

Next Generation Thermal Imagers for Room-Temperature Far-Infrared Detection

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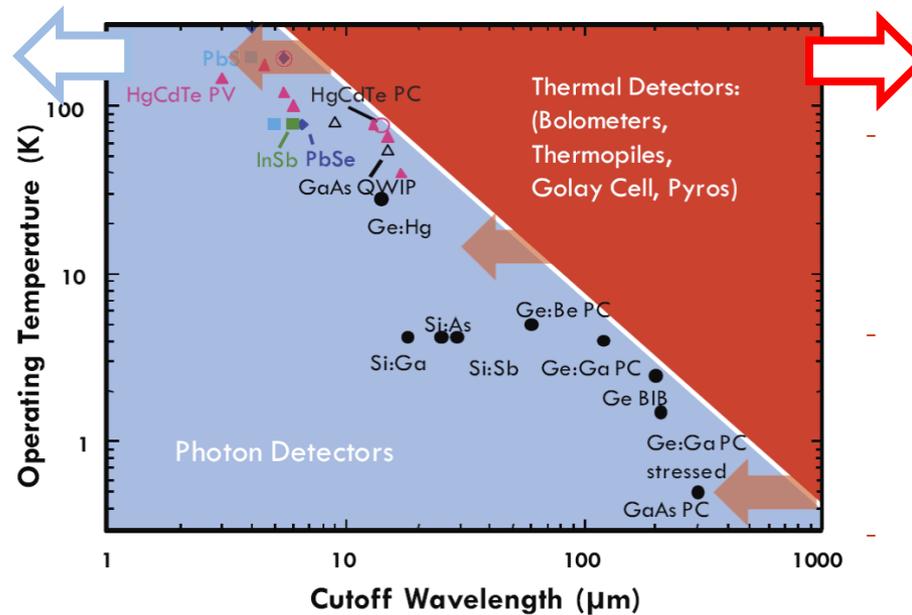
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- JPL Thermopile Technology
- Seebeck effect
- Gold Black Broadband Absorber
 - Gold Black parameters
- RBI Focal Plane Module (2-by-1 pixel format)
- Larger Arrays (64-by-16 pixel format)
- Improving Design and Performance
- Conclusions

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

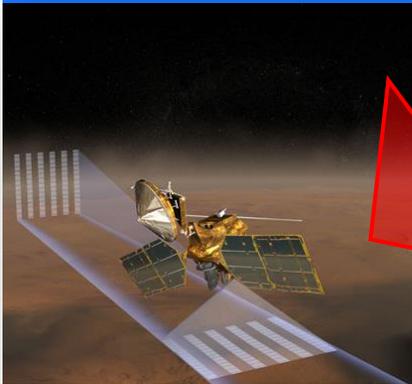


Mission-driven Technology

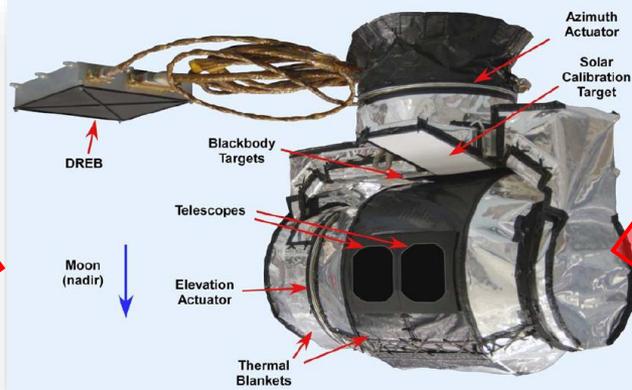
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FLIGHT HERITAGE

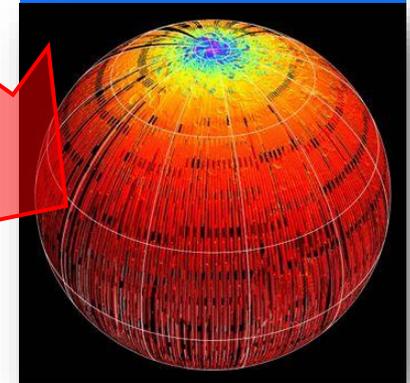
Mars Climate Sounder (MCS)



Multi-spectral, filter radiometer with thermopile arrays



Diviner Lunar Radiometer Experiment



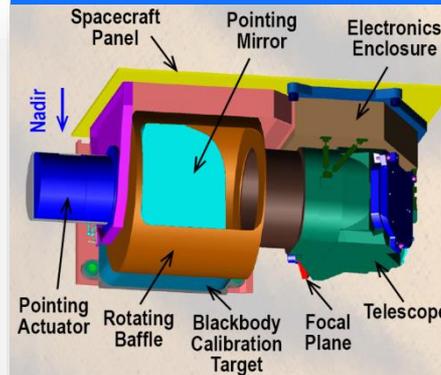
FUTURE OPPORTUNITIES

Earth



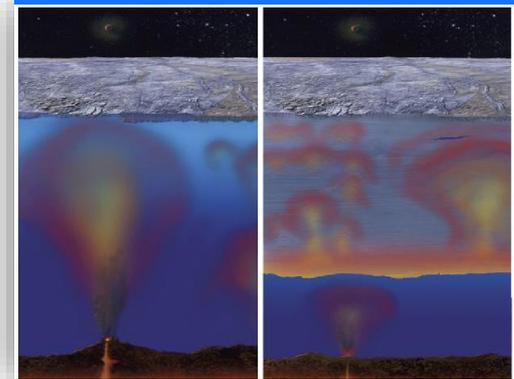
Radiation Budget Instrument, ISS, A-Train satellites

