SPICA / SAFARI Fourier Transform Spectrometer Mechanism Evolutionary design

Teun C. van den Dool[*a], Bob Kruizinga[a], Ben C. Braam[a], Roger F.M.M. Hamelinck[b], Nicolas Loix[c], Dennis van Loon[d], Johan Dams[e]
[a]TNO S&I, Stieltjesweg 1, 2628 CK Delft, Netherlands.
[b]Entechna Engineering, Horsten 1, MMP 1.02, 5612 AX Eindhoven, Netherlands.
[c]Micromega Dynamics SA, Rue du Trou du Sart 10, B-5380 Fernelmont, Belgium.
[d]SRON, Sorbonnelaan 2, 3584 CA Utrecht, Netherlands.
[e]Magnetic Innovations BV, Oude Kerkstraat 61a, 5507 LB Veldhoven, Netherlands.

ABSTRACT

TNO, together with its partners, have designed a cryogenic scanning mechanism for use in the SAFARI[1] Fourier Transform Spectrometer (FTS) on board of the SPICA mission. SPICA is one of the M-class missions competing to be launched in ESA's Cosmic Vision Programme[2] in 2022. JAXA[3] leads the development of the SPICA satellite and SRON is the prime investigator of the Safari instrument.

The FTS scanning mechanism (FTSM) has to meet a 35 mm stroke requirement with an Optical Path Difference resolution of less then 15 nm and must fit in a small volume. It consists of two back-to-back roof-top mirrors mounted on a small carriage, which is moved using a magnetic bearing linear guiding system in combination with a magnetic linear motor serving as the OPD actuator. The FTSM will be used at cryogenic temperatures of 4 Kelvin inducing challenging requirements on the thermal power dissipation and heat leak.

The magnetic bearing enables movements over a scanning stroke of 35.5 mm in a small volume. It supports the optics in a free-floating way with no friction, or other non-linearities, with sub-nanometer accuracy. This solution is based on the design of the breadboard ODL (Optical Delay Line) developed for the ESA Darwin mission[4] and the MABE mechanism developed by Micromega Dynamics.

During the last couple of years the initial design of the SAFARI instrument, as described in an earlier SPIE 2010 paper[5], was adapted by the SAFARI team in an evolutionary way to meet the changing requirements of the SPICA payload module. This presentation will focus on the evolution of the FTSM to meet these changing requirements. This work is supported by the Netherlands Space Office (NSO).

Keywords: SPICA/SAFARI, Fourier Transform Spectrometer, Optical Delay Line, active magnetic bearings, cryogenic, linear motor, fiber interferometer

1. INTRODUCTION

SPICA (SPace Infrared telescope for Cosmology and Astrophysics, see Figure 1) is the 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 3.2 m (previously 3.5 m) mirror operating at 4.5 Kelvin. The wavelength range will cover 5 to 210 μm. Five focal plane instruments are anticipated, one of them being SAFARI, a FIR imaging spectrometer (30-207 μm). SRON in the Netherlands is PI for the SAFARI instrument. TNO has been strongly involved in the optical design and is leading the development of the FTS mechanism (FTSM), which basically is an Optical Delay Line.

---

[*] teun.vandendool@tno.nl; phone +31 (0)8886 68036

Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave, edited by Mark C. Clampin,
Giovanni G. Fazio, Howard A. MacEwen, Jacobus M. Oschmann, Jr., Proc. of SPIE Vol. 8442, 84423R
© 2012 SPIE · CCC code: 0277-786/12/$18 · doi: 10.1117/12.926066

This paper describes the modifications that were made to the design after the phase-A study. These changes were necessary to meet the modified requirements and constraints. After phase-A it became clear that larger diameter optics were needed to limit diffraction effects. So the required volume increased. At the same time the available volume was reduced because a smaller launch vehicle was selected for the SPICA mission, leading to a smaller M1 mirror (3.2 m instead of 3.5 m). Additionally the optical bench carrying all instruments proved to be too flexible so stiffeners had to be added, further limiting the available space for the SAFARI instrument.

