**TITLE:** Set-up and alignment procedure for the Telescope Simulator imaging mirror

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| **1.0** | | First issue of the document |
| **2.0** | | **Modifications after lab trials** |

## CONTENTS

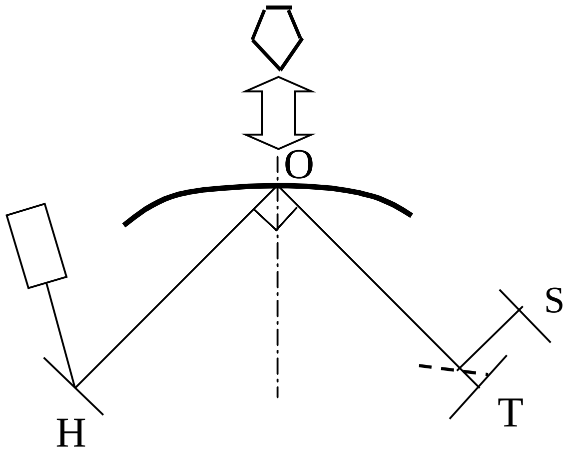


## APPLICABLE AND REFERENCE DOCUMENTS

**RD1** SPIRE-Design of the telescope simulator imaging mirror, SPIRE-RAL-NOT 000621 (21/05/2001)
**RD2** SPIRE-Telescope simulator optical design, SPIRE-RAL-NOT 000622 (08/05/2001)
**RD3** SPIRE-Telescope simulator requirements specification.

This document aims at presenting a procedure for alignment of the telescope simulator imaging mirror adopting a step-by-step approach. It follows the first remarks and considerations presented in the design document of the imaging mirror (see RD1).

**1. Required alignment.**



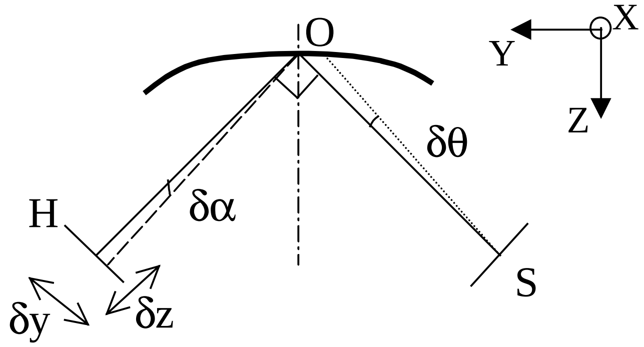

The objectives are:

a. To linear-position point O at the prescribed distance from H (= $R_{SM}$), in plane close to horizontal.
b. To angle-position the mirror (normal at O) to 45 degree from the line OH, in horizontal plane.

Any source focused through the pinhole H in the direction of O (the mirror centre referenced by a cross-like mark on the surface) will then be correctly imaged (aberration free). The absolute position S of the image is not critical to pre-define, as it can be determined during initial set-up of the FIR signal on SPIRE's centre detector, using the control-law optics to perform fine-tuned adaptation to the complete system (see RD2).

Taking into account the diffraction spot diameter ~2F#λ ("pixel" size), aberrations requirements are set to ~1/20 of the value leading to a rms spot diagram radius no larger than ~0.1 mm at the shortest wavelength 250 μm.

Taking separately the different possible deviations (lateral, longitudinal and angular, see figure below), with constraints based on GO max rms spot diagram radius of ~0.1mm, the following tolerance limits are defined:




- Longitudinal shift of H along direction HO: $\delta z = \pm 2$ mm max.;

- Lateral shift of the source (with respect to H, parallel to HO): $\delta y = \pm 1$ mm max.;

- Angular deviation (centred about O): $\delta\alpha_y = \pm 5$ arcmin max in horizontal plane (Oy),
  $\delta\alpha_x = \pm 10$ arcmin max in vertical plane (Ox);

- Angular deviation of calibration source S (centred about S): $\delta\theta < \pm 30$ arcmin (limited by the clipping at the mirror edge of a source gaussian beam , 1/e amplitude level);

Grouping the effects would lead to more stringent tolerance requirements as seen below with the case of the composition of some critical errors (lateral position error δy can not occur at the same time as the horizontal angular deviation $\delta\alpha_y$):

- Case $\delta z = +1$ or -1 mm: $\delta\alpha_y$ is restricted to the range ± 3 arcmin

- Case $\delta y = +1$ or -1 mm: δz is restricted to the range ± 0.7 mm

Measurements of the deviations from ideal position could be performed during alignment and set-up at visible wavelength. This global tolerance budget can then be divided into different parts, detailed below, specific to component (mirror surface definition) or step of the alignment procedure.