Primitive Bodies



Trojans Tour and Rendezvous & Asteroids

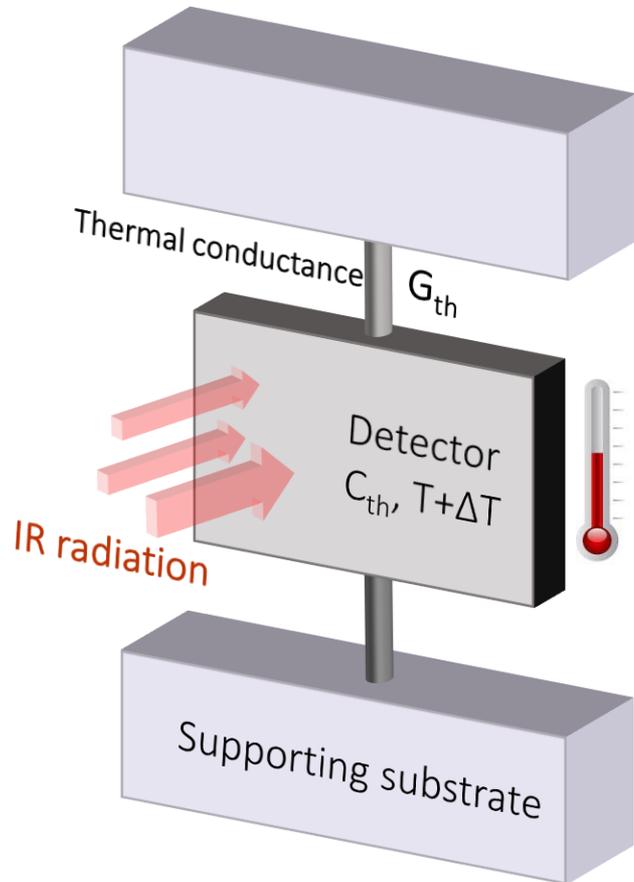
Jupiter



Reconnaissance Package on Clipper

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

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)

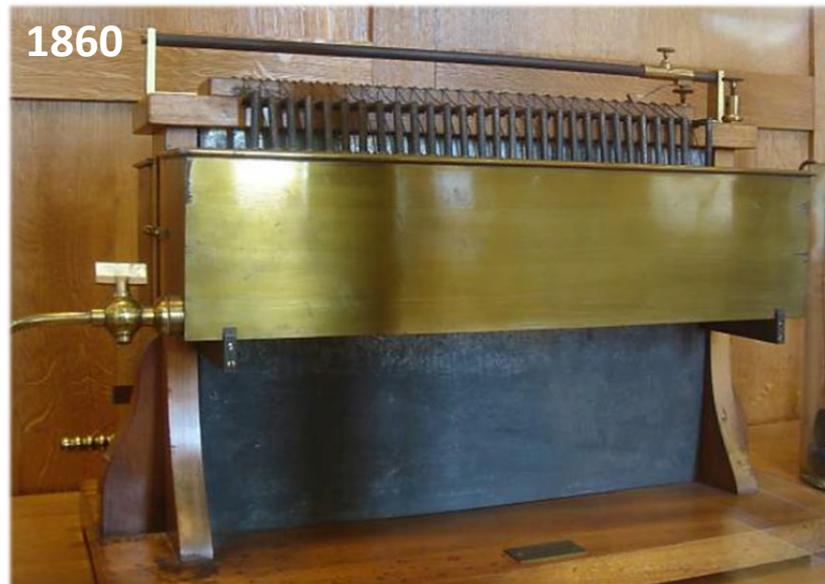
$$\Delta T = \frac{\epsilon \Phi_o}{(G_{th}^2 + \omega^2 C_{th}^2)^{1/2}}$$

