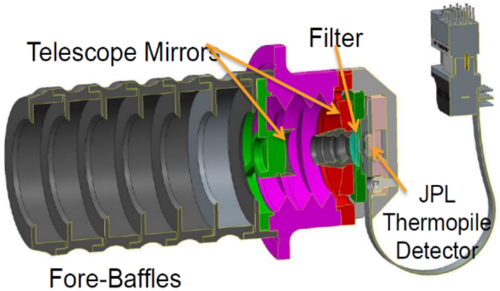
-3 separate radiometric channels: short wave (SW) 0.2-5µm, long wavelength (LW) 5-100µm, total 0.2-100µm

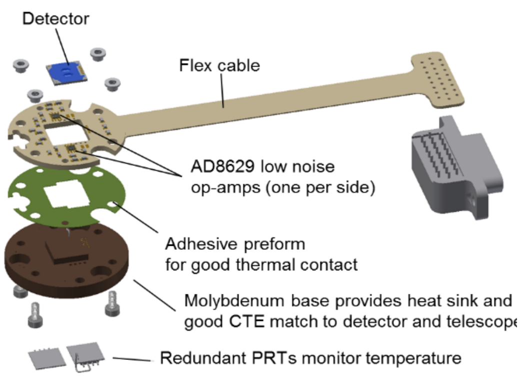
RBI – Focal Plane Module (2-by-1)

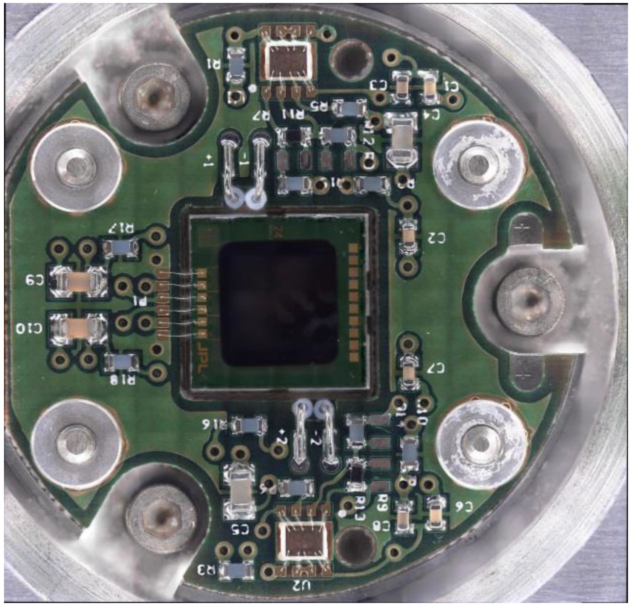


Focal Plane Module is a Thermal Detector that compares heat sink temperature with a membrane coupled to the radiation from the telescope

1. Passive Thermopile Detector
2. AD8629 single op-amp analog gain circuit
3. PRT for heat sink monitoring

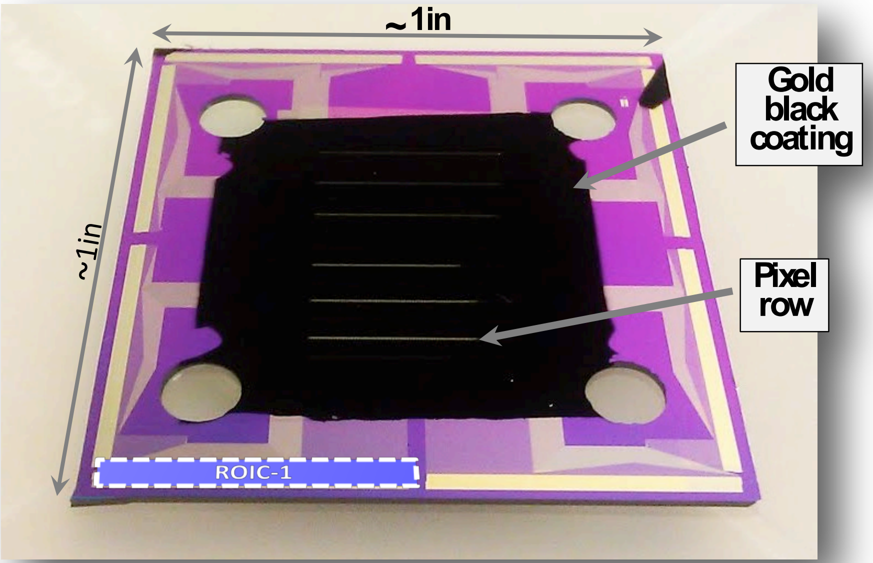






Larger Format Arrays (64-by-16)

