The SPICA-SAFARI Detector System: TES Detector Arrays with Frequency Division Multiplexed SQUID Readout

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***Abstract*—The SAFARI instrument is a far-infrared imaging Fourier transform spectrometer for JAXA's SPICA mission. Taking advantage of the low emission of SPICA's 5 K telescope, SAFARI will provide background-limited, Nyquist-sampled spectroscopic imaging of a 2'x2' field-of-view over 34-210 µm, revolutionizing far-infrared astronomy.**

SAFARI's aggressive science goals drive the development of a unique detector system combining large-format Transition Edge Sensor arrays and frequency division multiplexed SQUID readout with a high 160x multiplexing factor. The detectors and their cold readout electronics are packaged into 3 focal plane arrays that will be integrated into SAFARI's focal plane unit.

This paper presents the preliminary design concept for the SAFARI detector system.

***Index Terms*— Astrophysics, Bolometers, Frequency division multiplexing, Superconducting devices, System-level design**

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I. Introduction

Far-infrared (far-IR) observations are critical to answering some of the most fundamental questions in astronomy:

- What is the universe made of and how does it evolve?
- Are we alone in the universe?
- How do galaxies, stars and planets form and evolve?

However, far-IR observations also face major challenges. To start with, the atmosphere is virtually opaque in the far-IR, requiring space or stratospheric observatories. Developing these observatories is further complicated by two factors: 1) diffraction requires large telescopes at long wavelengths; and 2) thermal emission from all but deep cryogenic telescopes is orders of magnitude brighter than the far-IR signals of interest.

To-date, space observatories have addressed one or the other of these challenges, but not both. Small (< 1 m) cryogenic telescopes like ISO [1] and Spitzer [2] provided high sensitivities but limited spatial resolution. In contrast, while ESA's Herschel Space Observatory is revolutionizing far-IR astronomy with its 3.5-m telescope [3], its passively cooled 80-K telescope's thermal emission is ~ 10^6 times brighter than the far-IR sky background.

The Japanese Space Agency's proposed SPICA mission will be the first to address both of these challenges by actively cooling a large (3.25-m) telescope to below 6 K to enable sky-background-limited observations at 4-210 µm [4]. In doing so, SPICA offers the potential for orders of magnitude higher sensitivity than is achieved in Herschel.

When considering SPICA's potential sensitivity improvements versus the Herschel photometers, it is noted that SPIRE [5,6] and PACS' 160 µm channel [7] are confusion-limited – deeper integrations will not detect weaker sources because they will not be resolved by the telescope. However, because PACS' 110 and 70 µm channels are not confusion-limited, SPICA's higher sensitivity will increase mapping speeds and enable larger-area surveys. This being said, the real far-IR niche for SPICA is in spectroscopy, as the PACS spectrometer is sensitivity-limited – while it benefits from Herschel's large telescope, it is limited to observations of relatively few and strong sources, and to narrow-band spectroscopic mapping. Thus, while Herschel's photometric maps reveal not-before-seen structure in the interstellar

TABLE I
KEY SAFARI PERFORMANCE REQUIREMENTS

Characteristic	Requirement
Wavelength range	34-210 μm
Instantaneous field of view	2'x2'
Angular resolution	Diffraction-limited above 40 μm
Spatial sampling	Per wavelength band, Nyquist-sampled at band-center [a]
Focal plane fill factor	80% (goal)
Spectral resolution	
- photometric imaging	R ~ 2-3
- low-resolution mode	R ~ 100 @ 100 μm
- medium-resolution mode	R ~ 2000 @ 100μm
Sensitivity	
- photometric	< 50μJy (5σ-1 hr) [a]
- spectral (med. res. mode)	< few x10^{-19} W/m^2 (5σ-1 hr) [a]
Maximum signal level	0.5Jy (10 Jy [b] for 34-57μm)

[a] This required spatial sampling may be achieved post-processing (i.e. with a dither mode).
[b] Instrument sensitivity may be degraded (eg. by the use of neutral density filters) for input signal levels greater than 0.5 Jy.