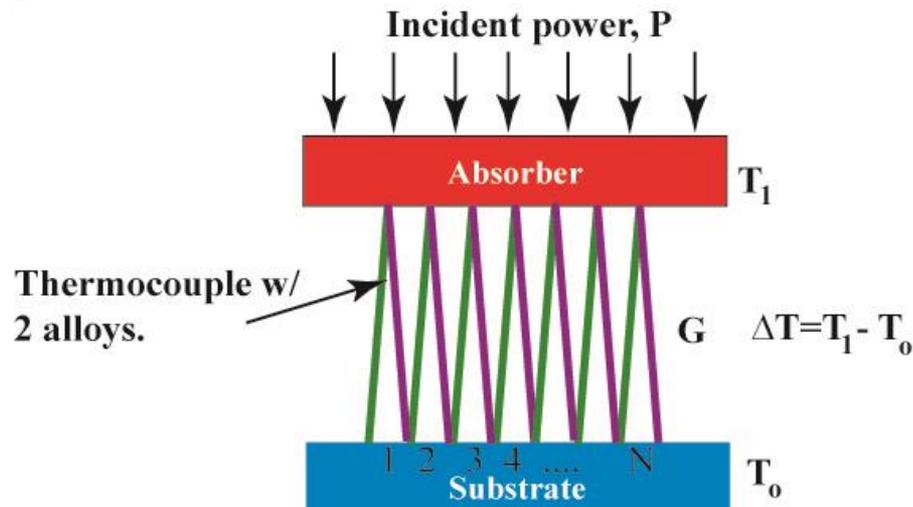
where $\Phi = \Phi_o e^{i\omega t}$ is a periodic radiant power, G_{th} is the thermal conductance w.r.t. the surroundings, C_{th} is the thermal capacitance of the detector

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

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





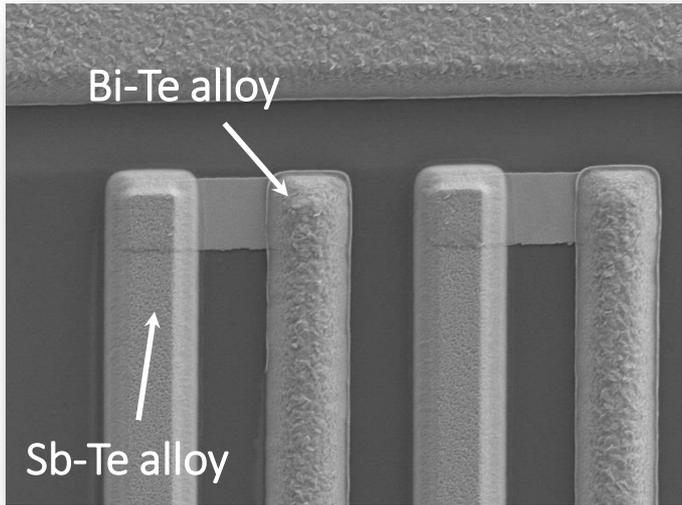
- Seebeck effect: direct conversion of temperature difference to electromotive force
- Thermopiles work by measuring the absorber-to-substrate temperature gradient $\rightarrow \Delta T = P/G$
- A voltage is induced across a series of N couples, proportional to the Seebeck coefficient

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

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



Thermocouple Junction

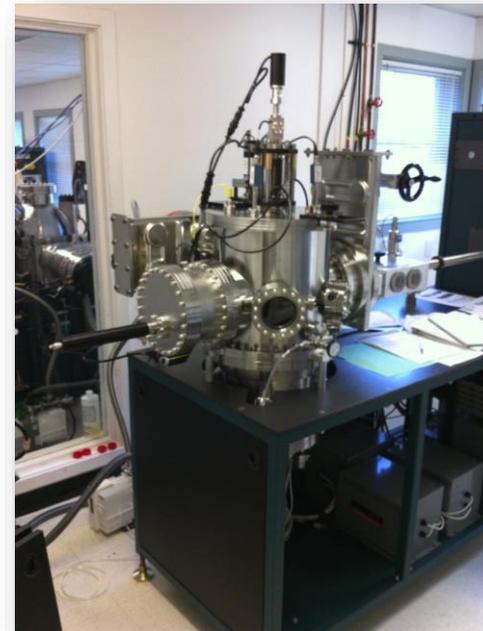


Properties	Bi ₁ Te _{1.9} (n-type)	Sb ₁ Te _{1.7} (p-type)
S: Seebeck Coefficient (uV/K)	-150	120
r: Resisitivity (mOhm x cm)	1.0	3

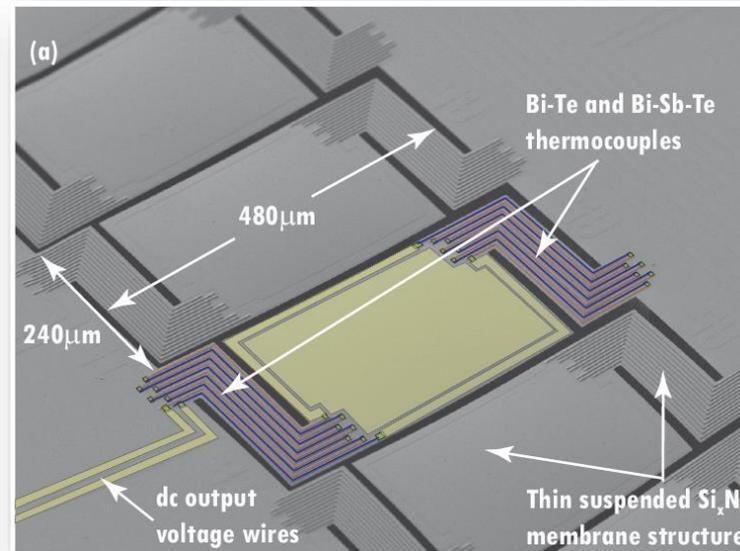
$$SNR \propto \frac{(S_{p-type} - S_{n-type})}{\rho_{p-type} + \rho_{n-type}}$$

