FIRST-SPIRE

Photometer pupil alignment budget

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1. Introduction

An alignment budget for the SPIRE photometer instrument is presented. Of three proposed performance criteria, image quality, image displacement, and pupil displacement, only the latter is found to be critical for alignment. The budget considers defaults of the optical design (pupil aberrations and effects of chopping), instrument internal alignment, and alignment with respect to the telescope.

The current photometer design is BOLPHT126B.

2. Reference documents

[RD1] Instrument requirement document, Issue .00 draft 2, 14/5/99

[RD2] FIRST alignment plan, PT-PL-02220, 9/5/96

3. Performance criteria

The current IRD [RD1] requires an image quality corresponding to a Strehl ratio of 0.9 over the entire FOV. The current optical design offers sufficient margin with respect to image quality to ensure that this is not a driver for alignment tolerancing.

There is no requirement for absolute lateral alignment of the image plane. We have considered a displacement corresponding to one Airy disk at 250 microns, or 15% of the FOV, to be a reasonable goal. Again, this is found not to be a driver for alignment tolerancing.

Pupil alignment is the most sensitive criterion for alignment tolerancing. The telescope pupil is located at the secondary mirror and its alignment with respect to the instrument cold stop is essential. Although the IRD does not mention it, it is clear that SPIRE philosophers currently favour the **undersized cold stop**. Although a matter for discussion and serious study, this will be assumed in the present document. The undersized cold stop ensures that no detector sees anything outside M2. A pupil misalignment of ΔR therefore requires the pupil radius reduced to $R - \Delta R$, giving a fractional loss of pupil area, hence throughput, of $\Delta A/A = 2\ \Delta R/R$. Pupil alignment is considered in terms of **fractional alignment**, $\Delta R/R$.

The IRD requires a total throughput for mirrors, filters, and dichroics greater than 27%, accepting a throughput loss of 73%. This includes losses due to manufacturing defects, surface finish, and alignment tolerances. It is outside of the scope of this document to distribute the allowed loss between all contributors, but it is clear that minimizing the losses due to alignment is the main driver for instrument alignment.

It is found that alignment tolerances of 1 arcmin tilt and 0.1 mm decenter, compatible with "blind alignment", i.e. without optical aids, offers a 90% probability of a fractional alignment better than 4%. This compares favourably with the other contributors to the alignment budget.

4. Budget

The fractional pupil alignment budget, see Figure 1, is divided into two main branches, "Design" and "Alignment". The total alignment error is estimated as the SUM of these two branches.

Design takes account of pupil aberrations, representing the reduction in cold-stop radius for the worst pixel in the chopped system.

Alignment represents the RSS of the telescope-to-instrument alignment specification provided by ESA and the SPIRE internal alignment budget. Figure 2 summarizes our understanding of the telescope-to-instrument optical and mechanical interfaces. By Monte-Carlo simulations it has been found that the actual misalignment will be less than the value calculated by RSS summation in 90% of the simulated cases.

