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SAFARI: INSTRUMENT DESIGN OF THE FAR-INFRARED IMAGING SPECTROMETER FOR SPICA

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ABSTRACT

The next great leap forward in space-based far-infrared astronomy will be made by the Japanese-led SPICA mission, which is anticipated to be launched late 2020's as the next large astrophysics mission of JAXA, in partnership with ESA and with key European contributions. Filling in the gap between JWST and ALMA, the SPICA mission will study the evolution of galaxies, stars and planetary systems. SPICA will utilize a deeply cooled 3m-class telescope, provided by European industry, to realize zodiacal background limited performance, high spatial resolution and large collecting area.

Making full advantage of the deeply cooled telescope (<6K), the SAFARI instrument on SPICA is a highly sensitive wide-field imaging photometer and spectrometer operating in the 34-210 μm wavelength range. Utilizing Nyquist-sampled focal-plane arrays of very sensitive Transition Edge Sensors (TES), SAFARI will offer a photometric imaging ($R \approx 2$), and a low ($R = 100$) and medium resolution ($R = 2000$ at 100 μm) imaging spectroscopy mode in three photometric bands within a 2'x2' instantaneous FoV by means of a cryogenic Mach-Zehnder Fourier Transform Spectrometer.

In this paper we will provide an overview of the SAFARI instrument design and system architecture. We will describe the reference design of the SAFARI focal- plane unit, the implementation of the various optical instrument functions designed around the central large-stroke FTS system, the photometric band definition and out-of-band filtering by quasi-optical elements, the control of straylight, diffraction and thermal emission in the long-wavelength limit, and how we interface to the large-format FPA arrays at one end and the SPICA telescope assembly at the other end.

We will briefly discuss the key performance drivers with special emphasis on the optical techniques adopted to overcome issues related to very low background operation of SAFARI. A summary and discussion of the expected instrument performance and an overview of the astronomical capabilities finally conclude the paper.

I. INTRODUCTION

The SPace Infrared telescope for Cosmology and Astrophysics (SPICA) is a mission led by JAXA with significant European contributions [1]. SPICA is the logical next step in a range of space telescopes addressing the infrared Universe. Previous missions like IRAS, ISO, Spitzer and AKARI used relatively small but deeply cooled telescopes based on bath cryostat architectures. The largest space telescope ever launched into space was Herschel, which had a relatively warm telescope at 80K. In the nearby future JWST will employ a very large telescope, which is passively cooled to about 45K. In order to be truly background limited in the far-infrared wavelength range between JWST and Herschel (20-210 μm) it is however required to have a deeply cooled telescope. Making use of mechanical cryocoolers SPICA will combine a deeply cooled telescope (about 6K) with a large aperture like Herschel (3.2m). Filling the gap between Herschel, ALMA and JWST this observatory will feature a cryogenic 3m class telescope opening up the scientific window of zodiacal background limited observations in the far-infrared [1].

Making full advantage of the deeply cooled telescope (< 6K) the Safari instrument on SPICA is a highly sensitive wide-field imaging photometer and spectrometer operating in the 34-210 μm wavelength range [2]. Safari will address the following three core science themes:

- Galaxy formation and evolution over cosmic time
- Lifecycle of gas and dust within the Milky Way and the local universe
- Tracing gas, ice and dust evolution in (proto)planetary systems

Safari will study large populations of weak points sources. It therefore requires the best possible "mapping" speed for a given detector performance. Utilizing Nyquist-sampled filled arrays of very sensitive Transition Edge Sensors (TES), Safari offers a photometric imaging ($R \approx 2$), and a low ($R = 100$) and medium resolution ($R = 2000$ at 100 μm) imaging spectroscopy mode in three photometric bands within a 2'x2' instantaneous field of view [2].