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

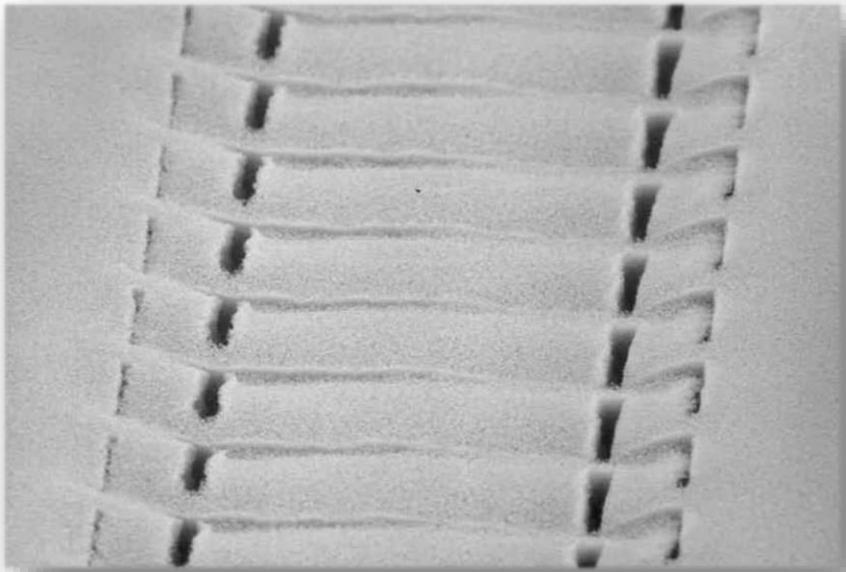


Thermopile pixel

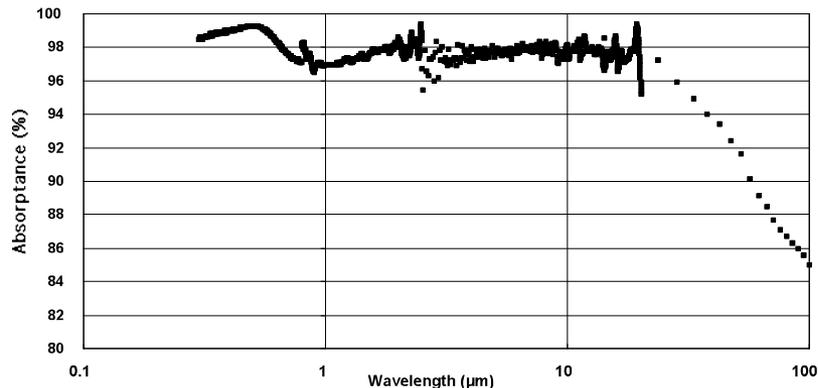


- Room-temperature operation, no need for cryogenic refrigeration
- Mass is a prime concern in space missions: lighter and exceptionally compact instrument
- No electrical bias required
- Broadband range $0.3\mu\text{m}$ to $>200\mu\text{m}$
- Negligible excess $1/f$ noise (long integration time)
- Detectors 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