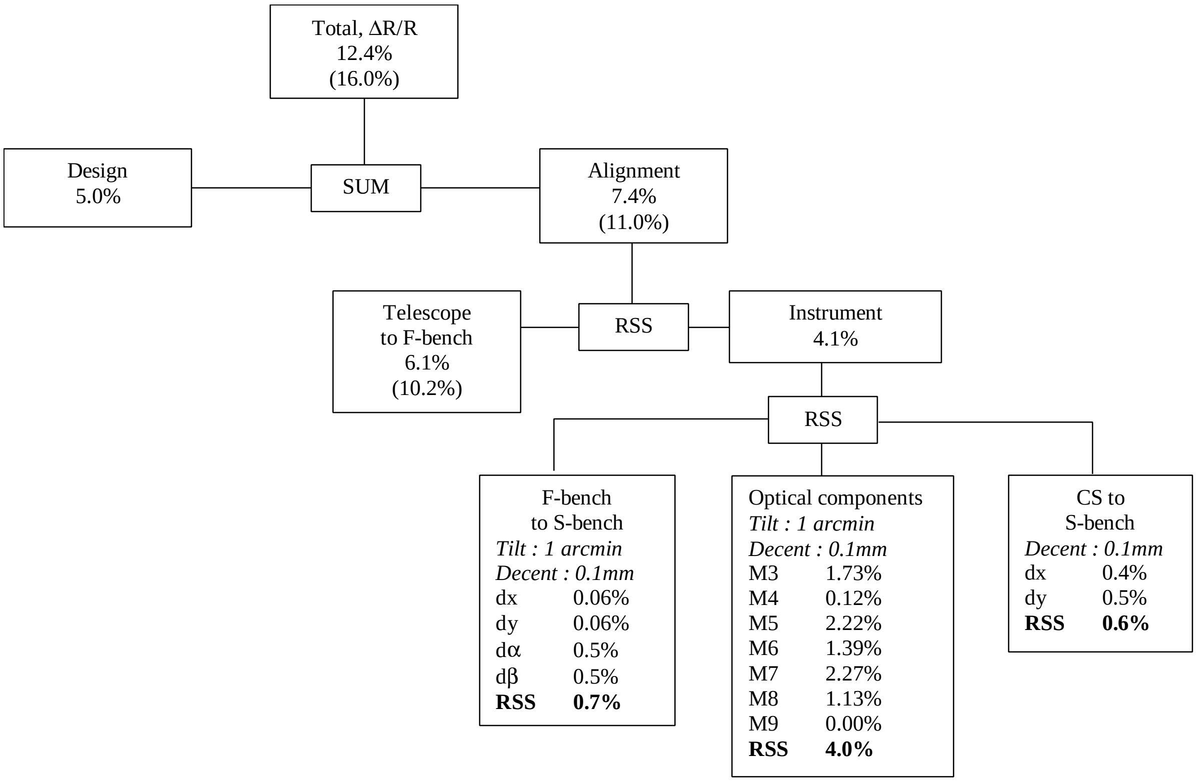

Figure 1. Fractional pupil alignment budget for the SPIRE photometer instrument in terms of ΔR/R. Values in brackets represent an uncertainty in ESA's telescope-instrument alignment specification, see text.

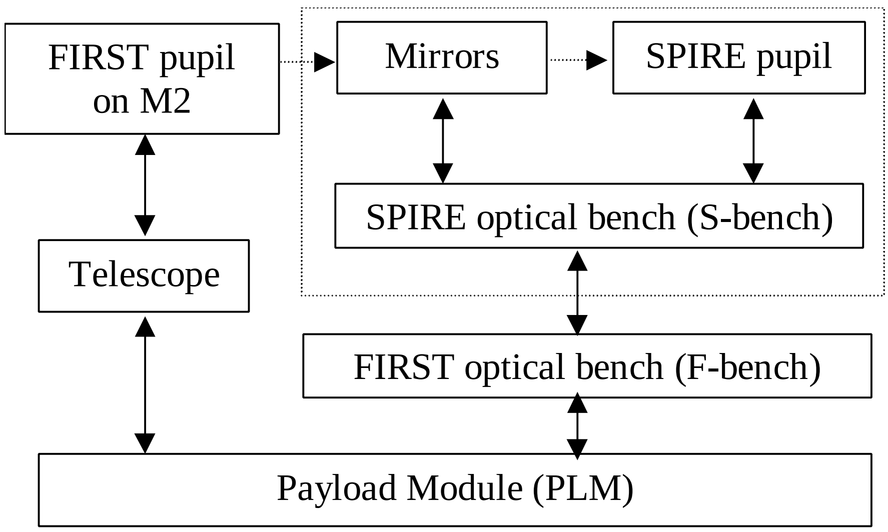

Figure 2. Summary of the mechanical (vertical, solid arrows) and optical (horizontal, dotted arrows) interfaces to be considered for pupil alignment. The dotted rectangle encloses the interfaces for which SPIRE is responsible.

