Terahertz Intensity Mapper Focal Plane and Array Design

Reinier Janssen[1,2,], Lunjun (Simon) Liu[2], Rong Nie[3], Jianyang (Frank) Fu[3], I. Trumper[4],*
Steve Hailey-Dunsheath[2], Matt Bradford[1,2], Jeff Filippini[3], and the TIM consortium
1. Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109 USA
2. California Institute of Technology, Pasadena, CA 91125 USA
3. University of. Illinois at Urbana-Champaign, Urbana, IL 61801 USA
4. Intuitive Optical Design Lab LLC, Tucson, AZ 85705 USA
**reinier.m.janssen@jpl.nasa.gov*

Terahertz Intensity Mapper

TIM is a NASA Antarctic balloon with two main goals:
1. **(scientific) unravel the 3D structure of the dust-obscured star-forming universe.**
2. **(technological) demonstrate key technological developments for future (far-)infrared space missions.**

The Terahertz Intensity Mapper (TIM) [1] is a NASA balloon mission aimed for launch from Antarctica in 2024. Its goal is to further our understanding of the history of star formation through cosmic time by observing the 3D distribution of dust obscured star forming galaxies, which have been shown to host >50% of the star formation. TIM will perform a low-noise, broad bandwidth, large area survey to observe the bright and unextincted far-infrared emission lines of ionized carbon and nitrogen, both of which are diagnostics for the star formation, metallicity and other crucial galaxy properties. While only ~100 galaxies are expected to be detected directly, stacking and line intensity mapping methodologies will give a complete view of the star formation in the dust obscured universe at the peak of cosmic star formation.

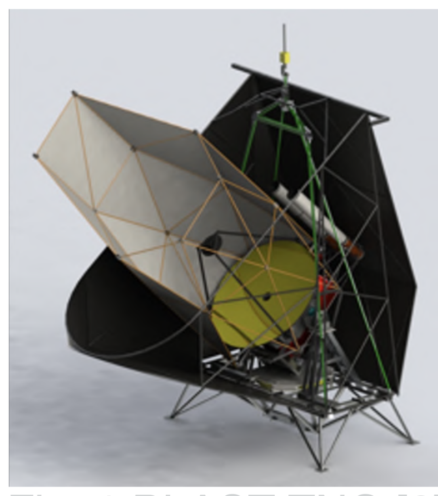

Fig. 1 BLAST-TNG [2] mechanical design, which is a baseline for the TIM gondola.

The TIM design is based upon the BLAST [2] heritage, while implementing a number of key technologies required for future (far-)infrared space mission, such as a low emissivity 2.0 m primary mirror and large-format arrays of high-sensitivity detectors. To perform its observations TIM has two long-slit (1 degree slit length) grating spectrometers covering the 240-317 µm (SW) and 317-420 µm (LW) wavelength bands at R~250, respectively. Each spectrometer has a ~4000 pixel array of hex-packed, horn-coupled, lumped-element Kinetic Inductance Detectors to observe the incoming radiation. Each full array will consist of four quadrants containing ~1000 pixels, which can be read out using either a ROACH2 or RFSoC based readout system. The detectors are cooled to 250 mK using a liquid helium pre-cooled He-10 sorption cooler.

TIM has two long-slit grating spectrometers together covering the 240 - 420 µm wavelengths at R~250.