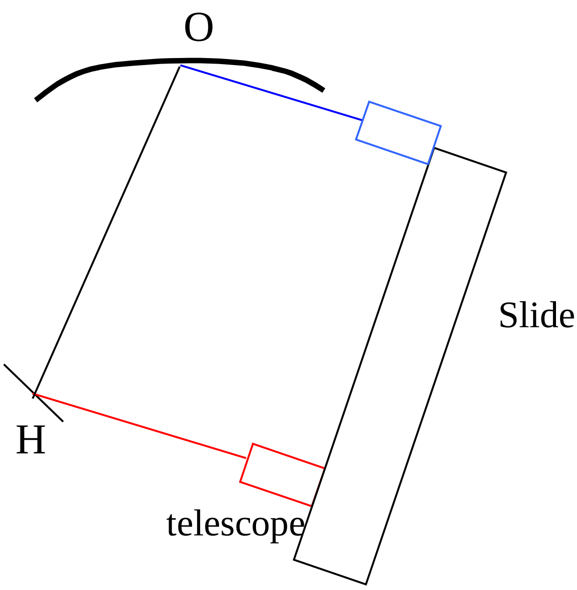
The complete simulator system should simulate a real telescope which was originally designed with a WFE (wavefront error) of smaller than 10 µm (goal of 6 µm) which translates into a Strehl ratio of at least ~0.95. Attempts to analyse incoming diverging beams (finite diameter, gaussian amplitude distribution) reflecting on the mirror seems to show that the Strehl ratio would not be below 0.95 for the above defined constraints (max input field positions); although not all component dimension and shape effect affecting the beam (diffraction, beam-clipping) are taken into account (i.e. pupil mask geometry).

## 2. Detailed method.

Below are discussed the 2 main processes required to correctly position (linearly and angularly) the reference point H and the imaging mirror. After full-scale practical trials, it was found that the angular position procedure (see step b below) should be rather performed before the linear position (step a).

### a. Linear position

- Set-up H & O as shown in figure below, and view using alignment telescope (AT) or microscope mounted on RAL's radius slide.

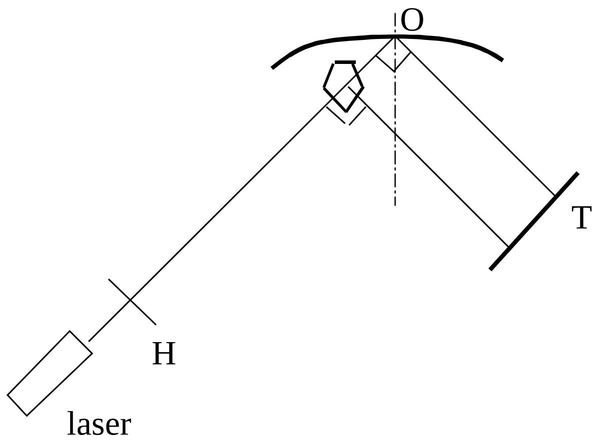



Using a fixed focus for the AT ensures that the OH is parallel to the slide direction. The slide mounting should ensure that the slide travel is horizontal, i.e. parallel to the bench, so that OH is too (for in-plane propagation). The distance OH is set to the $R_{SM}$ value (see RD1 and RD2 for details concerning constraints and consequences of this value).
In practice, the radius-slide is not long enough for the measurement in one go. But a first measurement over a metre distance (~$R_{SM}$/2, precisely known with the electronic box of the radius-slide) between O and intermediate point H can be made accurately (with the AT pointing first at the fiducial mark in O then being translated on the radius-slide parallel to the bar/optical rail supporting pinhole H). The ref. H can then be translated along the bar, which has a mm graduated scale, to reach the total required $R_{SM}$ distance.

-> *Tolerance:*

- longitudinal position of H with respect to the mirror O (on the common base-plate) $\delta z < \pm 1$ mm.

