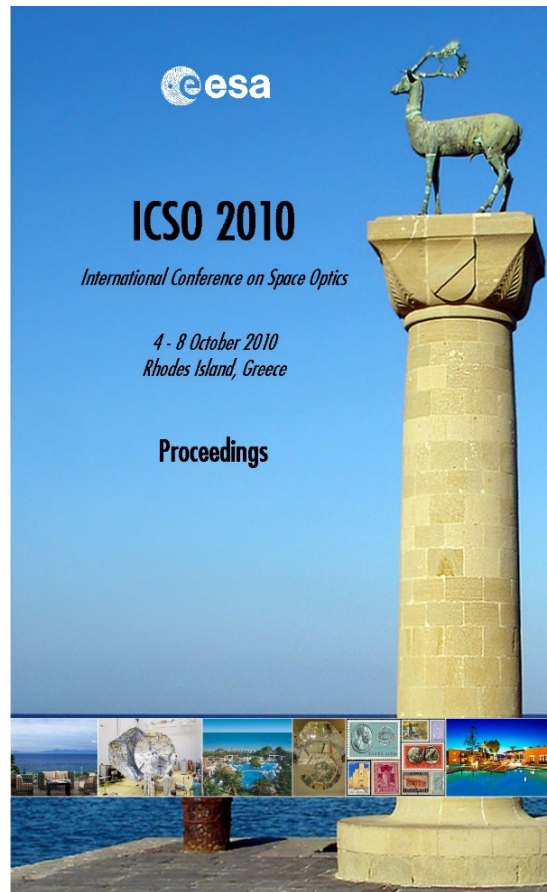


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SPICA/SAFARI CRYOGENIC MAGNETIC BEARING FOURIER TRANSFORM SPECTROMETER MECHANISM

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INTRODUCTION

SPICA (SPace Infrared telescope for Cosmology and Astrophysics, see Figure 1) is a proposed next generation space infrared observatory. The mission will study formation of planets, solar system processes, and the origin of the universe. SPICA is an international project, led by the Japanese space agency JAXA, with contributions from Europe. SPICA has been selected as a candidate ESA M-class Cosmic Vision mission.

SPICA will have a single 3.5 m mirror operating at 4.5 Kelvin. The wavelength range will cover 5 to 210 μm . The SAFARI (SpicA FAR infrared Instrument) imaging FTS (Fourier Transform Spectrometer) is one of five anticipated focal plane instruments. It will operate in the wavelength range of 35 to 210 μm .

The proposed European contributions to SPICA will consist of the telescope subsystem, the ground segment and SAFARI. SAFARI will be financed through national contributions. The Rutherford Appleton Laboratory (RAL) in the UK has been leading the Phase A study for this European SAFARI spectrometer. Currently SRON in the Netherlands has taken over this leading role from RAL.

SAFARI contains an Optical Delay Line (ODL) scan mechanism: FTSM. TNO has been participating in a SPICA SAFARI study, led by SRON, to support the RAL SPICA SAFARI Phase A investigations. The objective of this study was to increase the overall SAFARI TRL and improve the chances for SPICA in the ESA Cosmic Vision down selection. TNO participates in the optical design trade off between the SAFARI instrument and the FTS scan mechanism and leads the preliminary design of the FTS scan mechanism. Micromega-Dynamics contributed to the magnetic bearing design. SRON is developing control electronics for the FTSM.

TNO has previously been developing a cryogenic optical delay line mechanism breadboard with magnetic bearings together with Micromega-Dynamics and SRON for the Darwin mission. That heritage was the basis for the development of the SAFARI FTSM.

This paper describes the result of a phase-A conceptual design study on the FTSM.

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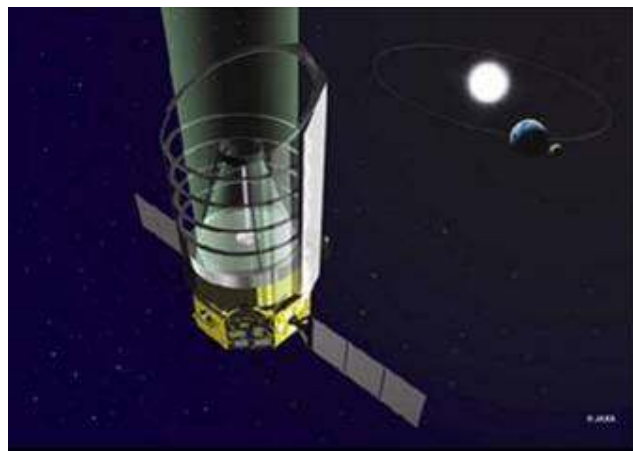


Fig. 1. The SPICA IR space observatory (courtesy JAXA).