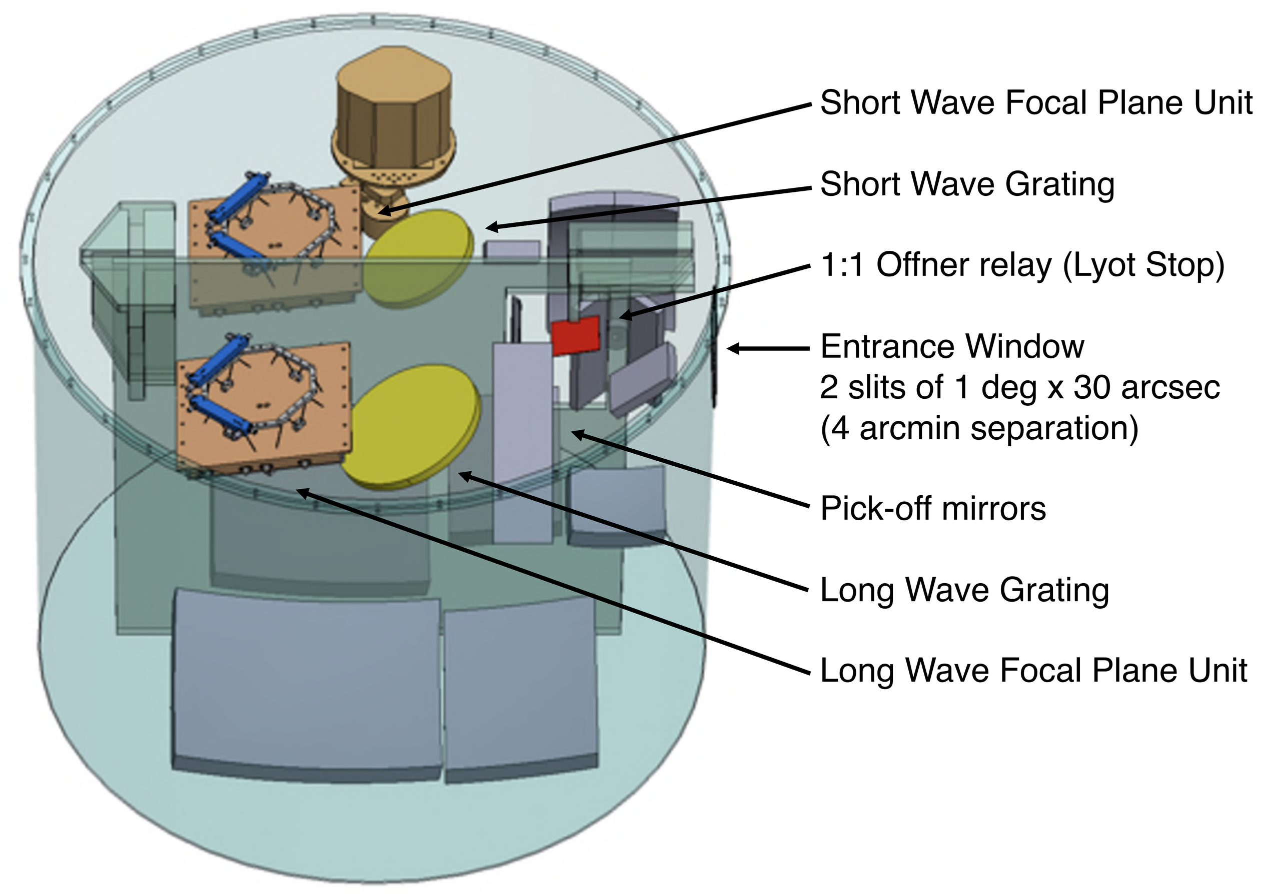

Fig. 2 Cold optics design, showing the two spectrometers and their components.

Kinetic Inductance Detectors

Each TIM pixel is a high-sensitivity Kinetic Inductance Detector with an absorption efficiency >80%.

The design of the Kinetic Inductance Detectors (KIDs) for the TIM arrays are based upon the lumped element design presented by Hailey-Dunsheath et al. [3]. Measurements of a small array have shown that these KIDs achieve a sensitivity of NEP = 4×10^{-18} W/Hz$^{0.5}$, which meets the TIM requirements.

The quasi-mesh absorber is based upon the MAKO design. HFSS simulations show that this design, once adjusted for the impedance of superconducting Al, achieves an absorption efficiency of >80% across the TIM band [4], or 20% without backshort, which was experimentally verified [3].