Like the SPIRE instrument on Herschel [3-4], Safari utilizes an imaging Fourier Transform Spectrometer (FTS). An imaging FTS architecture most efficiently addresses the scientific need for large-area, wide-band spectroscopic mapping [5], enabling wide-field spectroscopic surveys to characterize the chemistry and dynamics of many sources. The combination of very sensitive large-format filled TES arrays, fully sampling a large instantaneous FoV, and its high spectral resolving power, makes Safari an extremely powerful spectroscopic imaging instrument characterizing for example the spatial and spectral energy distribution of very faint point sources just above the natural background. An overview of the key scientific themes to be addressed by Safari and the instrument design is given in [2, 6-8].

II. INSTRUMENT DESIGN

A. System concept and architecture

Based on a realistic estimate of the achievable sensitivity of a far-infrared TES detector operated in a large-format array, we identified that the core science case of Safari was best addressed by an imaging FTS system architecture [5]. This analysis assumed a 3.2m telescope cooled to 6K and a detector NEP of $2x10^{-19}$ W/√Hz. The science case furthermore requires:

- Low (R = 100) and medium (R = 2000 at 100 µm) resolution spectroscopy
- Three-band photometry covering the 34-210 µm wavelength range
- Nyquist sampled imaging arrays spanning an instantaneous FoV of 2'x2'
- A limiting line sensitivity of a few times 10^{-19} W/m^2 and continuum sensitivity of 20 µJy (5σ-1h)

Figure 1 shows the system block diagram of the Safari instrument from an optical perspective.

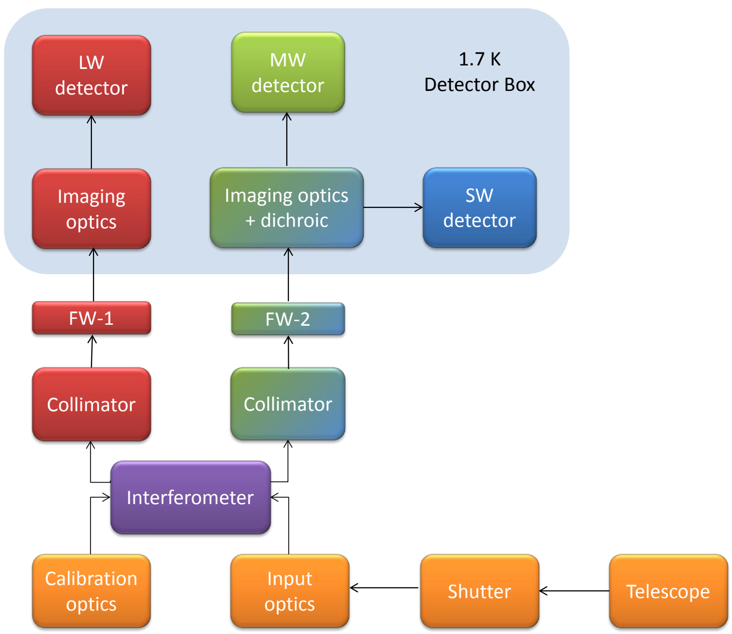


Fig. 1. System block diagram of the Safari instrument.

Central to the instrument is an interferometer with dual input and output ports. The interferometer is based on a Mach-Zehnder configuration. The signal from the telescope enters one of the input ports via an instrument shutter and some input optics. In the second port a calibration source is placed, than can also be switched on and off by an integrated shutter. The output port of the interferometer couples into two separate paths. One path is dedicated for long-wave operation, and contains the LW detector band. The other path is split into the MW and SW bands by means of a dichroic. At an intermediate pupil plane behind the interferometer a filterwheel is positioned. This filterwheel is equipped with a neutral density filter to be able to observe bright sources. There are also free positions for other optional components, such as a dispersive element (grism), a Fabry-Perot filter, or a phase mask. The detectors are all placed in a cold box, cooled to 1.7K to reduce thermal background radiation and out-of-field straylight.