Kilopixel array

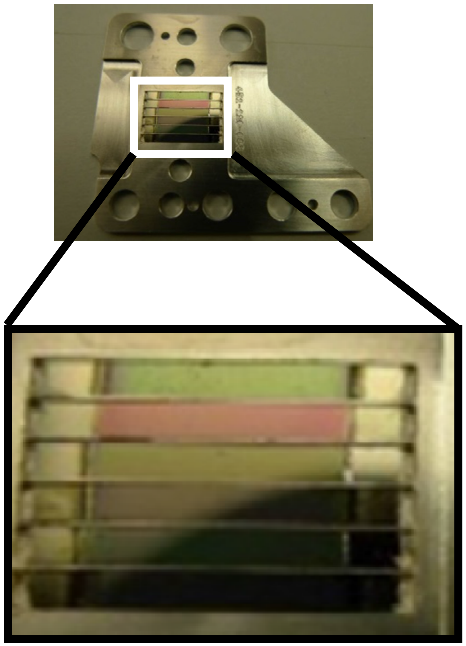


- 150µm x 150µm pixel size
- 16 rows (in-track) x 64 columns (cross-track)
- Read-out chip designed by Black Forrest Engineering (as MCS/DLRE experiments)
- Gold black as efficient broadband, radiative coupler
- Patterning of gold black thru controlled laser ablation

blocks

Previous generation

6 Filter blocks on Diviner/MCS

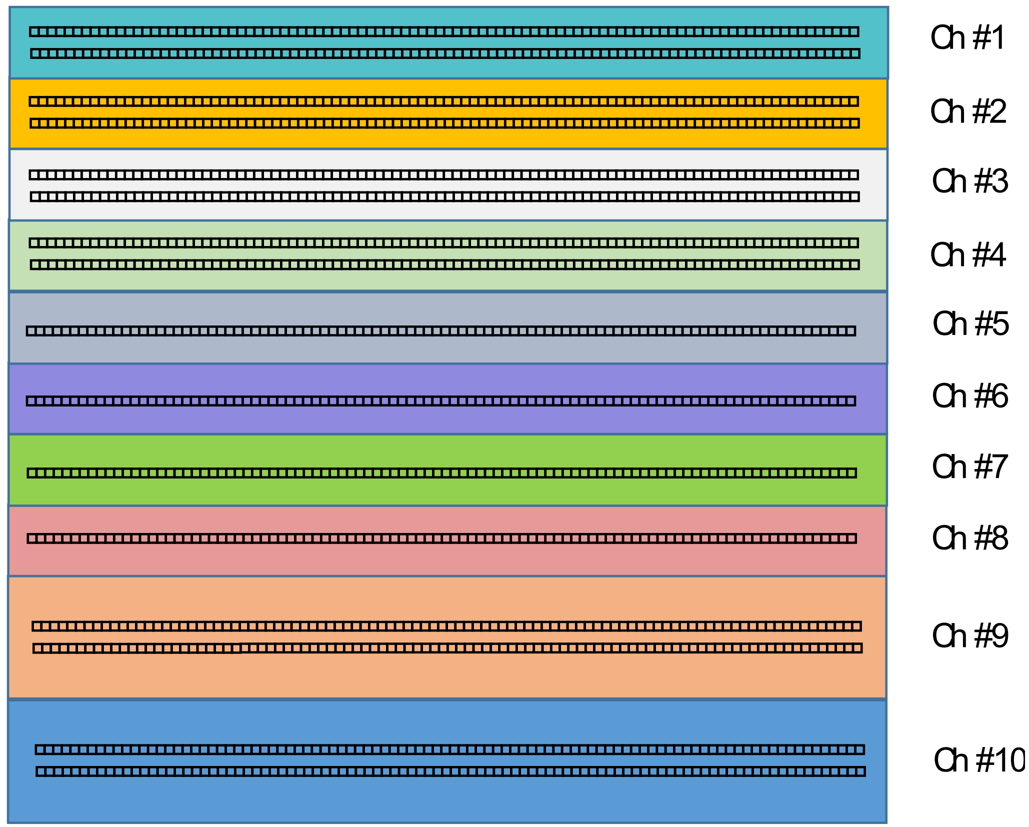


Europa Clipper generation (pre-decisional)