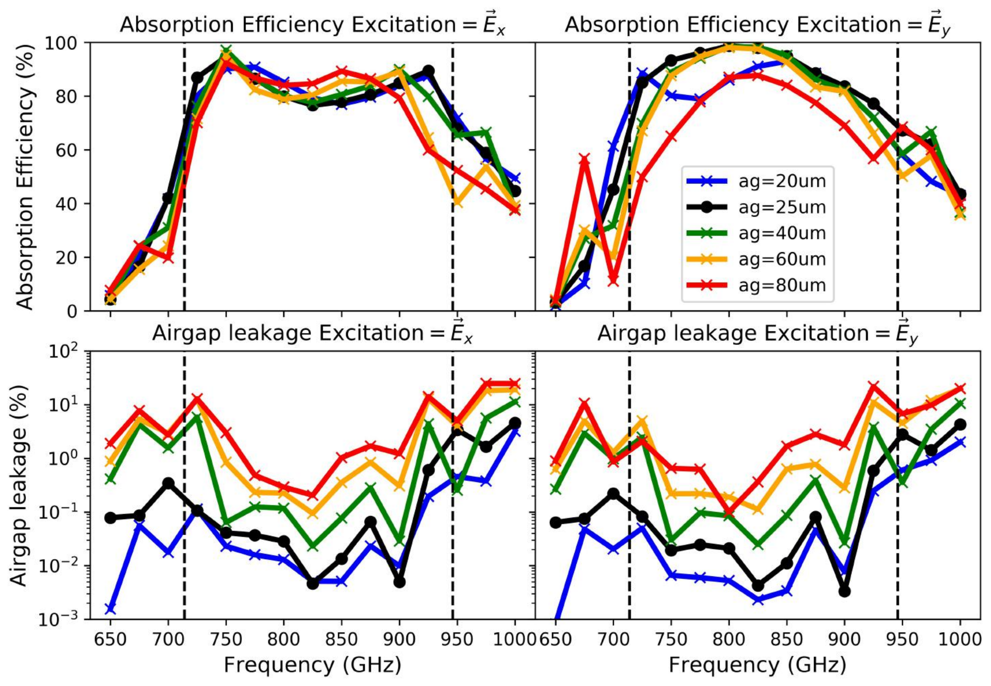

Fig. 3. HFSS simulated performance of the TIM quasi-mesh absorber [3]. The top panels show the absorption efficiency in the two polarization directions. The low frequency cut-off is the result of the horn waveguide cut-off. The bottom panels shows the power leaking through the airgap creating optical cross-talk. This increases significantly when the airgap between hornblock and absorber increases.

Mechanical Design

The mechanical design accurately maintains a 50 µm airgap between the absorber and the hornblock.

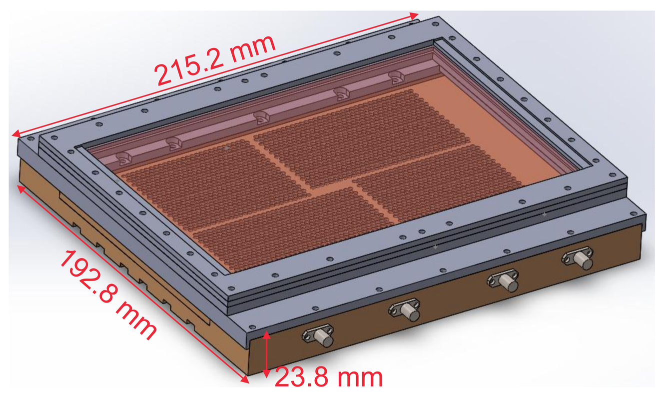

Fig. 4. Array housing, which from top to bottom contains:
1. the filter assembly
2. top lid, which covers the wire bond regions.
3. hornblock, which clearly shows the horns for each array quadrant.
4. the bottom box with the SMA connections.

To limit optical cross-talk, maintaining a 50 µm airgap is crucial. To achieve this, the detector array is clamped between 50 µm bosses that extend from the hornblock (about 1 boss per unit cell, see array design) and spring-loaded pogo-pins in the bottom box. The detector wafer extends beyond the hornblock to enable wirebonding between the top-side readout line and SMA connectors thereby avoiding through-wafer vias.