B. Mechanisms and other sub-units

The functionality of the instrument requires a variety of cryogenic mechanisms. Given the limited thermal budget available to the instrument, these mechanisms have to satisfy very stringent requirements. Each mechanism has to work at cryogenic conditions with active dissipation less than 1 mW. Furthermore the volume is very limited. We successfully developed design concepts satisfying these challenging requirements for the following mechanisms:

- Instrument shutter
- Filter Wheel (FW) mechanism
- FTS scan mechanism

Figure 2 shows the design concepts of the instrument shutter and FW respectively. The instrument shutter is based on a push-pull electromagnet, that only requires a current pulse to change from one to another stable position without static dissipation. The FW mechanism is based on a brushless DC motor design. The limiting factor is the friction in the bearing. The FTS mechanism is discussed below.

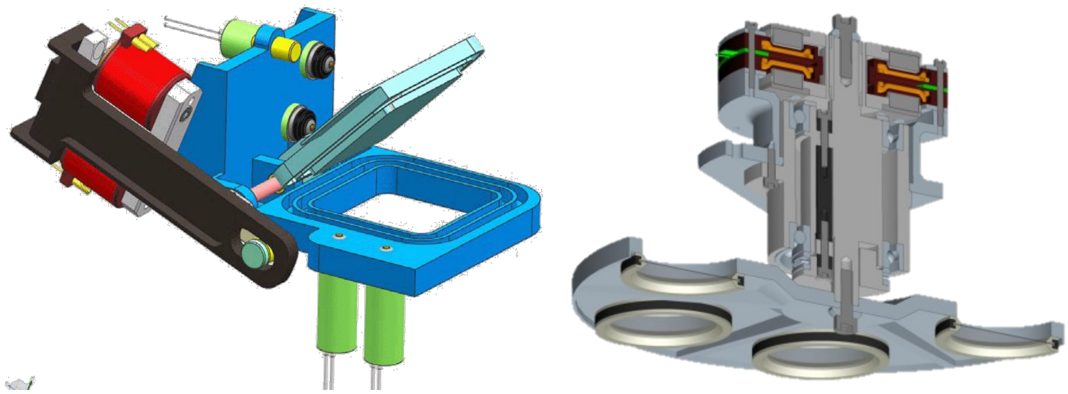
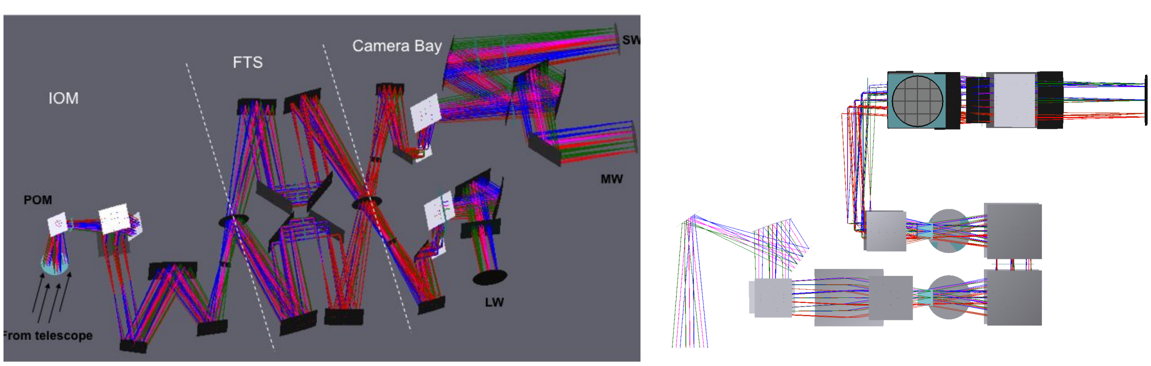


Fig. 2. Shutter mechanism concept (left) and Filter Wheel mechanism concept (right) for Safari.