2. REQUIREMENTS

We recapitulate here the most important requirements for the FTS mechanism from a former paper[5]:

- Pupil diameter: 33 mm
- Linear OPD (Optical Path Delay) stroke: -4 to +31.5 mm
- OPD resolution: < 15 nm
- OPD internal sensor sampling frequency: >1 kHz
- Mechanical scanning velocity: 30 to 500 μm /s, in steps of 1 μm /s, and an accuracy < 3 μm /s
- Travel distance for acceleration and deceleration between stand-still and maximum speed: < 0.5 mm
- On-earth testing angle: up to 0.5 degrees
- FTSM mirror optical axis rotation: < ±30''
- FTSM mirror lateral displacement: < ±100 μm
- Life time: >150,000 scans
- Operational temperature: 4 to 6 Kelvin
- Operational power dissipation including heat leak from warm electronics: < 1.3 mW
- Mass: < 3 kg
- Size: < 420 x 220 x 125 mm^3

Both the previous and the current FTSM design meet all these requirements. The 1.3 mW power dissipation is still a critical requirement because of the many electronic wires and some optical fibers running from the warm electronics to the cold mechanism. Especially during testing in an earth environment, the need to counter forces due to the 1g earth gravitational field can lead to extra power dissipation.

3. ORIGINAL 2009 DESIGN

Many FTS use a mechanism with two back-to-back retro-reflectors. E.g. the HERSCHEL/SPIRE instrument design[6], which was used as the starting point for SPICA/SAFARI, had two roof-tops. The original SAFARI design[5] had two cat's-eyes, see Figure 1. Apart from being back-to-back the retro-reflectors were also placed side-by-side to further limit the overall size. This allowed for a central "back-bone" tube with all mechatronic guiding and driving components included: 4 degree-of-freedom magnetic bearing system, linear motor for driving the OPD direction stroke of 35.5 mm, a 1-g off-loading magnet, a launch lock system, and OPD metrology.

A magnetic bearing was chosen because of its capability to give a large stroke and high resolution in a small volume at low power. This magnetic bearing is designed by Micromega Dynamics, who also developed the magnetic bearings for the DARWIN ODL and MABE mechanisms. This design from 2009 constrained the rotation around the z-axis only in an indirect way, which was a disadvantage, although the impact on the optical performance was considered low, especially during operation in space.

The magnetic bearings are designed to guide the system in an (space) environment without gravity. If gravity is present the dissipation in the magnetic bearings will be too high to meet the power requirement. Therefore a permanent magnet was added to generate a 1g countering force during earth testing. This magnet could be shunted through a mechanism operated by the launch-lock motor after launch.

The OPD actuator driving the 35.5 mm stroke was a special linear motor with circular cross-section instead of the more standard U-shaped type. This was needed because it had to fit in the circular cross-section of the central tube and still produce sufficient power. The design driver for this actuator is to operate with low power dissipation in a small volume at 0.5 degrees tilt during earth testing. This leads to a force of ~0.1 N because of 1 kg moving mass, which is far more than the forces required for accelerating and decelerating the scanning profile. This motor is designed by Magnetic Innovations.

A fiber based interferometer with 10 nm resolution was selected as OPD metrology system[7]. It has high resolution at large stroke and fits in a small volume.

SRON has been developing an FPGA based controller for the magnetic bearings, OPD, metrology, and launch-lock. The targeted sampling frequency is 10 kHz and the power dissipation target is 5 W.