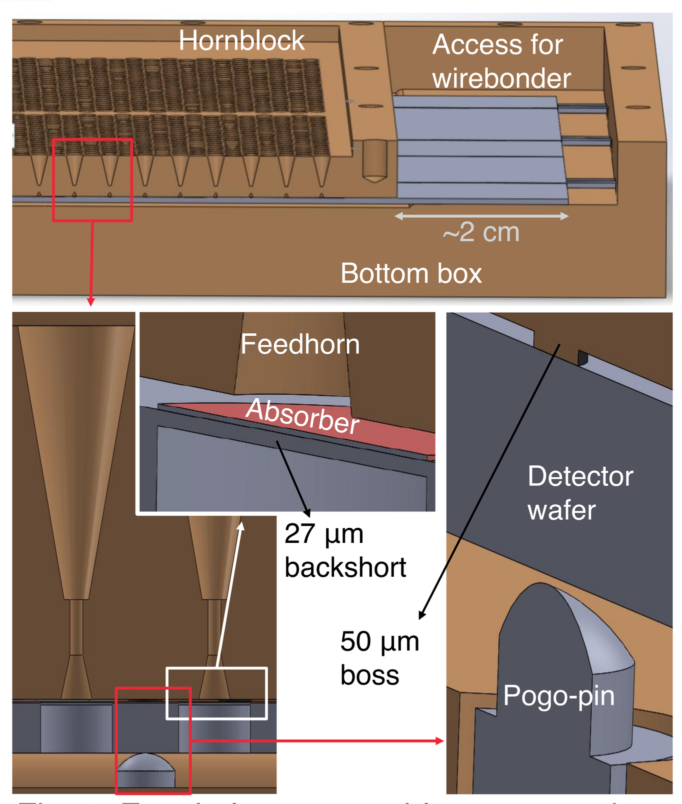

Fig. 5. Focal plane assembly cross-section.

Array Design

Each array consists of 4 detector quadrants of ~1000 pixels. Each quadrant is build up of 4x4 pixel unit cells and is designed for 0.5 – 1.0 GHz readout band.

