The SPICA-SAFARI Detector System: design concept and critical technologies

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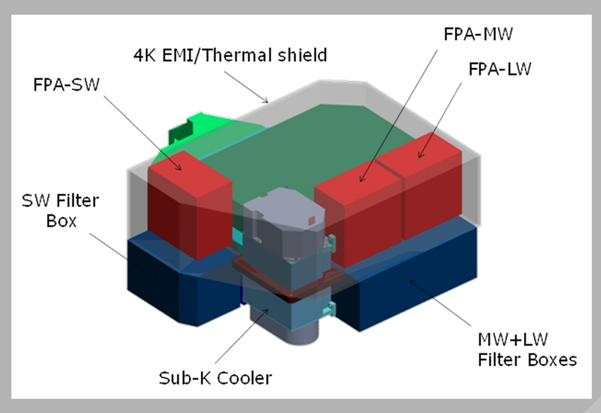
At the heart of the SAFARI instrument, three large-format Transition Edge Sensor (TES) arrays are used to realize background-limited imaging and spectroscopy between 34 and 210 μm. These detectors are read out using a Division Multplexing (FDM) scheme that allows 160 TES pixels to be operated with a single SQUID amplifier chain. Three Focal Plane Arrays are used to package and shield the detector arrays and their cold readout electronics within the instrument's Focal Plane Unit.

SAFARI, the SPICA Far-Infrared Instrument

A far-IR Fourier transform imaging spectrometer and photometer being developed by a European-led consortium for JAXA's SPICA mission.

The low thermal background of SPICA's 6 K telescope and low-NEP detector arrays enable background-limited (BLIP) spectroscopic imaging over 34-210 μm.

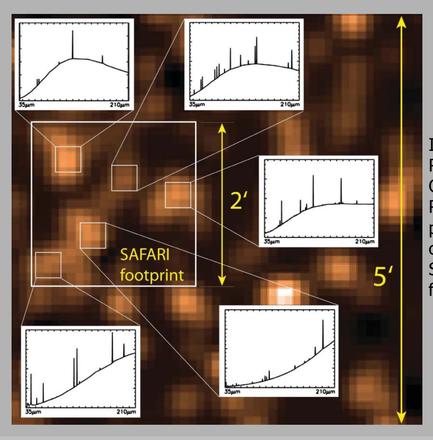
SAFARI's 3 key enabling technologies:
- Fourier transform spectrometer
- Detector system
- 50 mK instrument cooler



SAFARI Science Case

Spectroscopic imaging: ~ 10x higher point-source sensitivity vs. PACS and 10^4x higher speed for blind, broad-band spectroscopic mapping. Major science cases include:
- Extragalactic point-source spectroscopy: map 1°x1° to a few 10^{-19} W/m², yielding ~ 5 sources per 2'x2' SAFARI FoV
- Characterize gas and solid state features in a large sample of protoplanetary disks

Photometric imaging: ~ 100x higher sensitivity + shorter wavelength vs. PACS yields larger and deeper maps.



Images: Rosenbloom, Oliver, Smith, Raab private communication SPIRE map from HERMES

Large-Format Waveguide-Coupled TES Arrays for Low-Background Observations

SAFARI Detector Requirements

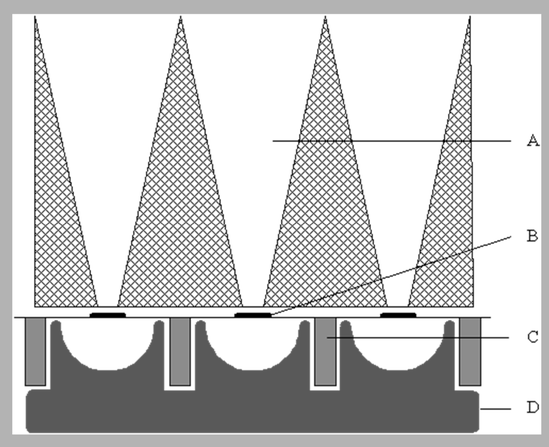
SAFARI's goals of background-limited sensitivity in both photometry and as a fast-scan imaging FTS spectrometer result in a unique and sometimes conflicting set of requirements for the instrument's detector arrays. The following tables summarize key requirements for the 3 detector bands that cover the instrument's 34-210 μm signal band.