Thermopile Array with Gold Black



Gold Black Absorbance Vs. Wavelength



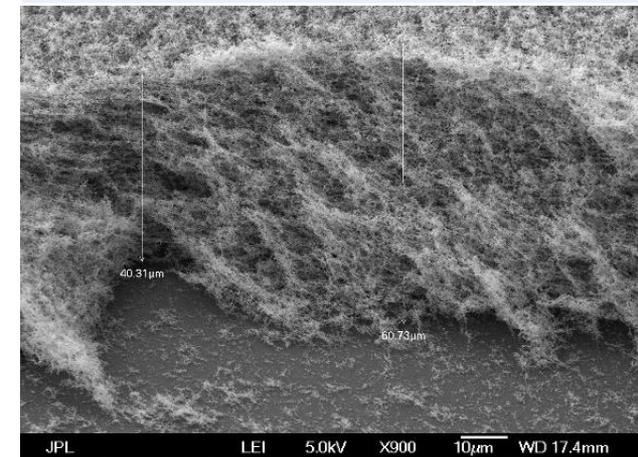
Electrical and Thermal Properties

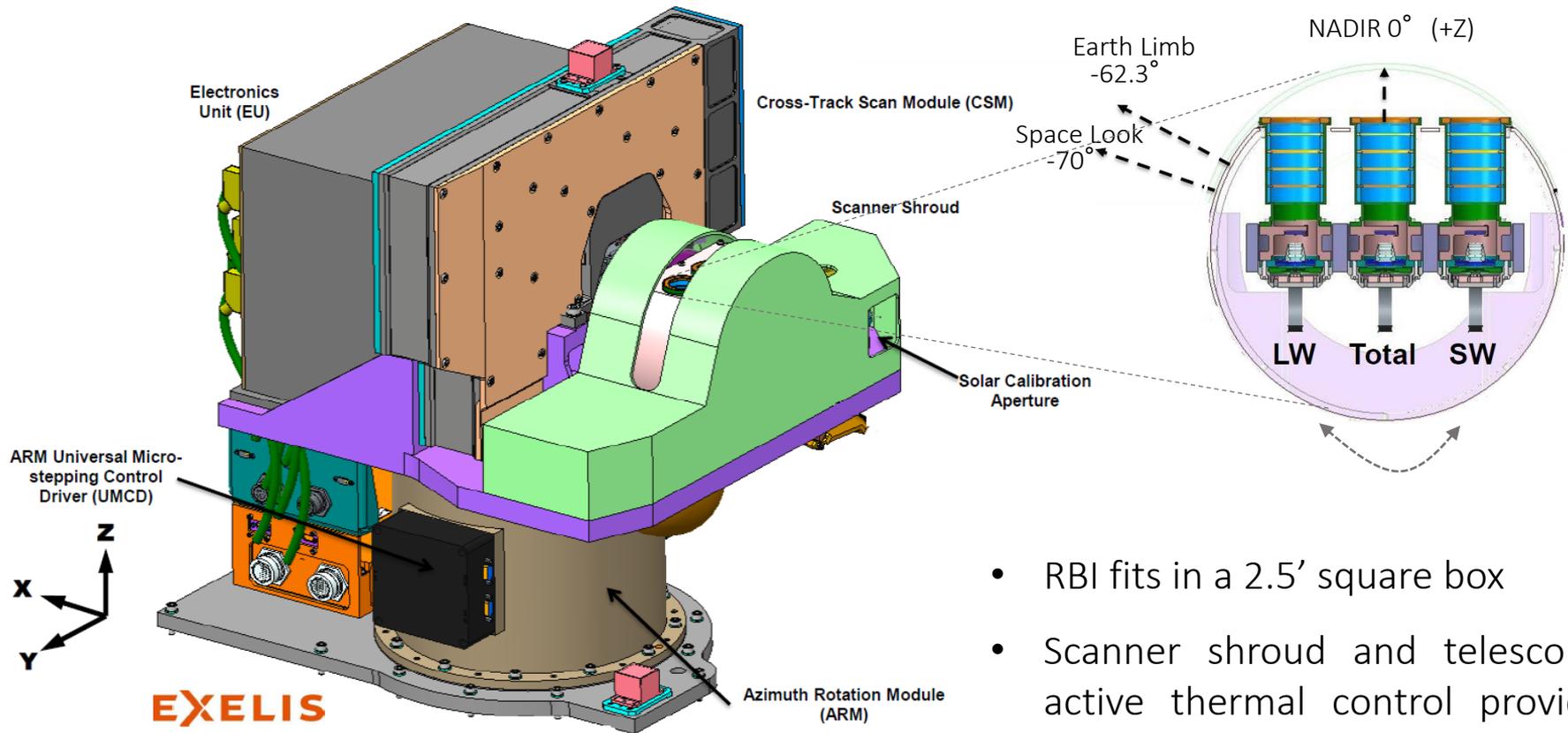
RES Part No.	GB Thickness (um)	Resistance	Anneal Temperature (C)	Resitivity (Ohm-m)	Thermal Conductivity (mW/mK)
K151117.3	40	62.7	200	8.4E-04	8.8
K151207.4	41	60.9	200	8.3E-04	8.8
K151207.5	39	60.5	200	7.9E-04	9.3
K151207.6	41	58.4	200	8.0E-04	9.2
K151207.8	41	57.4	200	7.8E-04	9.3
K151217.5	40	60.3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

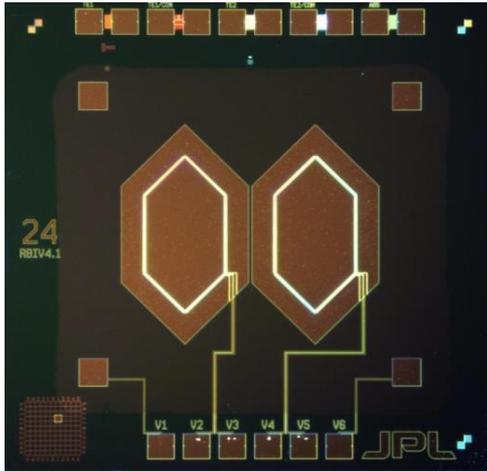
Thermal Cond. AVG (mW/mK) 200C	9.0
Thermal Cond. STD (mW/mK) 200C	0.26
% STD	2.9%
Resistance AVG (kohm) 200C	60.1
Resistance STD (kohm) 200C	1.4
% STD	2.4%