10 Filter blocks

64 pixels in each of 16-line arrays

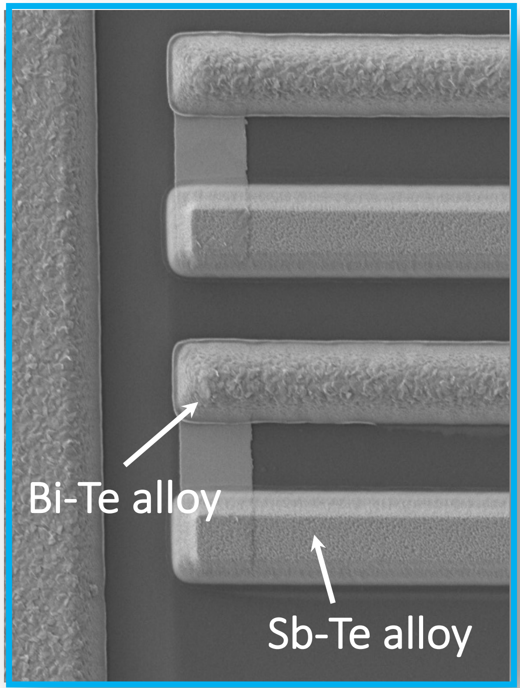
1 pixel = 180 µm x 180 µm



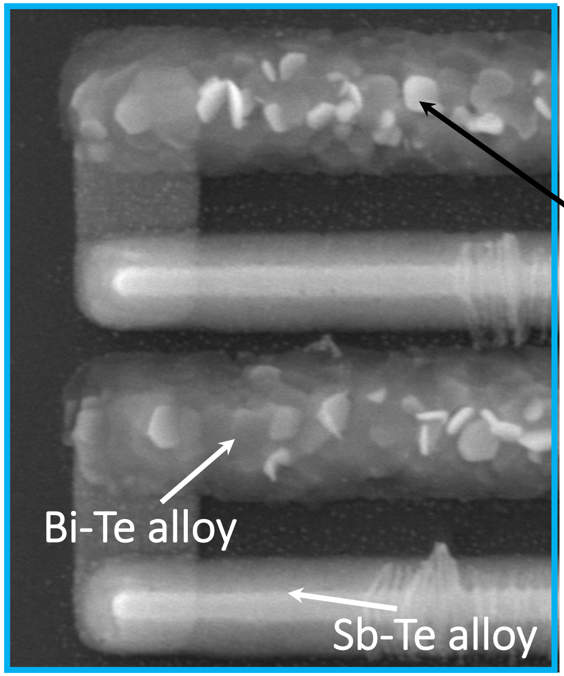
Future Thermopile Technology

- New materials exploit a high-temperature deposition step to achieve crystalline thermoelectrics