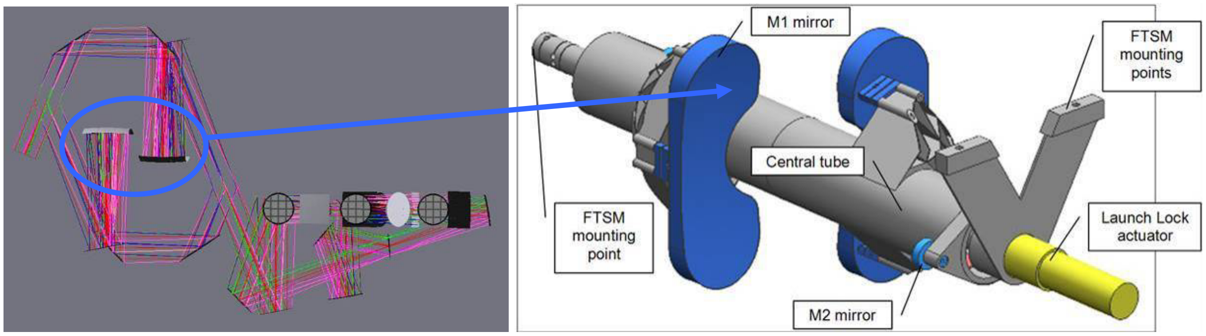

Figure 1. Left: 2009 optical design of SAFARI with the 3 detectors for the 3 wavelength channels close together on a row aiding proper cooling.
Right: the FTSM had a central tube with all mechatronic components included for driving the 35.5 mm linear OPD stroke.

4. UPDATED DESIGN, STATUS 2012

In 2010 a couple of changes to the SPICA mission led to important changes in requirements. The diameter of the optical bench, which carries all instruments, was reduced because a smaller launch vehicle was selected and therefore the size of the primary mirror was reduced, from 3.5 m to 3.2 m. Moreover, the optical bench appeared to be too flexible and stiffeners were added to decrease flexing. This all led to a much smaller volume available for the SAFARI instrument. Instead of a large triangular space, now a smaller trapezoid surface is available, see Figure 2. Also volume needed for the many cables, mainly for the detectors/cameras, required considerable volume.

It also was discovered that to limit diffraction effects, the front-optics which sits between the pick-off point from the telescope and the remainder of the FTS, needed to have larger diameter. This again led to more required volume.

The solve the volume conflict, the complete optical layout was altered. Instead of a design in nearly a single layer, the available height was used more effectively by folding the optics in three layers/decks, see Figure 3. The upper level still has the three cryogenic detectors close together on a single row, aiding proper thermal control.

In the new optical layout the cats-eye retro-reflectors proved ineffective (relative large) and were changed to roof-top types. The roof-top retro-reflectors are more sensitive to Rx rotation than the previous cats-eyes. So the MB guiding system should be more accurate. But this didn’t prove to be restrictive.

In the new optical layout the linear guiding mechanism was obstructing the optical path. Volume for the guiding was reserved at the side of the roof-top mirrors instead of at the centre. This made a guiding design with everything included in a central tube not fit. It was changed to a box-like structure with the roof-top mirrors at one side and magnetic bearings at the other side as shown in Figure 4. The upper two Magnetic Bearing (MB) blocks now constrain 2 degrees of freedom each (x,y,Rx,Ry) as in the previous design. A third MB was added at the lower side to constrain 1 degree of freedom (Rz). The OPD (z) direction is not constrained by any MB. The configuration of each of the five MB is similar and modified relative to the previous design such that the power dissipation remains constant now over the complete stroke in case that a constant force in z-direction is present, such as might occur during testing on earth (1-g environment). The moving mass still is < 1 kg, and the total mass < 3 kg.

The circular linear motor serving as an OPD (z-direction) actuator in the original design didn't fit either in the new box-like structure. So it was changed to a more standard U-shape type of linear actuator. This motor is put in the centre of gravity of the FTSM to prevent cross-talk to the magnetic bearings. It's stroke still is 35.5 mm.