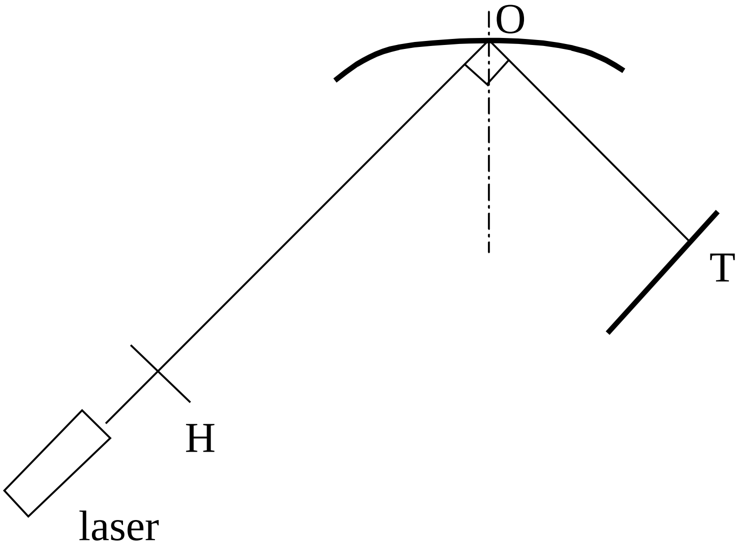
### b. Angle position.




- A collimated test beam (laser) is introduced and aligned to point through H & O.
- The pentaprism is introduced ahead of point O to turn the beam through 90 deg. in horizontal plane after being independently referenced to the optical bench surface and/or by setting PP output pointing in vertical plane to maintain constant beam height above the bench and so preserve the horizontal.
- The reference flat mirror T is then added, and angle-aligned to retro-reflect the test beam.
- The pentaprism is then removed and the laser is directed via O to retro-reflect from T.
- The imaging mirror is then angle-aligned to bring the beam returning from T back onto H. It requires a small polished area around O (see mirror definition in RD1), and the mirror surface curvature will cause some defocus for the laser beam. If this prevents sufficient accuracy being reached, then it may be necessary to make the distance OT close to $R_{SM}$ and use a laser focused through H (but with small relative aperture to respect the small used area on the imaging mirror).

-> *Tolerance:*

- angular position of H with respect to the mirror O (on the common base-plate) $\delta\alpha_y < \pm 1$ arcmin and $\delta\alpha_x < \pm 2$ arcmin, corresponding respectively to $\delta y = \pm 0.6$ mm and $\delta x = \pm 1.2$ mm at H,
- mirror surface (parallelism of surface symmetry axis + mounting with respect to optical axis): $\delta\alpha_y = \pm 1$ arcmin max, $\delta\alpha_x = \pm 2$ arcmin max.

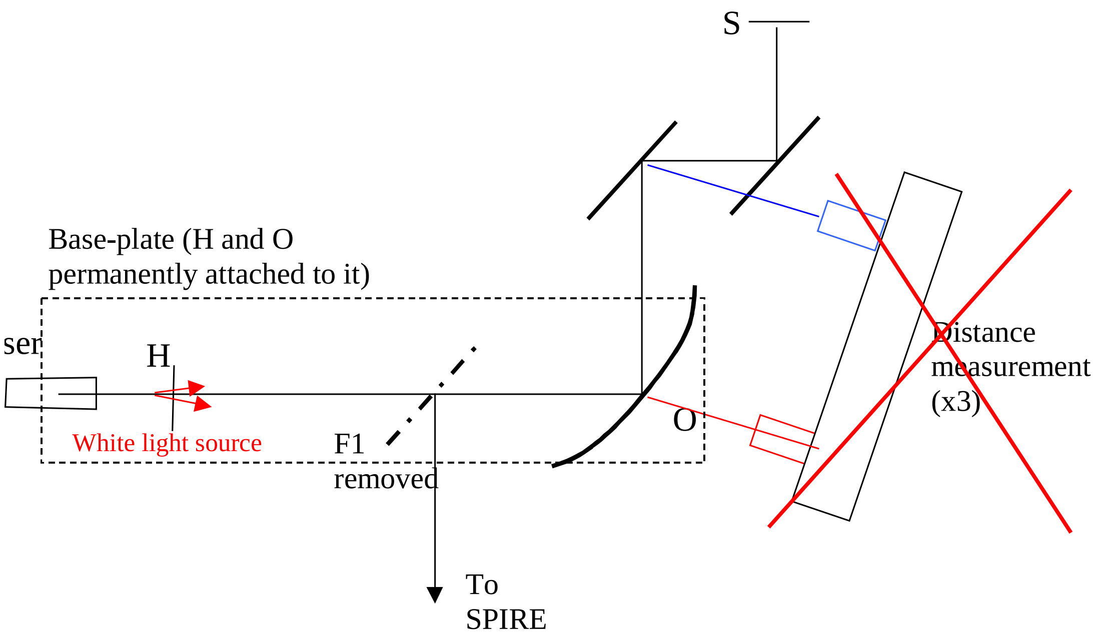



In general, angle-alignment at O will lead to linear-position drift, and this must be monitored & corrected during alignment i.e. the position & angle at O must be iterated until both are within spec. Because the mirror is large, shims will be used and need to (re-)calculated at each iteration.