Wavelength Band	LW	MW	SW
Wavelength (μm)	210-110	110-60	60-34
Optical loading, extragalactic sky background (aW)	68	34	74
Detector NEP goal x10^{-19} W/√Hz	2.0	2.0	2.8
Optical loading for a 1 Jy point source (fW)	5	8	24
FTS audio band (Hz)	3.2-6.2	6.2-11.3	11.3-20
Min. detector speed (Hz)	12.5	22.7	40
Goal detector speed (Hz)	≥ 31	≥ 57	100
Pixel size (mm)	1.6	1.03	0.81
Incident optical beam	F/16.5	F/20	F/20
Focal plane sampling (pitch = 1.22·F·λ/X)	2	2	√2

Beyond these performance requirements, the detector system design is heavily constrained by the limited capacity of SPICA's 1.7 and 4.5 K cryo-coolers and SAFARI's 50 mK ADR, and by the EMC environment of the SPICA spacecraft, the predicted high vibration loads during launch, and repeated deep thermal cycling during the detector and instrument test programs.

SAFARI Detector Optical Coupling Concept

The SAFARI detectors employ SiN-suspended TES thermometers to realize SAFARI's low goal NEPs. The thermometer is suspended together with an impedance-matched optical absorber (B), with a multi-mode waveguide horn (A) concentrating incident optical power onto the absorber. This combination offers efficient dual-polarization coupling over octave bandwidths while keeping the absorber small (w_{abs} ~ $2\cdot\lambda_c$), to allow high aspect-ratio SiN legs to be realized for SAFARI's small detector pixels.



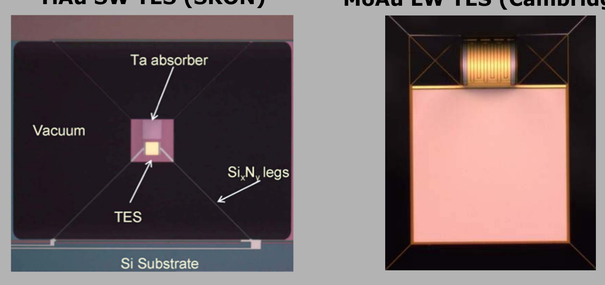
Ongoing analysis and tests are optimizing this geometry, including exploring how the horn's coupling to the instrument optics scales with its optical throughput, different backshort geometries (D), and the dependence of optical coupling and detector NEP on the size of the optical absorber.

Large-Format Low-NEP TES Detector Arrays

Low-NEP TES detectors are realized by suspending a TES thermometer and Ta absorber on high-aspect ratio SiN legs. Feasible SiN leg dimensions (0.4-1 mm x 1-2 μm x 0.2-0.3 μm) offer sufficient thermal isolation to approach the instrument's goal NEP of 2x10^{-19} W/√Hz for T_c = 100 mK and a T_{bath} = 60 mK. NEP ~ 4x10^{-19} W/√Hz has already been demonstrated using both MoAu and TiAu TES's, with development continuing both to optimize sensitivity and to scale up to 2000-pixel arrays for the SW band.

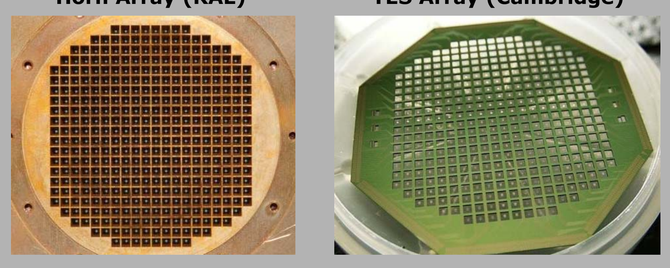
SiN-Suspended Single-Pixel TES Devices

TiAu SW TES (SRON) — MoAu LW TES (Cambridge)



384-Pixel Long-Wavelength Detector Array

Horn Array (RAL) — TES Array (Cambridge)



Detector Readout Electronics and Focal Plane Arrays

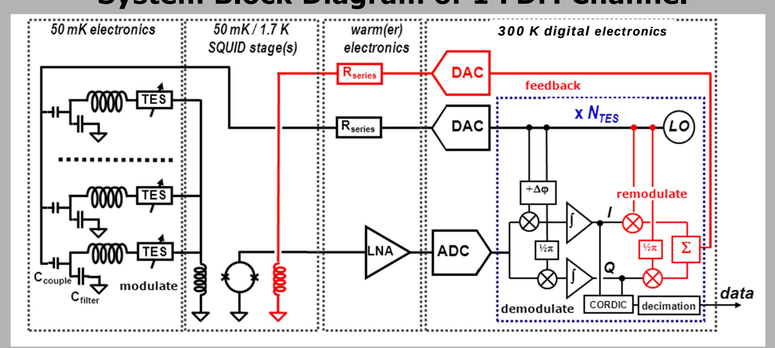
Frequency Division Multiplexed SQUID Readout with Baseband Feedback

SQUID amplifier chains are used to read out the instrument's low-impedance TES detectors, with 3 amplifier stages overcoming losses in the spacecraft's long cable harness (SQUID amplifers at 50 mK and 1.7 K, followed by a SiGe amplifier at 136 K).