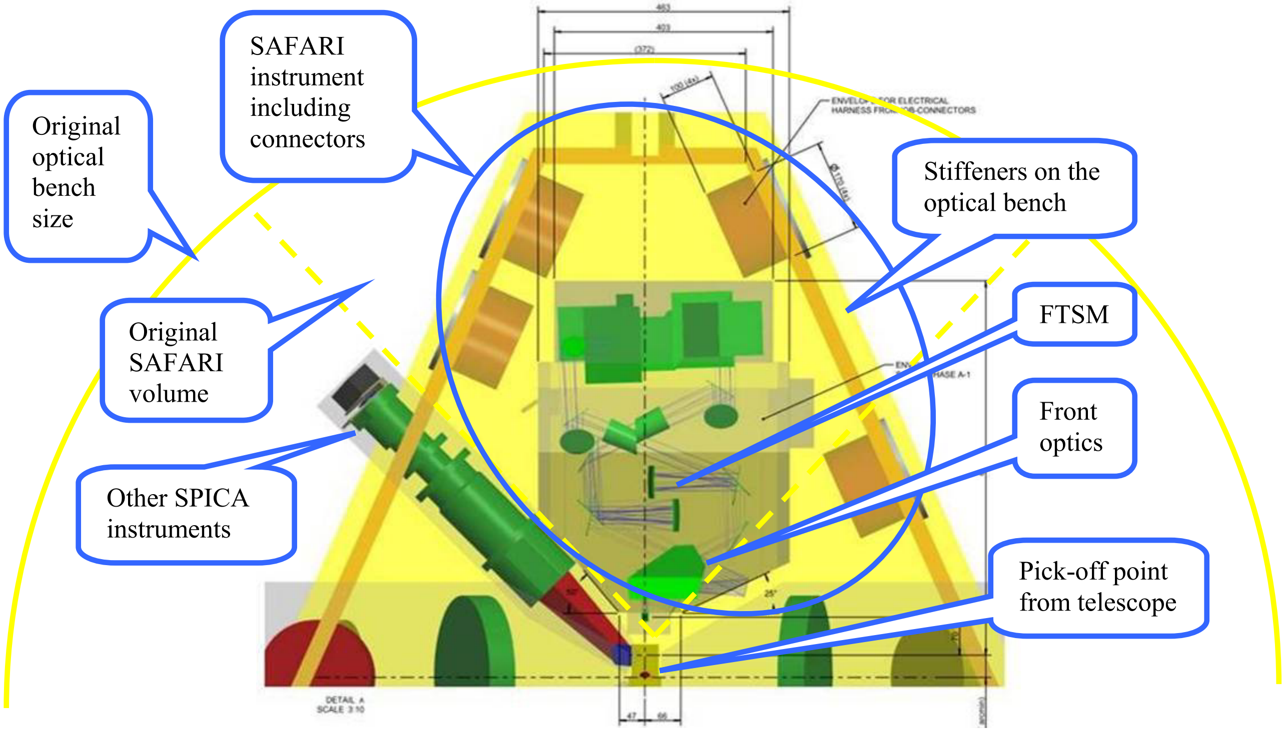

Figure 2. In 2010 the space available on the SPICA optical bench available for SAFARI reduced considerably, making the original design not fit anymore.