I. OPTICAL LAYOUT

The optical layout is set by some of the main requirements:

- Pupil diameter: 33 mm
- Field of View of the FTS (FoV on sky is 2'): 3.5 x 3.5 deg
- Optical distance between Beam Splitter and retro-reflector first mirror (at zero OPD): < 375 mm
- Angle between the beams at BS and BC: 20 to 25 deg
- Linear OPD (Optical Path Delay) stroke: -4 to +31.5 mm
- Mass: < 3 kg
- Size: < 420 x 220 x 125 mm3
- WFE of optics between BS and BC – nominal (in both branches the same): < $\lambda/2$ RMS @ $\lambda=633$ nm
- WFE differences between the two branches including variations over the full scan: < $\lambda/20$ RMS

Figure 2 shows the optical configuration of SAFARI at the start of this project. It was based on HERSCHEL/SPIRE heritage (see reference [1]). The delay line was drawn as two roof-top retro-reflectors in a back-to-back configuration. This was replaced by a design with two f-number=4.5 cat's-eye because of the inherent pupil reimaging of a cat's-eye which allows for smaller Beam-Splitter (BS) and Beam-Combiner (BC), and therewith a smaller overall layout, matching the required dimensions and distance between BS and first reflecting surface of the retro-reflector. Another advantage is the less critical alignment, only the distance between M1 and M2 needs accurate alignment (to a few μm). There is no mass penalty relative to other retro-reflector types. A disadvantage is the inherent nominal WFE (Wave Front Error) for the large required FoV (Field of View), but this was still within the required value of < $\lambda/2$ at 3.5 x 3.5 deg.

The two side-by-side cat's-eye configuration allowed for a central "back-bone" tube in which all mechatronic guiding and driving components could be housed, leading to an overall compact design. The draw-back of this side-by-side design is that two extra folding mirrors are required, see Figure 3.

The optical layout between the FTS mechanism and the detectors (three cameras for three wavebands) was changed such that the detectors could be placed close together on a row, see Figure 3. This made the design compact and more easy to cool.

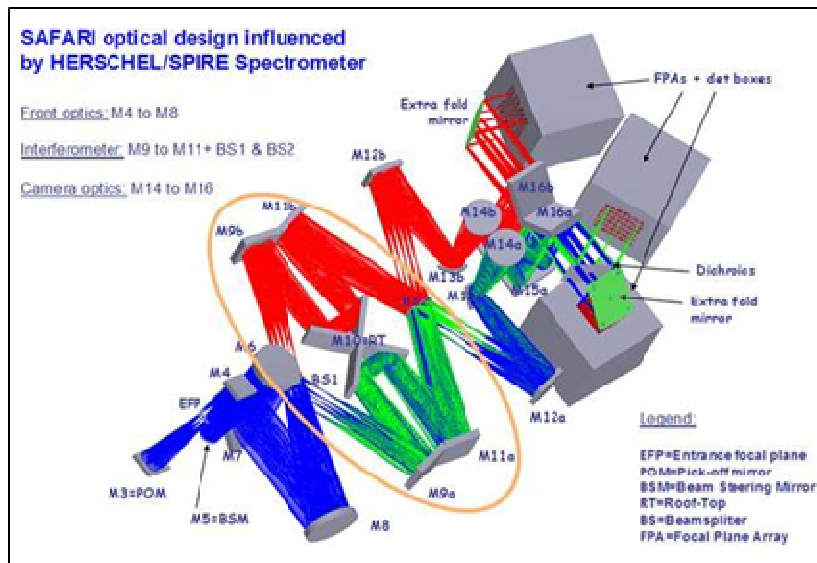


Fig. 2. Preliminary SAFARI optical layout with the FTS mechanism encircled. Here still with a roof-top retro-reflector which was replaced by a cat's-eye design in this project.

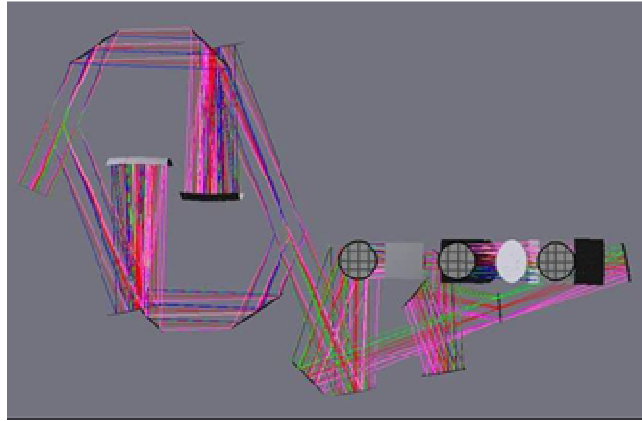


Fig. 3. SAFARI Optical layout including detectors.