In addition to the mechanisms, Safari also requires an internal calibration source providing a flat-field source for photometric calibration, a spectral line source and a flasher for the calibration of the temporal response of the detector. Finally there is a 50 mK cryocooler, based on an ADR cooler, cooling the detectors to 50 mK [2,6].

C. Instrument reference design

Figure 3 shows the optical layout corresponding with the block diagram shown in Fig. 1. Not shown is the calibration source. On the left the light of the telescope enters the system and is picked-off by mirror POM. After some input optics (IOM) the light is split by a broad-band beamsplitter. Shown as an in-plane configuration, the FTS can be recognized in the middle. It is based on a pair of rooftop mirrors, which are mounted on a scanning mechanism. This optical arrangement provides a folding factor of four, meaning that the OPD equals 4 times the displacement of the rooftop mirrors. At the output (second dotted line) the light is recombined and split into the two output ports. The lower port couples into the LW channel, where the combined MW/SW band is shown on the top. A dichroic mirror splits the light into a separate MW and SW detector band. In order to save volume the optical arrangement was folded into a three-layer high optical system, as illustrated at the right hand of Fig. 3.



Fig, 3. Optical layout of the instrument design.

Figure 4 shows the reference design of Safari. It includes the mechanical design, the optical design, integration of all mechanisms and other units, and shows how the instrument operates as a whole. The instrument is shown from the bottom, the light from the telescope enters the system from above. In the bottom layer the input optics can be recognized and the central beamsplitter. At the output of the FTS optics (middle layer), after the beam combiner, there are intermediate field positions. At those locations we designed out-of-field straylight baffles for the detectors. The three blue boxes are the detector arrays, the unit in the corner is the cryocooler, whereas at the right hand side the calibration source is shown. At the bottom the two filterwheels operating in the output ports of the interferometer can be seen.

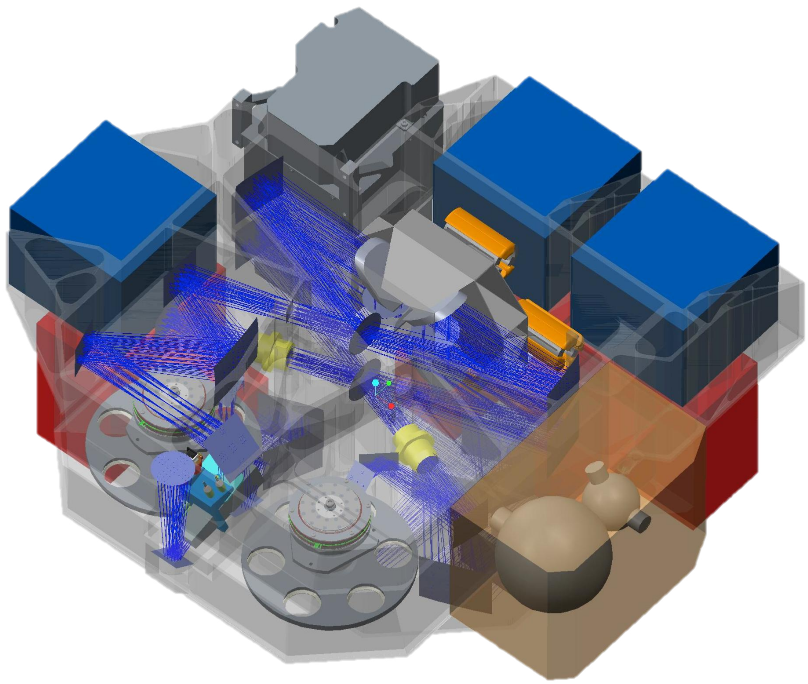


Fig. 4. Safari reference design.