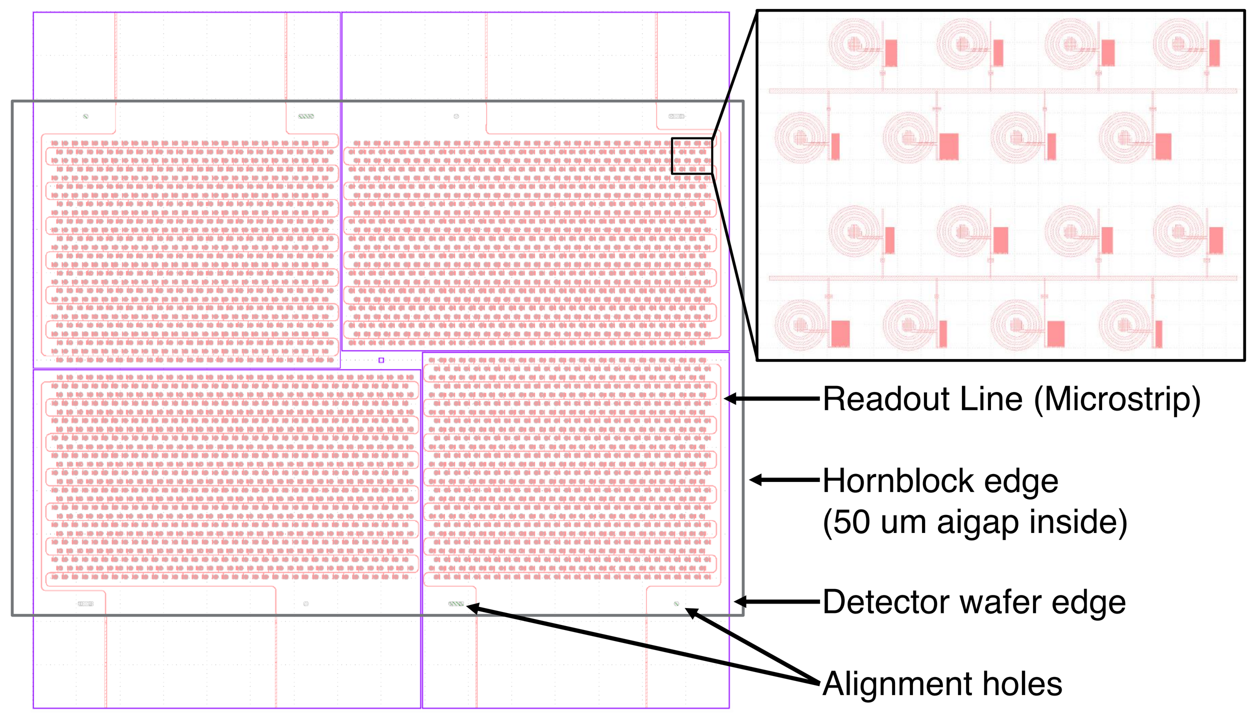

Fig. 6. Layout of the TIM detector wafers. The two unique quadrant designs, each of which is present twice in the full array, are build up from a sixteen pixel unit cell as shown in the zoom. Note that the unit cell resonators only have the (bottom) half of the lumped element capacitor. A second unit cell, containing the other (top) half, completes the capacitors and allows frequency variations through the adjustment of the tine lengths.

Each TIM focal plane unit contains four detector wafers (two unique designs) that together cover the 64 spectral by 51 spatial pixels in the full array. The single line of spatial pixels and 1 or 2 spectral pixels, which is not covered due to the gaps and presence of the readout lines, are offset to avoid loss of a full spectral or spatial channel. The resulting gap is used to connect the hornblock and bottom box to improve thermalization. Through-holes in the wafer provide in-plane alignment using guide pins in the hornblock.

Each array is patterned using two unit cells of 4 by 4 KIDs or components thereof. The first unit cell containing most of the KIDs is shown in Fig. 6 and contains all but the top half of the capacitors. The second unit cell contains these top halves. The resonance (readout) frequencies is varied by changing the capacitor heights, hence the total capacitance. This creates 16 banks within the 0.5 GHz readout bandwidth.

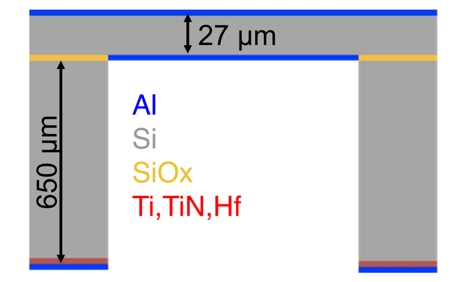

Fig. 7. Detector wafer cross section. Using SOI technology a 27 µm backshort is created. A low-T_c superconductor on the backside reduces the effects of cosmic rays.

Note that the original KID design presented by Hailey-Dunsheath et al. [3] couples to both a readout line and explicit ground wire. We rely upon the parasitic capacitances between the KIDs and the grounded hornblock to complete the circuit.

All KIDs on a single quadrant are capacitively connected to a single readout line. This readout line is a microstrip formed between the on-chip stripline and the hornblock, which acts a the dominant groundplane. The stripline widens as it enters the wirebond access. Simulations of this transition show a <0.5 dB reflection loss.

References

[1] Vieira et al., arXiv 2009.14340 [3] Hailey-Dunsheath et al., JLTP 2018
[2] Galitzki et al., arXiv 1409.7084 [4] Nie et al., *IEEE TTST 2020*

Acknowledgements

TIM is supported by NASA under grant 80NSSC19K1242, issued through the Science Mission Directorate. R.M.J. Janssen is supported by an appointment to the NASA Postdoctoral Program at the NASA Jet Propulsion Laboratory, administered by Universities Space Research Association under contract with NASA. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).