II. GUIDING SYSTEM

The mechanical system is determined by the optical layout and additional requirements on the guiding accuracy and operational constraints:

- OPD resolution: $< 15 \text{ nm}$
- FTSM mirror optical axis rotation: $< \pm 30''$
- FTSM mirror lateral displacement: $< \pm 100 \mu\text{m}$
- Mechanical scanning velocity: 30 to 500 $\mu\text{m/s}$, in steps of 1 $\mu\text{m/s}$, and an accuracy $< 3 \mu\text{m/s}$
- Travel distance for acceleration and deceleration between stand-still and maximum speed: $< 0.5 \text{ mm}$
- Life time: $> 150,000$ scans
- Operational temperature: 4 to 6 Kelvin
- Operational power dissipation including heat leak from warm electronics: $< 1.3 \text{ mW}$
- On-earth testing angle: up to 0.5 degrees

There is not a large choice of guiding mechanisms that will meet the required large stroke, small volume, and low power. Similar requirements for the DARWIN ODL (Optical Delay Line, see reference [2]) led to choosing an active Magnetic Bearing (MB), which was based on the MABE mechanism developed by Micromega Dynamics. The same magnetic bearing technology was used for the SAFARI FTS mechanism. An additional advantage is that the OPD resolution is only limited by metrology performance, because a magnetic bearing has no friction or other OPD performance limiting non-linearities.

In the SAFARI FTS mechanism the bearings are put in between the optics inside a central “back-bone” tube (see Figure 4). This was a natural way of construction because of the side-by-side configuration of the retro-reflectors in the SAFARI FTS. All other opto-mechatronic parts could be placed inside the tube as well, such as: MB sensors, OPD actuator, a stepper motor operated Launch-Lock (LL), and OPD metrology. The back-bone design also leads to a high first eigen-frequency: $f_0 \sim 1000 \text{ Hz}$. The central tubular structure including mirror mounts is designed such that it can be manufactured by spark erosion out of a single piece of Aluminium, which makes the system a-thermal so the optics are automatically in focus at any temperature.

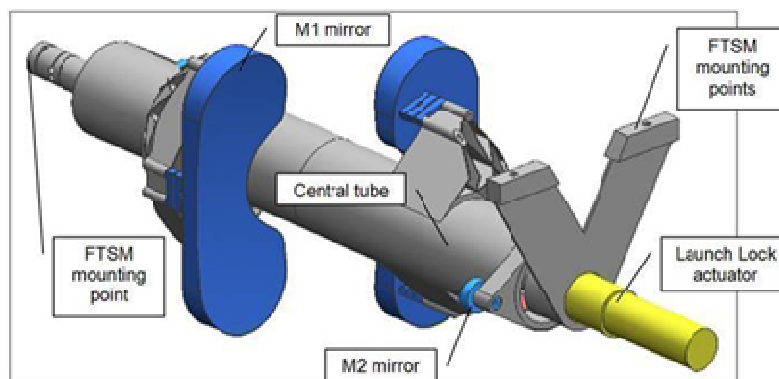


Fig. 4. The FTS mechanism consists of a central back-bone with all guiding and driving inside.

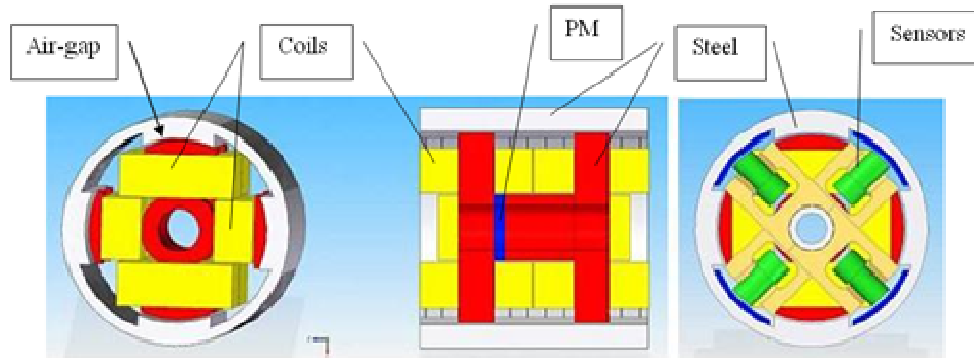


Fig. 5. The FTS mechanism consists of a central back-bone with all guiding and driving inside.

Figure 5 shows the active magnetic bearing layout. Two of these sets, one at either side of the central tube, constrain 4 degrees of freedom (DoF). The fifth degree of freedom (rotation around the central axis; R_z) is only constrained in a weak and passive way. It is still under investigation if this is sufficient or if one of the MB sets has to be replaced by a 3 DoF type. This MB design can be made fully redundant by only modifying the wiring and accompanying electronics.