Figure 5 finally shows how we plan to reject out-of-band straylight. Since the detectors are sensitive to straylight levels as low as 1 aW (10^{-18} W), we divided the instrument in closed compartment. Each compartment is sealed by quasi-optical filters blocking out-of-band straylight [12]. The whole sequence defines the spectral bandpass of each detector band. Rejected out-of-band straylight stays in the light-tight compartment preceding the optical filter element. At the right hand side of Figure 5 we show the results of thermal analysis. By careful thermal and mechanical design we make sure that the self-emission of the structure stays low, does not show hot-spots, and the compartments are light-tight.

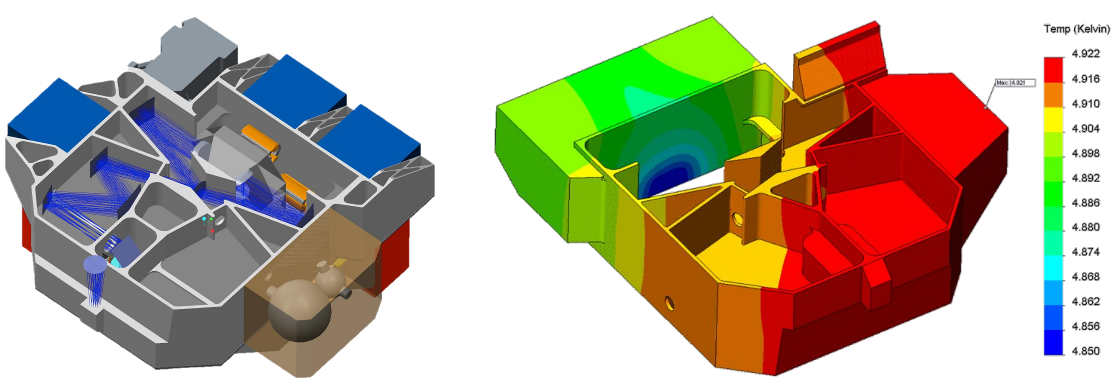


Fig. 5. Design of light-tight compartments and result of thermal analysis.

D. FTS system

The FTS system is defined as the sub-chain of the Safari instrument between beam-splitter and –combiner, including harness and control electronics. A functional block diagram of the FTS system is shown in Fig. 6. The FTS optics includes parabolic and rooftop mirrors as well as the quasi-optical beam-splitter and –combiner. The FTS structure comprises the whole mechanical compartment providing a light-tight environment, opto-mechanical interfaces to the mirrors, beam-combiner and –splitter, and the scan mechanism. The FTS mechanical compartment is an integral part of the main monolithic structure of the FPU providing the required stiffness and ensuring the opto-mechanical stability and integrity of the interferometer. The FTS scan module consists of a FTS mechanism, its harness (electrical and optical), and the FTS control unit.

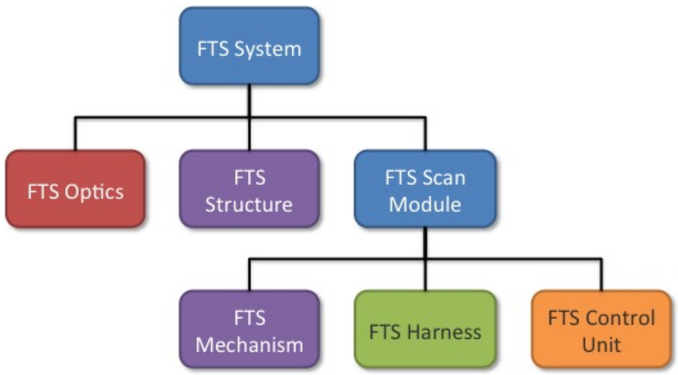


Fig. 6. Block diagram of the FTS system.