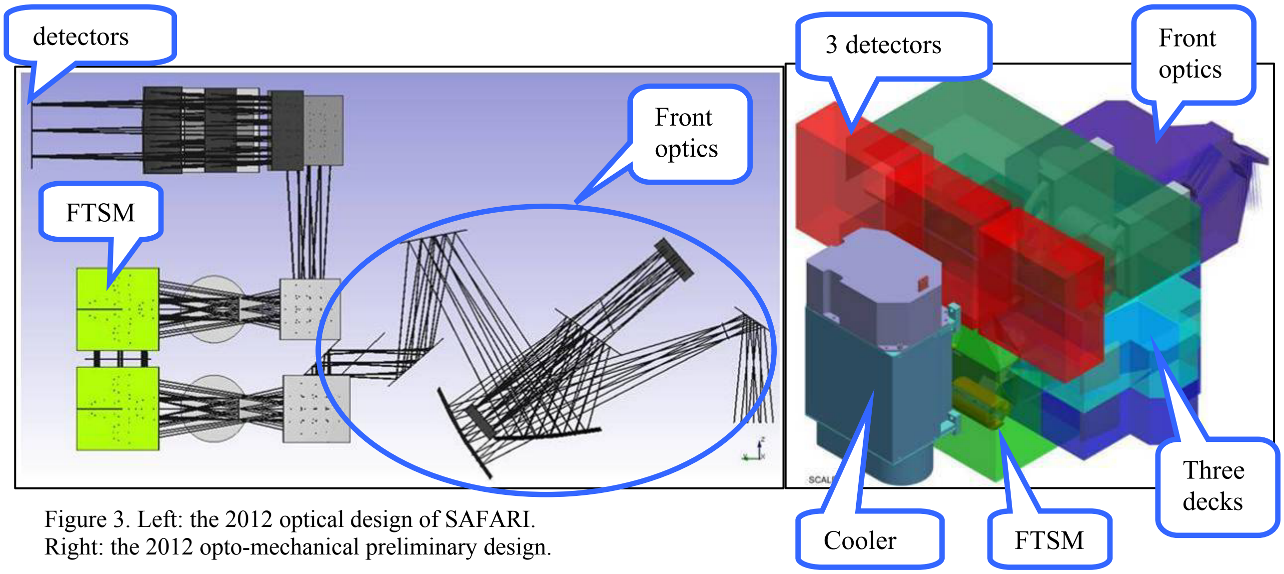

Figure 3. Left: the 2012 optical design of SAFARI.
Right: the 2012 opto-mechanical preliminary design.

Instead of a permanent magnet and shunting mechanism for relieving the magnetic bearings from the 1g-gravity forces during testing on earth, now an electromagnet is proposed for the same purpose. It can be controlled more easily to adapt to any changes in mass or mechanical tolerances.

A preliminary design of a launch lock has been carried out too, see Figure 5. It consists of an isostatic mount formed by two ball-grooves at the upper side of the FTSM and a single cup-cone at the lower side. The cup-cone at the lower side is mounted on a lever. This lever is actuated by a stepper motor through a pull-rod. The pull-rod is spring loaded such that the locking force remains constant irrespective of mechanical tolerances.

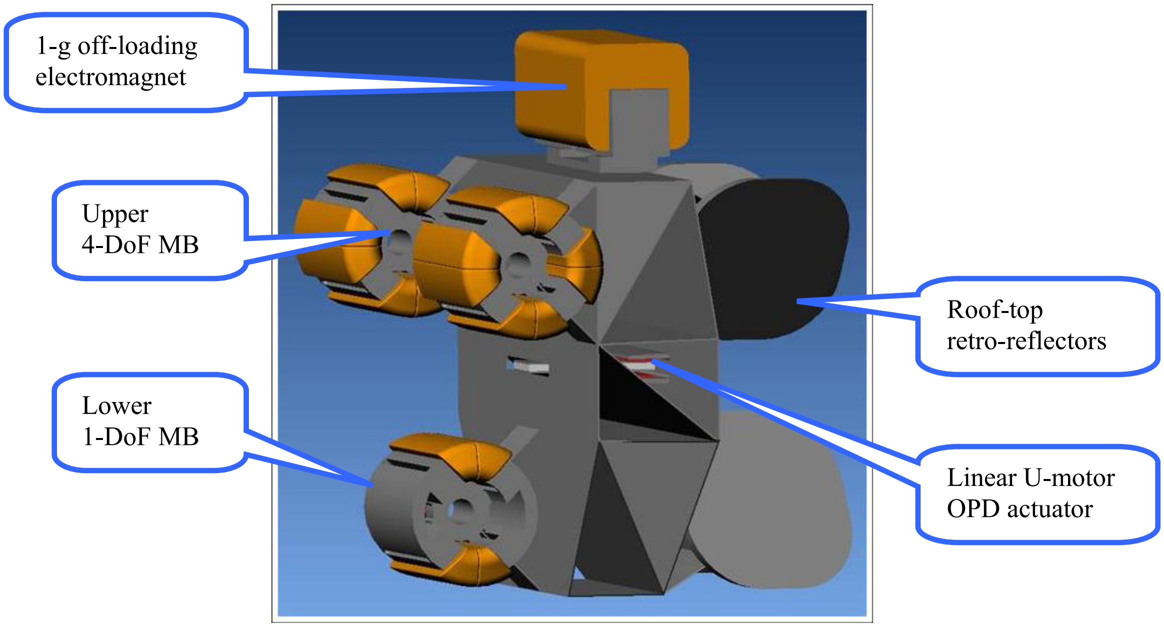

Figure 4. The 2012 FTSM design (moving part).