The power dissipation inside the FTS mechanism is negligible in space (zero-gravity environment). The heat leak through the wires can form a considerable part of the total FTS mechanism power budget especially if the magnetic bearings also need to carry the 1-g forces. Therefore during earth testing (1-g environment) some measure is needed to keep the power dissipation low. One option for 1-g offloading is to use a permanent magnet that is turned by the launch-lock motor such that on earth it is supplying an extra lifting force, and in space it is turned such that it is shunted and doesn't supply a force.

VI. OPD actuator, sensor, and electronics

For the required large stroke and low power dissipation a moving-coil linear motor design was needed. The total length of the motor (magnets) is 56 mm at a diameter of 22 mm. This OPD linear motor design doesn't set a limit on speed and resolution of the rotor position because of the inherent frictionless and step-less behaviour. The performance is only limited by the OPD metrology.

The driving requirement for the OPD actuator force is the ability to operate on earth at an angle of 0.5 degrees. Because of the ~ 1 kg moving mass this leads to a horizontal gravitational force of 0.1 N. This far exceeds the acceleration and deceleration requirements. With a linear motor this force can be generated at a moving (coil) mass of 100 gram and a stationary (magnet) mass of 300 gram. The power dissipation at cryogenic temperatures is below 0.1 mW.

At a stroke of more than 35 mm and a resolution of 15 nm (dynamic range = $2.4e6$) only counting type of sensors will comply. Such include magnetic, capacitive, inductive or optical linear scales (as in SPIRE). A fiber optic interferometer (see reference [3]) was selected as the baseline metrology system. It is very small such that it can be mounted inside the central tube. Also the power dissipation inside the cold mechanism is negligible. Fiber optic interferometers currently are starting to be used in commercial applications, also in cryogenic-vacuum environments. Space compatibility including connectors, radiation hardness, and vibration and shock resistance have been reported independently as being viable.

The resolution is in the order of 1 nm or lower and the absolute accuracy can be in the order of 10 nm. The band-width can be easily made in the order or 10 kHz. Stray-light has to be shielded because the SAFARI detectors are very sensitive.

In the framework of the Darwin ODL project, SRON developed an FPGA based combined MB/OPD controller "ODELCO" with a sampling/control rate of 10 kHz and a targeted power dissipation of 5 W (see Figure 6). It is further being developed for other applications including SAFARI. It is proposed as a baseline for control of the FTSM.

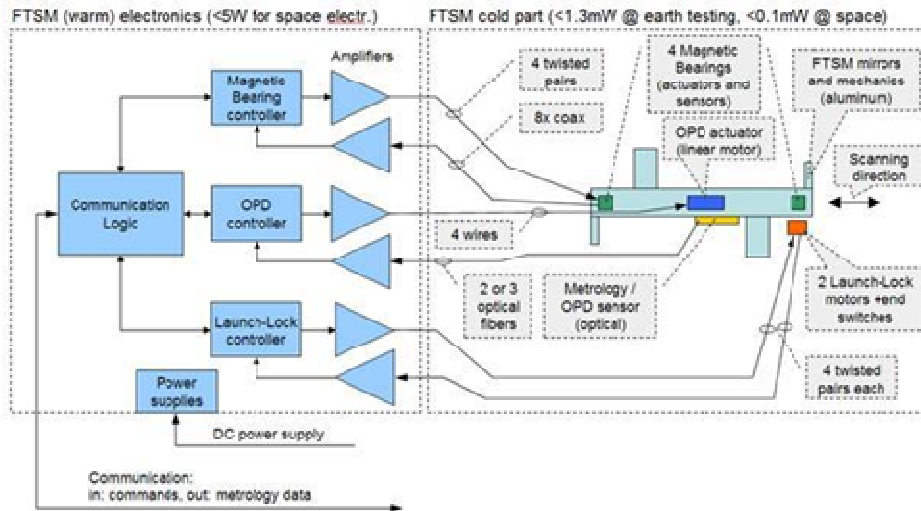


Fig. 6. Schematic of the SAFARI electronics.

VI. SUMMARY

A cryogenic space mechanism has been designed for use in the SPICA/SAFARI Fourier Transform Spectrometer. It is a double back-to-back cat's-eye with a linear guiding system based on magnetic bearings. The optics are mounted on a central "back-bone" tube containing all mechatronics: the magnetic bearing, a linear motor serving as the OPD actuator, internal metrology with nanometer resolution, and a launch lock.

A magnetic bearing is employed to enable a large scanning stroke in a small volume. It supports the optics in a free-floating way without any friction, enabling sub-nanometer accuracy in a single stage.

In the next development phase some of the most critical items will be further developed and a breadboard version of the FTS mechanism will be implanted and tested.

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