The procedure is complicated by the fact that, in the real design the path between O and the calibration sources S, is not straight, but is folded at least once (see optical layout of the complete system with sources in RD2). Also it is 'branched', i.e. there are different S positions for different sources.
This problem can be overcome by making the alignment in the reverse direction, i.e. placing H after the imaging mirror (see figure below). By omitting the first fold mirror F1 during alignment H can be made fixed permanent pinhole on the bench: the pinhole H and the imaging mirror are kept in fixed position with respect to each other, aligned via the above sequence, on a common base-plate+long bar.

## 3. Setting of source positions.

After making the above alignment steps, it is then necessary to determine the conjugate position S, as this is the location to which the relevant source must be aligned. This has to be done via whatever folding chain of elements lies between the chosen source & O, and it has to be repeated each time that the source is switched.




The angular position of S is given readily by the trace laser beam from H (the fold mirror F1 has to be removed to see it). ~~The linear position along the focus direction is more difficult to set, because visible imaging can't be made, and it is hard to measure the fold path length accurately.~~
~~However, the radius slide or travelling microscope method is the only way to set the path along OS equal to $R_{SM}$. This will require several separate distances to be measured, one of which is possibly vertical in the case of the FIR laser source due to height difference between the optical benches. For this purpose fiducial marks at the centre of each mirror will be needed, and position aligned on the laser spot before the OS distance measurement. This measurement is laborious but should only have to be done once for each source, with fixed reference pinholes for each of the source positions S then being set up.~~
Considering the size and weight of the radius-slide, the linear measurement of the different stages of the folded path between O and S are not practical, especially for the vertical stage required due to the difference in height between the FIR and Tel.Sim. benches. Instead the laser beam from H gives the longitudinal axis direction along which S should be set. Illumination of the mirror with visible white light[1] from H allows to track the focus position S either:

[1] White light was found better than divergent HeNe laser beam because the coherence of the latter can induce speckle patterns at the focus (from interaction with mirror surface roughness) that may lead to difficulties in interpretation of the mirror focus position. The possible sources of visible "white" light are:

- the fiber: bright source but not homogenous quality output + expected losses due to numerical aperture not adapted to the system F-number,

- manually with a black screen and with dark lab (to increase contrast), by recording the spot size when the screen is moved longitudinally along the propagation axis set earlier by the laser. The best focus position in term of beam shape can be estimated this way,
- or: using a detector (i.e. such as CCD video camera) moved longitudinally the same way as above, recording the intensity (and also the spot size eventually) of the refocus beam. The position of maximum intensity would define the estimation of the best focus location.

-> *Tolerance:*

- the rest of the budget dedicated for the path between O and S: $\delta z_{O\text{-}S}$ should be large enough to be broken down into the several parts to be measured,
- the source with respect to S: $\delta\theta < \pm 30$ arcmin.

Angular deviations $\delta\alpha_y$ and $\delta\alpha_x$, for both source and mirror, would result in a lateral position error $\delta y$ for the realised source point S. To limit the build-up of error from that effect, it is then necessary to ensure that the light source (calibration source) passing through S impinges on the mirror at O - or at least centred on O as the pupil mask may prevent direct view of the mirror centre from the source points S which may require that the pupil mask should be set later-. This lateral position error of S, after aligning any calibration source to S, is transferred into an angular misalignment error whose effects, on the image conjugate point (image focal plane of the telescope simulator) could ultimately be compensated during the setting-up of steering mirrors F1, F2, F3 nominal and angular position (see RD2 for the design of beam-steering control system) and do not affect the beam quality shape.

Preliminary tests of the above alignment procedure have been performed with a short focal length ellipsoidal mirror, not known accurately enough for further relevant measurements. Step described in the above section 2-a could not be fully completed as the AT was not mounted on a radius slide and its translation stage allows a minimal linear travel shorter than the expected focal length (a multi-step, more approximate method of translating the AT was used). Step 2-b with the pentaprism could be checked. Setting-up reference surface such as the flat mirror T can be made via auto-collimator mode of the AT. The degree of freedom in rotation needed for angle-alignment (step 2-b) requires rotation about vertical axis at O otherwise new introduced error in OH distance will need to be taken into account. The mirror, the pentaprism and the transfer mirror needs to be referenced initially to a common horizontal reference plane.

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- the internal lamp of the AT: it can be tuned to the right F-number for illumination but the source is not very bright and a lot of losses occur in the optics of the AT leading to low final contrast even if lab under darkness.