TABLE II
KEY SAFARI DETECTOR SYSTEM PERFORMANCE REQUIREMENTS

Characteristic	Requirement
Wavelength bands	34-60, 60-110, 110-210 μm [a]
Number of pixels	61x61, 34x34, 18x18 [a,b]
Sensitivity	
- goal	2 x 10^{-19} W/Hz$^{1/2}$ [b]
- requirement	4.5, 3.6, 3.5 x 10^{-19} W/Hz$^{1/2}$ [a,b]
Focal plane fill factor	80% (goal)
Coupling efficiency x fill factor	64% (goal) 56% (requirement)
Minimum system response speed	40, 28, 13 Hz [a]
Saturation power	~ 4 fW [a,b]

[a] Where 3 values are given, these apply to the system's short, medium, and long wavelength bands, in that order.
[b] The NEP goals and requirements assume a Nyquist-sampled focal plane. For filled arrays with less-than-Nyquist sampling, NEP figures scale with pixel dimension and saturation powers with pixel area.

medium in our galaxy and resolve large numbers of extragalactic sources, the spectrometers only touch the tip of this iceberg. Being able to extend this mapping capability to spectroscopy will enable blind, wide-field spectroscopic surveys to characterize the chemistry and dynamics of many sources. This is the next far-IR revolution that SPICA will enable, and it is this goal that drives the design of SAFARI – the SPICA Far-Infrared Instrument.

This paper summarizes the preliminary design concept for the detector system at the heart of SAFARI.

II. THE SAFARI INSTRUMENT CONCEPT

SAFARI is a far-IR imaging Fourier transform spectrometer (FTS) being developed by a consortium of European and Canadian institutes. An FTS concept similar to SPIRE [8] has been selected based on achievable detector sensitivities – an FTS in SPICA will reach background-limited sensitivities for detector Noise Equivalent Powers (NEPs) of ~ 2x10^{-19} W/Hz$^{1/2}$, which should be achievable within the available time (for detectors operating at 50 mK base temperature).

Table I summarizes key SAFARI instrument performance requirements. When combined with operational and calibration aspects of a fast-scan FTS instrument, these result in a unique and challenging set of detector requirements, as summarized in Table II. Beyond these performance requirements, the system is further defined by extremely tight constraints from the SAFARI instrument and SPICA spacecraft. SPICA's thermal budget is a particular detector system design driver, with ~ 3 and 0.5 mW of dissipation allowed at 4.5 and 1.7 K, and only ~ 2.5 mW of passive heat-load at 4.5 K from the detector system's cryo-harness.

III. THE SAFARI DETECTOR SYSTEM

The SAFARI detector system includes three large-format detector arrays, detector control and readout electronics (including both room-temperature and cryogenic elements), and infrastructure that is required to package the ultra-sensitive electronics in SAFARI's Focal Plane Unit. These elements are divided over the following main units:

- 3 "Focal Plane Arrays" (FPAs), each containing one detector array, its multiplexed SQUID amplifier readout electronics, and shielding and filtering needed to operate these components within the SPICA environment;
- a 136 K Low-Noise Amplifier (LNA) that amplifies the weak outputs from the cryogenic electronics; and
- the Detector Control Unit (DCU) containing room-temperature control and readout electronics.

The development of this system is divided into three main focus areas that are addressed in the sections that follow:

- the detector arrays;
- multiplexed detector readout electronics; and
- the packaging and shielding for the detector arrays and their cold readout electronics in the focal plane arrays.

IV. DETECTOR ARRAY CONCEPT

The SAFARI detectors combine superconducting Transition Edge Sensor (TES) thermometers with horn-coupled absorbers on SiN suspension structures to realize SAFARI's unique requirements for large-format arrays of small, fast detectors with low noise, high optical coupling efficiency, and moderate saturation power [9].

SiN-suspended TES detectors are used on many ground-based sub-mm and mm-wave telescopes [10-13]. However, SPICA's cryogenic telescope reduces the detectors' background load by orders of magnitude. This requires a revolutionary step in detector sensitivity, moving from typical NEPs of a few x 10^{-17} W/Hz$^{1/2}$ for ground-based observatories to a goal of 2x10^{-19} W/Hz$^{1/2}$ for SAFARI. Achieving very-low detector NEP's requires extremely low-conductivity thermal suspensions, which can be realized with high aspect-ratio SiN membrane structures. For the nominal 850 μm size of SAFARI's mid-wavelength band pixels, the classical diagonal