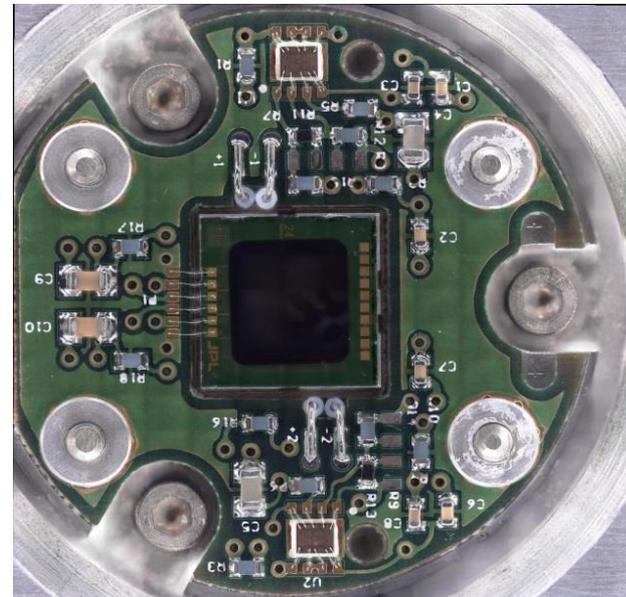
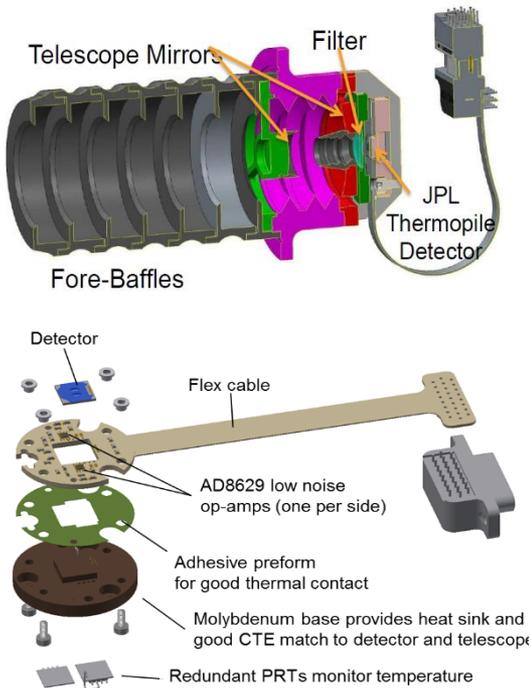
- RBI fits in a 2.5' square box
- Scanner shroud and telescope active thermal control provide stable detector temperature environment

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

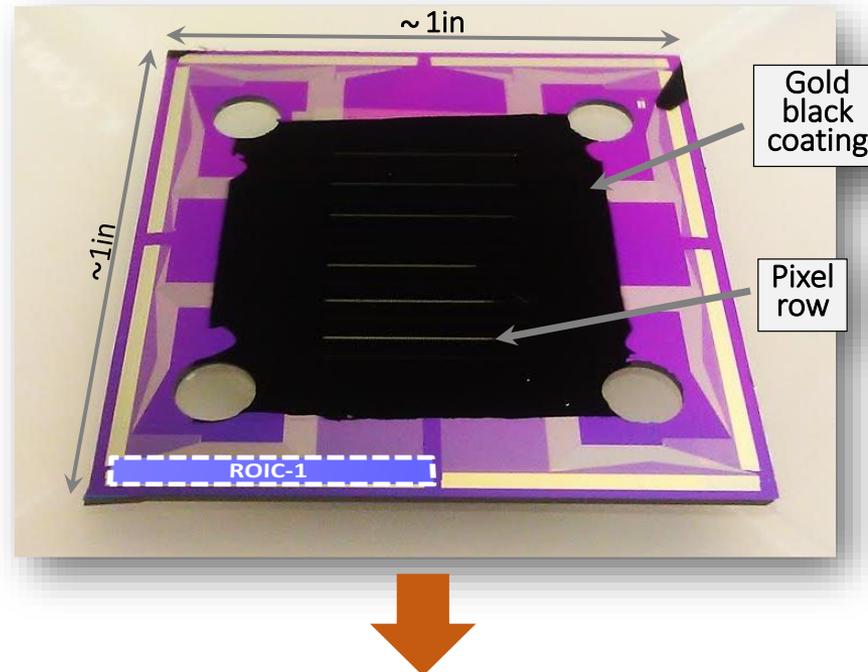


Focal Plane Module is a Thermal Detector that compares heat sink temperature with a membrane coupled to the radiation from the telescope