4.1. ESA alignment specification

An ambiguity in the FIRST alignment plan [RD2] leaves an uncertainty as to the telescope-to-instrument alignment specification. This is possibly due to a change in telescope parameters. The document reads (p. 5):

> "The absolute tilt error must be below [$\Delta\beta$ =] 12 arcmin which corresponds to
> [ΔR =] 16 mm lateral misalignment between the telescope and instrument pupils."

Angular specification is related to fractional misalignment by the focal ratio, presently given as F = 8.68:

$$\Delta R/R = 2\ \Delta\beta\ F = 6.1\%$$

Linear specification is related to fractional misalignment by the M2 diameter, presently given as D = 314.7 mm:

$$\Delta R/R = 2\ \Delta R/D = 10.2\%$$

While the former is assumed to represent ESA specification, the latter is included in the budget and following discussions enclosed between brackets.

4.2. SPIRE internal alignment

The instrument alignment budget has three components:

F-bench to S-bench: alignment between the FIRST and the SPIRE optical benches (denoted F-bench and S-bench, respectively). Pupil alignment is affected by displacements along the axes x and y in the plane perpendicular to the gut ray, and by rotations α and β about x and y respectively. We have the following relationships for relative pupil alignment:

$$\Delta R/R = 2\ dx/D_{M2}$$
$$\Delta R/R = 2\ dy/D_{M2}$$
$$\Delta R/R = 2\ d\alpha\ F_{FIRST}$$
$$\Delta R/R = 2\ d\beta\ F_{FIRST}$$

where D_{M2} is M2 diameter and F_{FIRST} is focal ratio at the FIRST focal surface. We assume D_{M2} = 314.7mm and F_{FIRST} = 8.68. Figure 2 gives the resulting alignment budget for 1 arcminute tilt tolerances and 0.1mm decenter tolerances. With an RSS total of 0.7%, these tolerances assure insignificant adjustment of the alignment budget.

Optical components: RSS of the pupil alignment errors induced by tilts and decenters of each component in the photometer separately, assuming a tilt tolerance of 1 arcminute and a decentering tolerance of 0.1 mm. Sensitivities calculated by ratracing. Since all optical components preceding the cold stop (M3–M8) are mounted directly from the S-bench, and assuming the S-bench to be stiff, these tolerances represent the alignment between each optical surface and the S-bench.

CS to S-bench: the CS is a hole in the 2K enclosure (cold box, CB) containing final optics (M9, dichroics, flat mirrors) and detectors. Relative pupil alignment is sensitive only to displacements x and y in the plane perpendicular to the gut ray:

$$\Delta R/R = 2\ dx/D_{CSx}$$
$$\Delta R/R = 2\ dy/D_{CSy}$$

where $D_{CSx/y}$ represent major and minor axes of the (generally elliptical) CS. The current design (bolpht126b) has D_{CSx} = 45mm and D_{CSy} = 39mm. Alignment tolerances of 0.1mm therefore gives relative pupil alignments of 0.4% and 0.5%, respectively, an RSS total of 0.6%. Again, this is insignificant for the total budget.

5. Conclusion

The fractional pupil alignment budget has three contributors: optical design, telescope alignment and instrument alignment, contributing with 5%, 4%, and 6.1% (or 10.2%), respectively. The total budget predicts a fractional alignment of 12.3% (or 16.0%), corresponding to a 25% (or 32%) loss in throughput. The throughput of teh undersized pupil is therefore 75% (or 68%).

For a total instrument throughput budget of 27%, the remaining throughput budget is 27% / 75% = 36% (or 40%).

Although the above budget depends upon changes in optical design, this dependence is weak. The instrument alignment budget has been found to be identical for an earlier design (BOLPHT80), and although one may wish to improve pupil aberrations, such improvements are limited.

It is important to clarify the specification for alignment between telescope and instrument, and to reduce it if possible. However, if the assumption made is correct then there is a good balance between the contributors in the presented pupil alignment budget.