Old Deposition



New Deposition

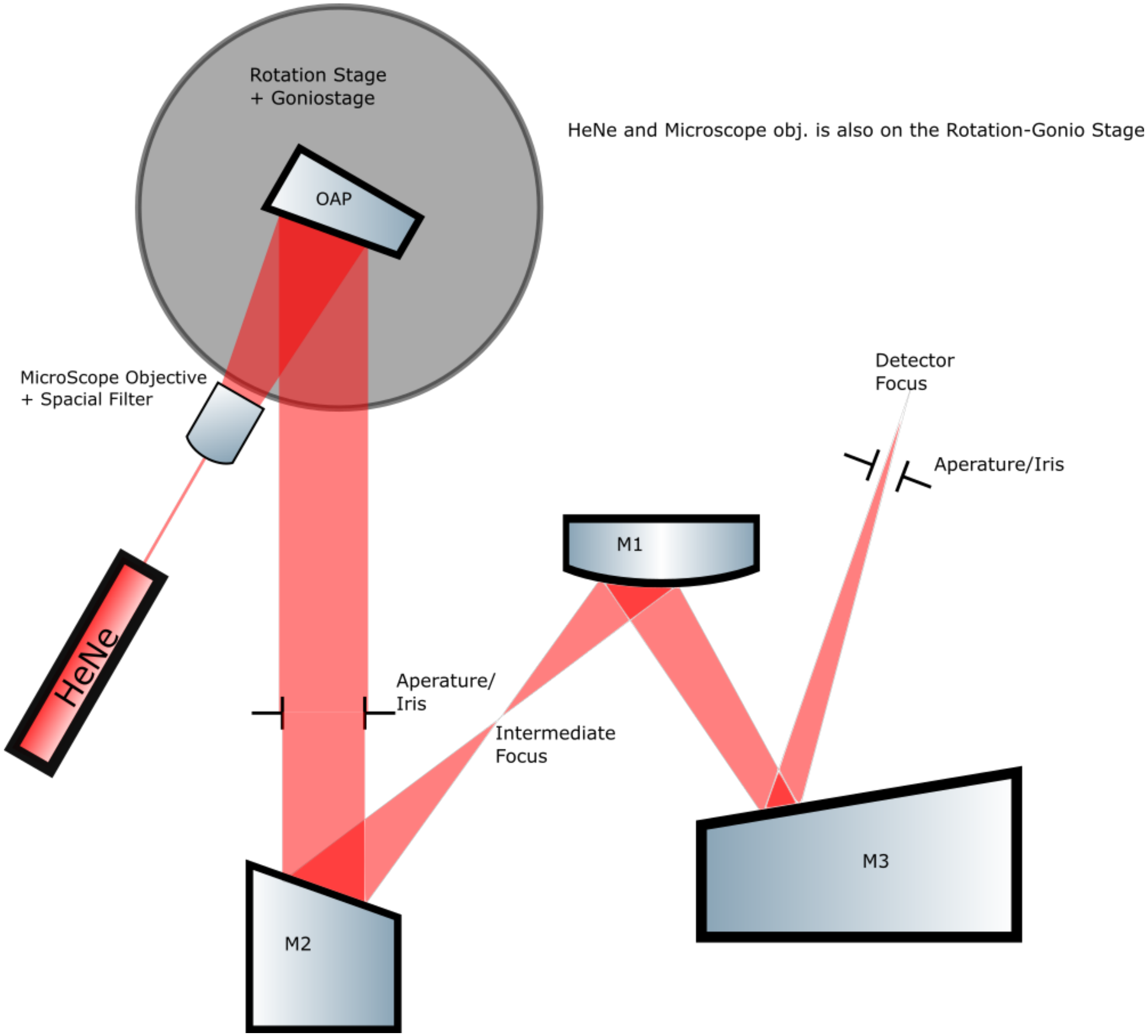


Crystalline platelet formation

1. n-type (Bi-Te) is historically resistive and lower Seebeck than p-type counterpart
2. Several papers reported low resistance, high Seebeck coefficient for high-temp deposition in thin films
3. Platelets formation suggests (poly) crystalline structure for n-type
4. Thin-film XRD measurements confirm the (poly) crystalline structure for Bi-Te
5. Optimization underway to control line width at the device level
6. This could result in a 2x increased performance (SNR)

Future Optical System

- Three mirror anastigmat (TMA) approach:



- Spatially aberrated intermediate focus
- Separate in space filter block from detector plane
- Filter block at the intermediate focus
- Enabling smaller pixels or 2x spectral channels
- Reduced size of optical bench by 2x, with a larger FOV

Conclusions

- ✓ Thermal detectors are critical to study the Earth, solar system, and the universe in the far-IR and beyond
- ✓ Gold black is a unique broadband absorber used in JPL thermopile
- ✓ Pixel format can be readily changed depending on mission requirements
- ✓ New technology infusion allows for crystalline thermoelectric lines that can outperform the old deposition configuration
- ✓ An improved optical system based on TMA can decouple in space the filter block from the detector plane
- ✓ Next-generation thermal detectors use designs, materials, and process techniques not found in typical foundries, resulting in state-of-the-art performance specific to space applications

Acknowledgements

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- ..and many others