The scan mechanism is based on magnetic bearings. The design concept assumed in the reference design was made by TNO [9-11], and is shown in Fig. 7. The magnetic bearings are based on the principle of magnetic levitation. By controlling the current through two magnetic loops in the stator, a rotor connected to the platform with the rooftop mirror can be accurately kept in the center of the bearing. Since we need to constrain 5 Degrees of Freedom (lateral x and y, rotation about x, y and z), we use two pairs of two-dimensional bearings at the bottom, and a one-dimensional bearing at the top to constrain the rotation about the optical axis. In the center of gravity there is a linear motor. Positions are readout by a laser metrology system. The control electronics take as an input the laser metrology signal, the magnetic bearing sensors and control the linear motor and the bearings guiding the system for linear motion in the z direction. In zero-g conditions this concept can be operated with very low dissipation (<1 mW). For 1g testing we use a separate electromagnet offloading the effect of gravity.

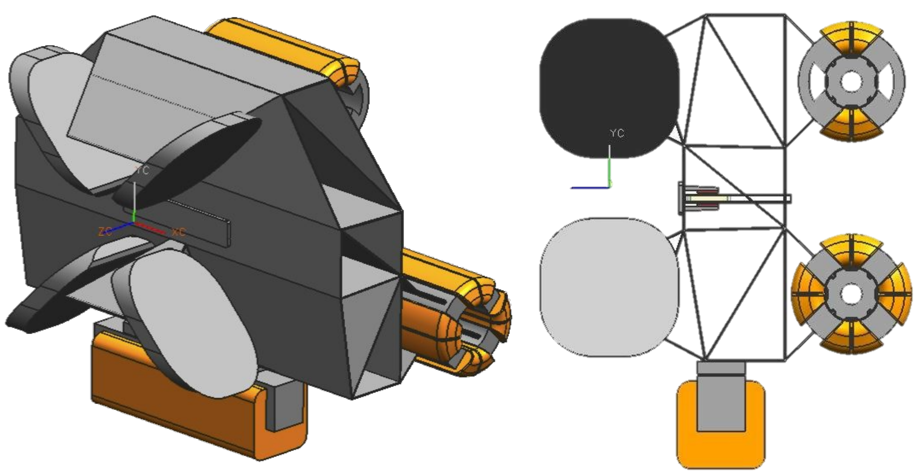


Fig. 7 Scan mechanism concept for the Safari FTS based on magnetic bearings [9-11].

E. Detector system

The entire instrument is designed around and optimized for the Safari detector system. As said before the detectors are extremely sensitive to external disturbances that can couple into the detector in various ways. An excellent review and description of the detector system is given in [6]. As far as the instrument design is concerned the detectors are contained in light-tight and magnetically shielded assemblies referred to as the Focal Plane Arrays (FPA's). The design concept of the FPA is shown in Fig. 8. In the middle a horn array can be recognized. The detector array chips are coupled to the optics via small horns and patches of absorber. The white elements are the detector chip and LC filter chips respectively connected via flexible interconnects. The detector array is contained in a light-tight shield (combined with a quasi-optical filter [12]). This shield is also shielding the device magnetically by means of Nb superconducting magnetic shield. The detector and shield are at 50 mK. They therefore have to be thermally suspended via Kevlar wires to the 1.7K level at the outside of the FPA in two steps via an intermediate 300 mK level (red). At 1.7K there is another level of magnetic shield provide by a cryoperm shield. The FPA finally includes light-tight thermal interfaces to the thermal straps of the 50 mK cryocooler in the instrument.