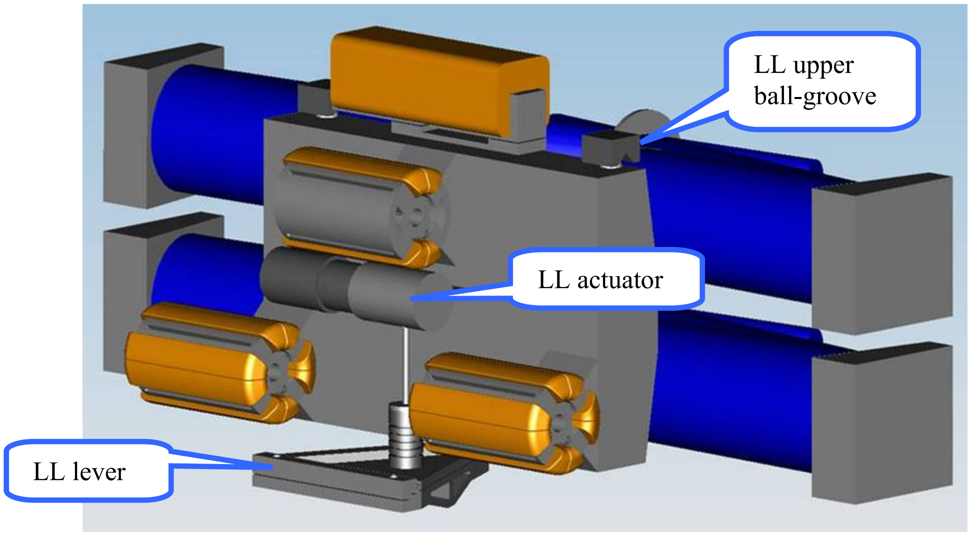

Figure 5. The 2012 FTSM moving part including Launch Lock (LL) and first folding mirrors of the optics.

The SAFARI detectors are susceptible to external magnetic fields, the preliminary requirement is < 100 uT for static fields and < 5 nT for dynamic fields. Note that the static earth magnetic field is in the order of 50 uT. The stray fields of the linear motor have been assessed as: ~10 uT without extra shielding and ~1 uT with shielding. The dynamic fields will be in the order of 1 nT (without extra shielding). The stray fields generated by the magnetic bearings are expected to be in the same order of magnitude. So the risk of influencing the SAFARI detectors seems low.

The wiring schematic (see Figure 6) has slightly changed relative to the previous design because of the need to drive the 1-g off-loading magnet.