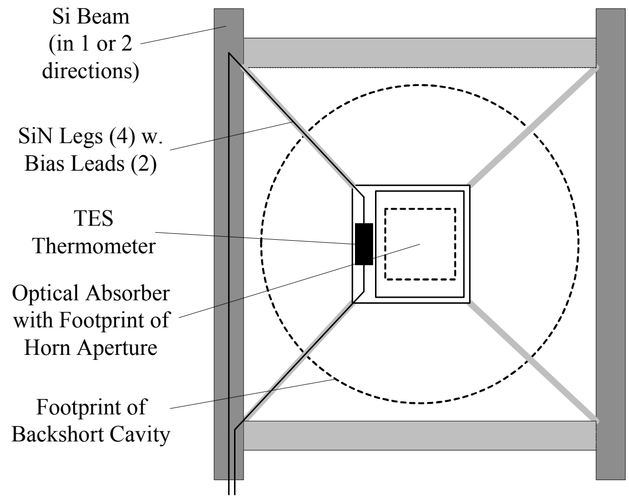

Figure 1 - Schematic of a SiN-suspended, absorber-coupled TES bolometer pixel in classical "diagonal-leg" geometry. Low NEP devices require very low thermal conductivity of the SiN suspension. See Ref. [14] for alternative low-conductivity geometries.

leg suspension geometry (see Fig. 1) allows 450 µm long SiN legs, which must be ~ 1 µm wide and 250 nm thick to reach the desired low conductivity.

The second critical requirement for the detector design is the optical absorption efficiency. The current design baseline combines an impedance-matched absorber in a non-resonant cavity with a multi-mode pyramidal horn that concentrates light into the cavity. This non-resonant design should offer high coupling efficiency over the nearly octave-wide bands in which the SAFARI detectors must operate.

TES detector arrays for SAFARI are being developed at SRON [14] and Cambridge [15], with both groups typically measuring detector sensitivities of NEP_d ~ 4-5x10^{-19} W/Hz$^{1/2}$ for single pixels and small arrays of detectors with T_c ~ 100 mK operating at ~ 50 mK. This is within a factor of ~ 2 of SAFARI's goal sensitivities. Ref. 16 presents preliminary measurements of the optical coupling efficiency of these detectors. Coupling efficiencies of ~ 50% are obtained, but with the horn-absorber-cavity geometry still to be optimized.

V. Multiplexed Detector Readout

A SQUID amplifier chain is used to read-out the weak analog signals from SAFARI's low-impedance TES detectors, without degrading the detector noise. The gain that is required to bridge the long cables between the instrument's focal plane unit and warm electronics will be realized using two SQUID amplifier stages inside the focal plane arrays [17], followed by a semi-conductor amplifier in the cable harness [18].

In order to minimize the complexity and heat-loads in the cryostat's cable harness, multiplexing is used to connect many TES detectors to a single SQUID amplifier. For SAFARI, a frequency division multiplexing [19] concept is used in which each detector within a readout channel is biased by a different AC carrier frequency. After modulation by the optical signals, the carriers are added to create a comb of amplitude-modulated signals that is coupled to a single SQUID amplifier.

The multiplexing ratio that can be realized by this scheme is limited by the dynamic range of the SQUID amplifier. However, this limitation can be overcome by applying negative feedback to suppress the signals at the input of the SQUID. Baseband feedback ensures a stable feedback loop despite the long cables between the warm and cold electronics. Based on past developments for IXO [20], an FDM system with a multiplexing factor of 160 is baselined for SAFARI.

VI. The Focal Plane Arrays

The third major development item for the SAFARI detector system is the focal plane arrays that package and shield the ultra-sensitive detectors and cold electronics for each of the three wavelength bands. Critical elements are the mounting, shielding, and thermal isolation of the 50 mK electronics, plus the high-density electrical interconnects that couple the 1000's of detector pixels to the LC filter and SQUID amplifier chips. Moreover, this functionality must be realized within the tight space and mass constraints of a flight instrument.

The FPA must protect the detectors and SQUID amplifiers from DC magnetic fields; high-frequency radiated E-fields (eg. from the downlink antennas); and straylight from the surrounding 4.5 K radiation environment. The requirements on this shielding are set by the ~ 1 aW noise levels and ~ 4 fW saturation powers of the TES detectors.

The detectors and first-stage SQUID amplifiers (at 50 mK) are isolated from the 1.7 K environment of the instrument's cold optical box by a two-layer Kevlar suspension system that minimizes the load on the SAFARI cooler (which provides 1 µW of heat-lift at 50 mK), while also surviving launch.