Frequency Division Multiplexing allows 160 TES pixels to be read out using a single SQUID amplifier chain, thereby minimizing the heat-load and complexity of the spacecraft's cryo-harness.

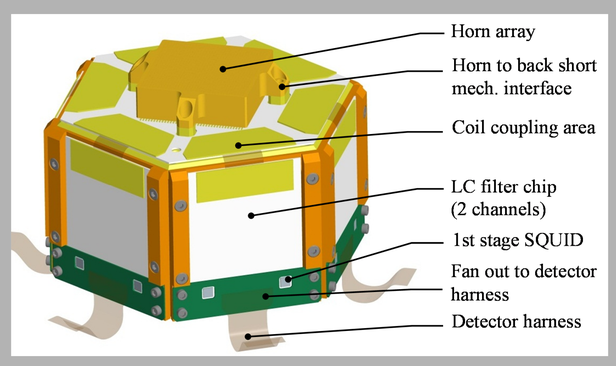
With 160 TES signals read out simultaneously, the otherwise excessive dynamic range requirement on the amplifier chain is substantially reduced by applying feedback at the input to the SQUID. This feedback signal is generated at low-frequency (baseband) in order to allow the feedback loop to be closed even when using relatively long cables.

System Block Diagram of 1 FDM Channel



The 50 mK Electronics Assembly

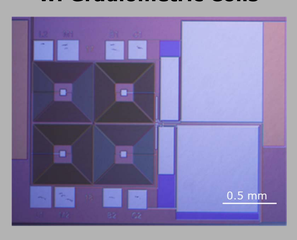
The TES array and its 50 mK readout electronics are packaged with the TES array on the top surface of a hexagonal box and 2-channel LC filter chips on each side panel, together with the 1st-stage SQUIDs.



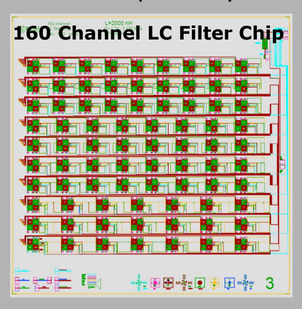
Superconducting LC Filters

A key to the readout concept are the LC filters that allow 160 signals to be multiplexed between 1-3 MHz combining accurate resonance frequency control, very-low parasitic resistance, and a compact layout.

2-Element LC Filter Unit Cell w. Gradiometric Coils

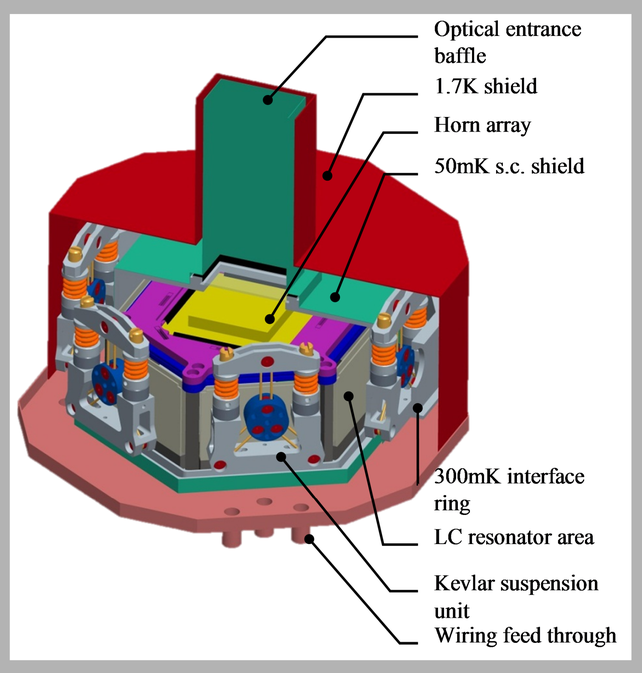


160 Channel LC Filter Chip



Focal Plane Array

The detectors and their cold readout electronics will be integrated inside 3 Focal Plane Arrays (1 per detector array), which provide three key functions:
- mounting, heat-sinking, and interconnection of the detectors and their cold readout electronics;
- thermal isolation of the 50 mK stage from the 1.7 K environment; and
- shielding from quasi-static magnetic fields, high-frequency E-fields (EMI), and straylight



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