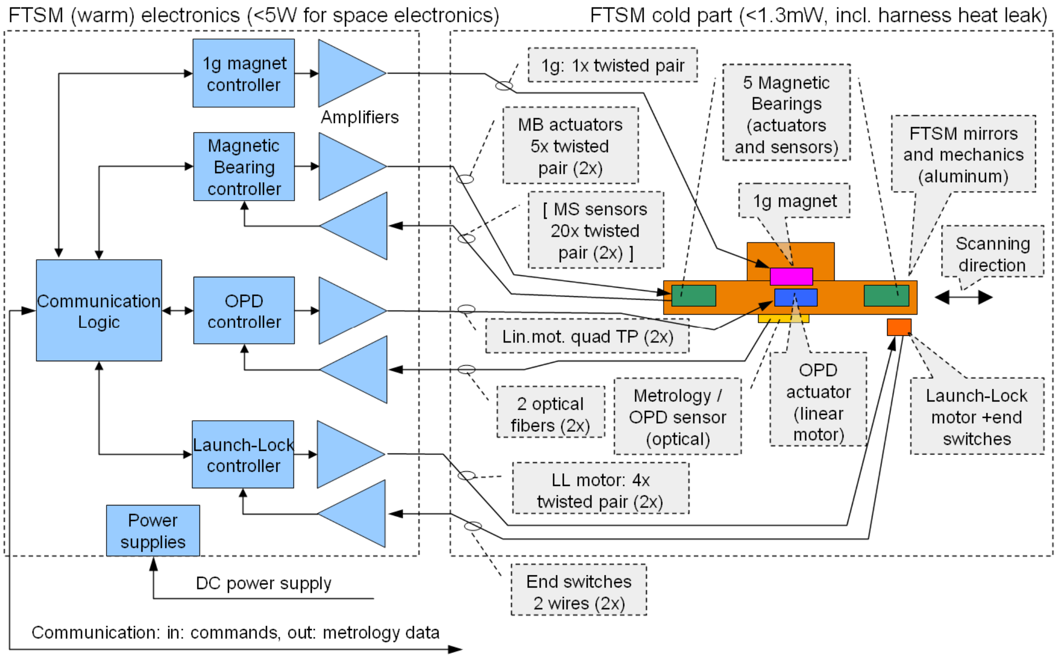

Figure 6. The 2012 SAFARI electronics and wiring layout.

5. ANTICIPATED DEVELOPMENTS

In the most recent design the cryo cooler is put at the place of one of the detectors and that detector is positioned “around the corner”, see Figure 7. This was again needed to further reduce the required volume. This leads to a (small) reduction in volume available for the FTSM. So the FTSM has to be modified again.

Other activities that will be carried out in the foreseeable future are:

- Design of the static part of the FTSM by Entechna engineering in the Netherlands.
- More detailed dimensioning of the magnetic bearings by Micromega Dynamics in Belgium.
- Dimensioning of the 1-g off-loading magnet.
- Optimization of the power dissipation and heat leak through the harness.
- Fiber interferometer design and testing.

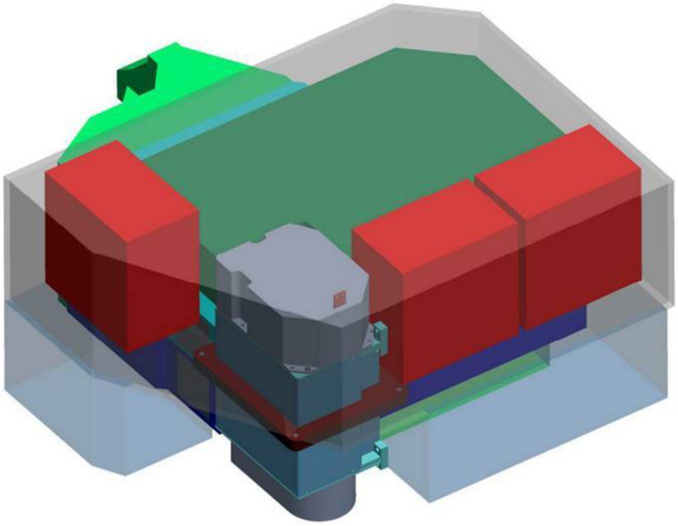

Figure 7. The 2012 SAFARI opto-mechanical design.

6. CONCLUSIONS

Despite a considerable reduction in available volume for the SAFARI instrument and the increased volume needed by the SAFARI instrument, we were able to still fit the instrument by making considerable changes to the original optical design and FTSM mechanism.

REFERENCES

[1] SRON's SAFARI website, http://www.sron.nl/spica-safari-missionsmenu-2253.html
[2] ESA's SPICA website, http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=42281
[3] JAXA's SPICA website http://www.ir.isas.jaxa.jp/SPICA/SPICA_HP/ippan-1_English.html
[4] T.C. van den Dool, et al. "The development of a breadboard cryogenic optical delay line for Darwin", Proc. SPIE 6692, pp.66920A.1-66920A.12 (2007).
[5] T.C. van den Dool, et al. "Cryogenic magnetic bearing scanning mechanism design for the SPICA/SAFARI Fourier Transform Spectrometer", Proc. SPIE 7739 (2010)
[6] Matt Griffin, et al., "Herschel-SPIRE: Design, Ground Test Results, and Predicted Performance", Proc. SPIE 7010, pp.701001-701006 (2008).
[7] L.K. Cheng, et al., "Development of a fringe sensor based on 3x3 fiber optic coupler for space interferometry", Proc. SPIE 5855, pp.1004-1007 (2005).