Fig. 2 shows a block diagram of the preliminary design concept for the SAFARI focal plane array.

VII. Conclusion

The SAFARI detector system combines large-format TES arrays with frequency division multiplexed SQUID readout to realize low-noise operation of up to 6000 pixels in three wavelength bands covering 34-210 µm. This system addresses the challenging performance requirements of a background-limited FTS spectrometer behind a cryogenic telescope, within SPICA's tight resource constraints.

Absorber-coupled TES thermometers on SiN membrane suspensions already offer sensitivities within a factor of 2 of SAFARI's goal sensitivity of NEP_elec = 2x10^{-19} W/Hz$^{1/2}$. Ongoing work aims to verify the detectors' optical coupling and demonstrate the design's scalability to large arrays.

Readout of 1000's of TES detectors within SPICA's interface constraints is a major challenge. A frequency division multiplexing system with baseband feedback is being developed for SAFARI to enable operation of 160 detectors per SQUID amplifier chain. The next step in this development is to integrate FDM readout with low-*NEP* TES bolometers in

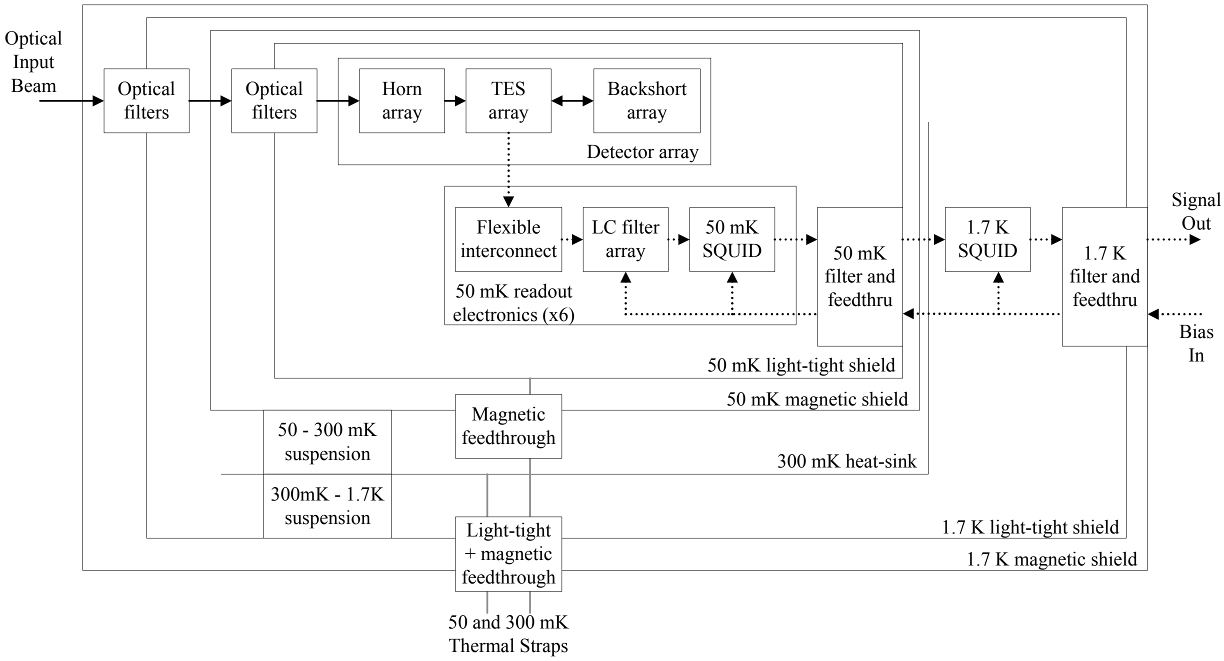

Figure 2 - SAFARI Focal Plane Array block diagram.

a 64-pixel experiment that confirms the system's scalability.

The third major challenge in this system is to package and shield the sensitive detectors and cold electronics within Focal Plane Arrays that isolate the 50 mK electronics from the 1.7 and 4.5 K environments of the SAFARI instrument and SPICA spacecraft. A preliminary concept has been developed and the next step is to demonstrate critical technologies such as the shielding and filtering needed to operate extremely low-noise detectors within a spacecraft environment.

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