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



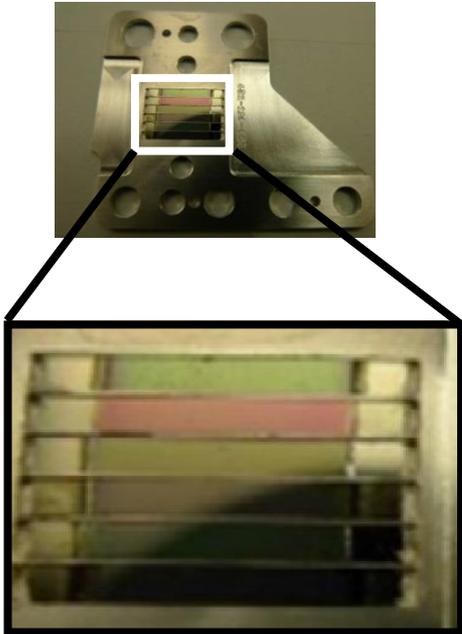
Kilopixel array



- 150 μ m x 150 μ m 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

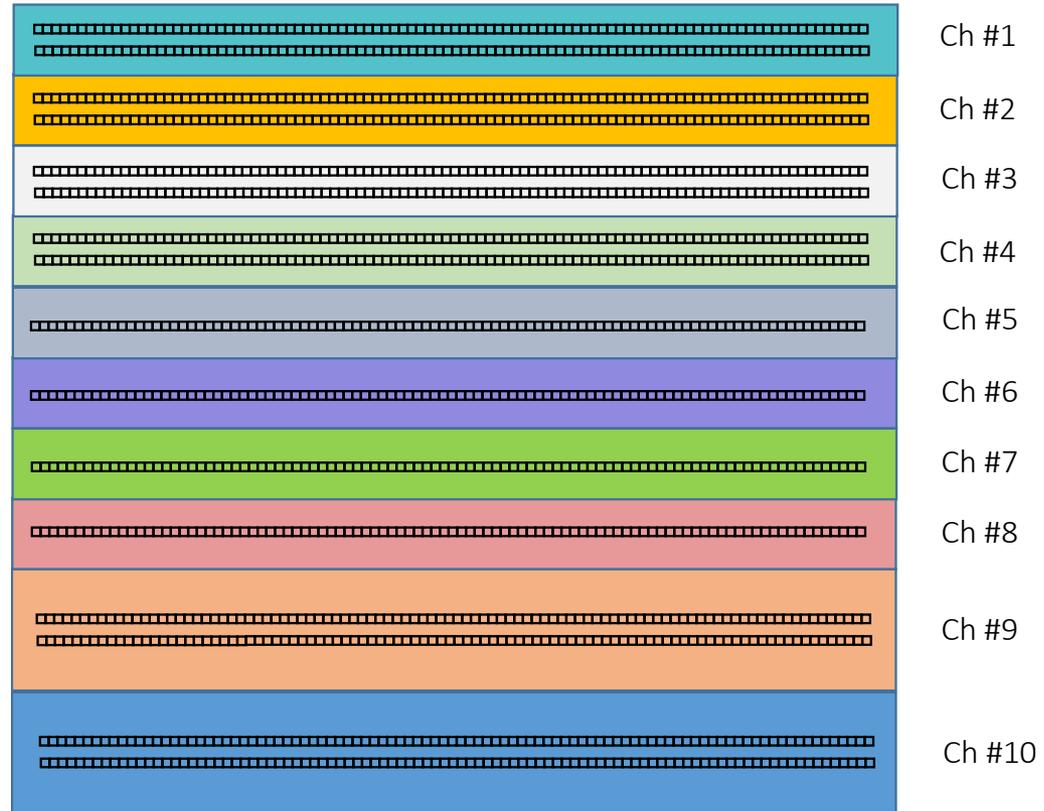
Previous generation

6 Filter blocks on Diviner/MCS



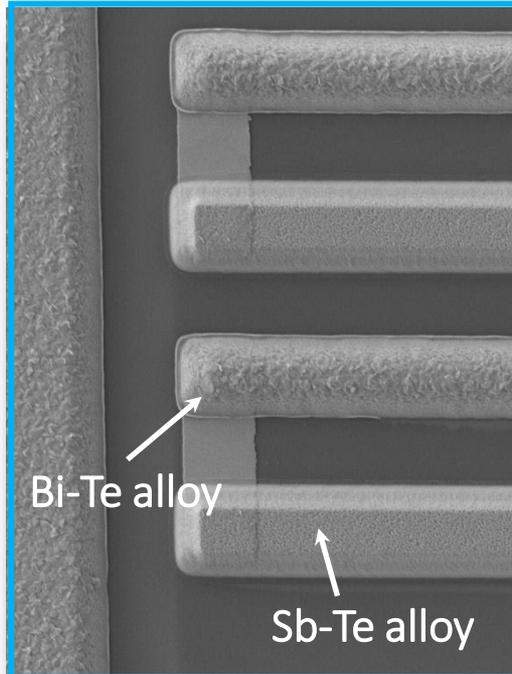
Europa Clipper generation (pre-decisional)