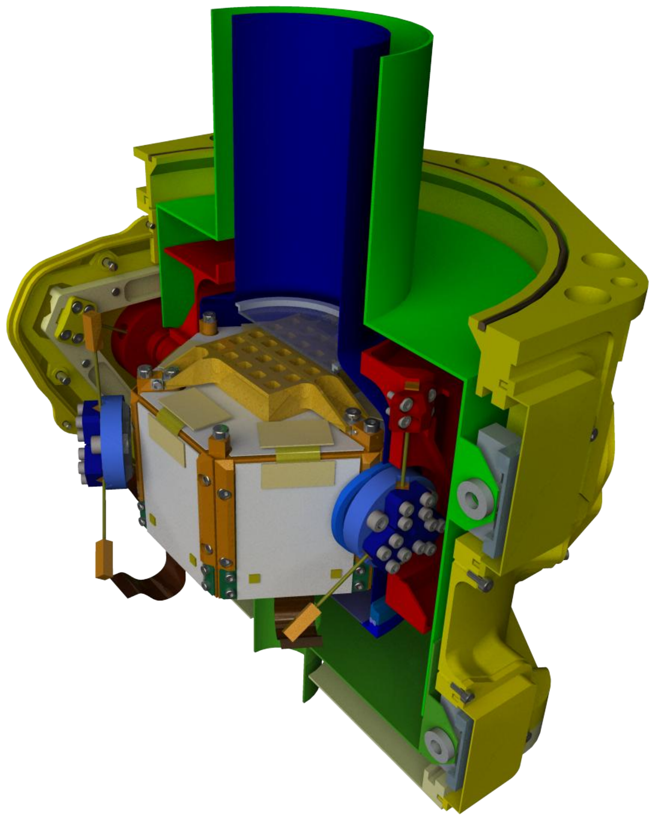


Fig. 8. Design concept of the Safari FPA.

III. INSTRUMENT PERFORMANCE AND CAPABILITIES

Using the instrument concept presented above we prepared an instrument sensitivity model describing the predicted performance. This model includes estimates of all transmission losses of the optics (filters and mirrors), diffractive losses in the system (spillover and truncation), as well as unwanted background sources (e.g the telescope baffle). The model considers the focal plane geometry of the pixels. Based on the sensitivity model we expect the sensitivities for Safari as shown in Table 1, which are compliant with the scientific requirements. The values listed between parentheses correspond to the potential gain in sensitivity when a dispersive element or narrow band filter is used reducing the Safari background loading by a factor of 20.

The Safari instrument finally offers the following capabilities:

- Fourier Transform Spectroscopy in 3 bands.
- Continuous wavelength coverage from 34-210 μm.
- Simultaneous broadband photometry in 3 bands.
- Offers background limited performance.
- Provides a synchronous FoV of 2'x2' in all 3 bands.

Table 1. Expected scientific performance for the Safari reference design.

Parameter		Waveband			
		SW	MW	LW	
Band centre / μm		47	85	160	General
Wavelength range / μm		34-60	60-110	110-210	General
Band centre beam FWHM		5″	7″	13″	General
Number of detectors		43 x 43	34 x 34	18 x 18	General
Confusion limit / mJy		0.015	0.5	5	Photometry
Minimum Zodiacal background / MJysr^{-1}		8.0	3.8	2.1	Photometry
Limiting source flux density (5σ-1hour) / μJy		14 (5)	21 (10)	32 (18)	Photometry
Time to reach confusion limit at 1σ / s		123 (16)	0.3 (0.06)	0.006 (0.002)	Photometry
Limiting line flux (5σ-1hour) / x10^{-19} Wm^{-2}		3.7 (1.4)	3.4 (1.6)	2.9 (1.6)	Spectroscopy
Limiting line flux density (5σ-1hr) / mJy	High Res. (R~2000*)	26 (9)	24 (10)	21 (10)	Spectroscopy
	Medium Res. (R~500*)	7 (2)	6 (3)	5 (3)	Spectroscopy
	Low Res. (R~50*)	0.7 (0.2)	0.6 (0.3)	0.5 (0.3)	Spectroscopy

IV. SUMMARY AND CONCLUSION

In this paper we presented the current design concept of the Safari instrument planned for SPICA. The instrument concept is built around very sensitive TES detector arrays and a Mach-Zehnder interferometer offering medium resolution spectroscopy, and 3 band photometry with background limited sensitivity in the 34-210 μm. We successfully developed a consistent reference design accommodating of units and functions in a single instrument satisfying the key interfaces and boundary conditions. The reference design, and expected performance, is compliant with the scientific requirements and it ready to be detailed for actual implementation.

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