10 Filter blocks
64 pixels in each of 16-line arrays
1 pixel = 180 μm x 180 μm

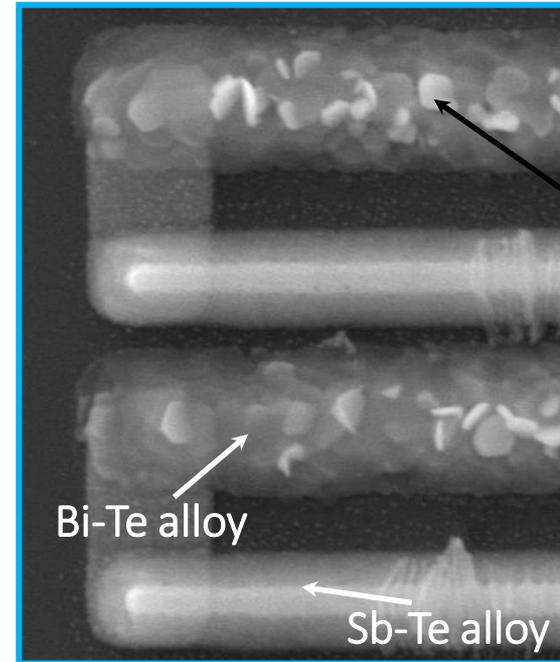


- New materials exploit a high-temperature deposition step to achieve crystalline thermoelectrics

Old Deposition

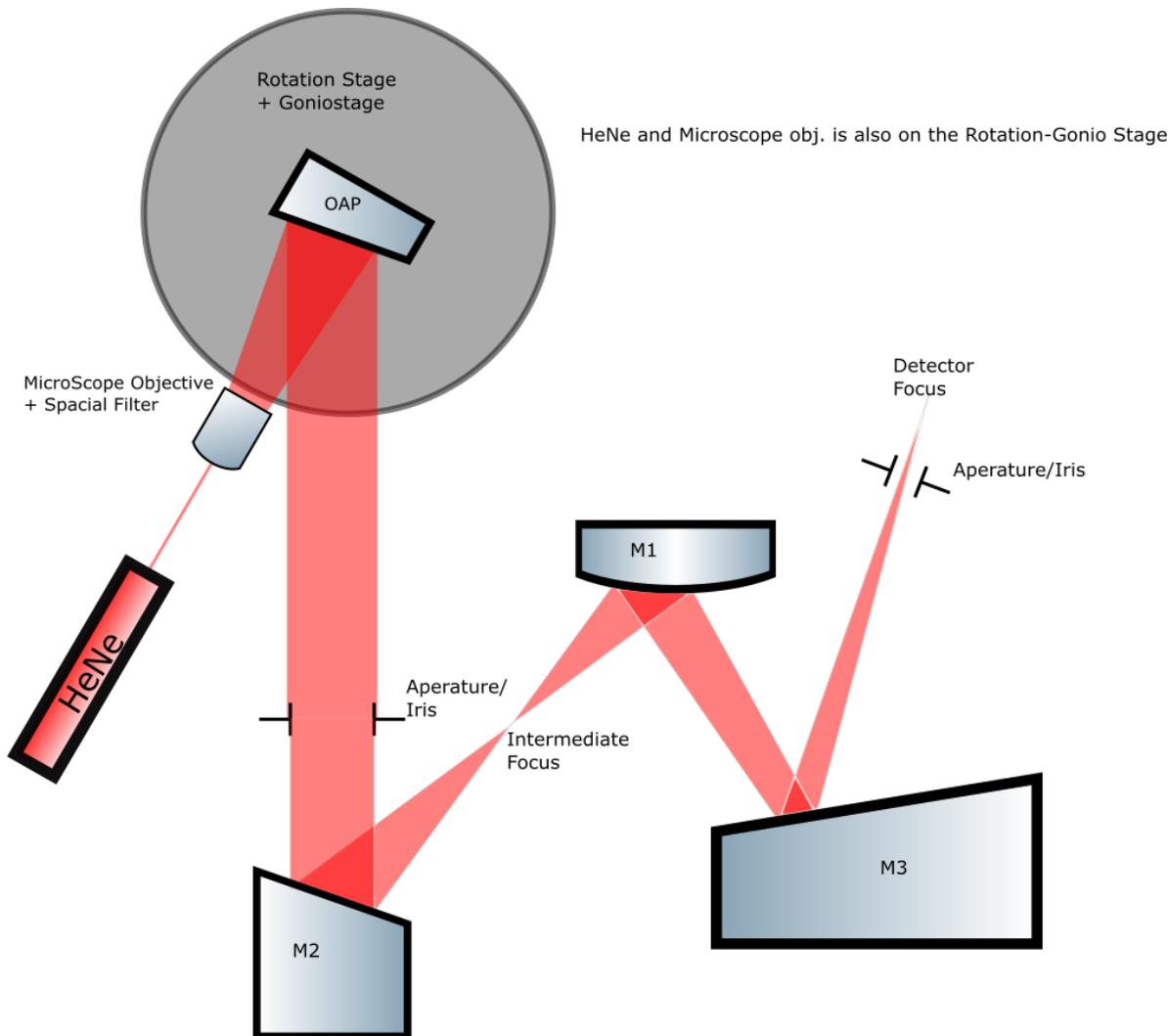


New Deposition



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)

- 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

- Matthew Kenyon
- Marc Foote
- John Pearson
- Sabah Bux
- William Johnson
- Zachary Small
- Warren Holmes
- ..and many others

