SUBJECT: **CM4 hole size considerations and Stray-light control**

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KEYWORDS:

COMMENTS: **This document considers the effect of a central hole in the steerable mirror CM4 on the control of stray-light seen by the SPIRE detectors.**

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1. INTRODUCTION

This note describes the way that a hole or an absorbing patch in the centre of the SPIRE beam steering mirror (BSM, also referred to by the symbol CM4) can be used to restrict the view that the SPIRE detectors may have of surfaces other than the main telescope surfaces and field directions other than those within the normal SPIRE field of view. Alternatively, it shows how too small a hole permits the detectors to receive stray radiation from directions other than from within the desired SPIRE field of view.

2. THE APPROACH

When considering straylight onto the SPIRE detectors, the best initial approach is to consider the view that the detectors have through the optical system that is used to collect and focus radiation onto them. This has been the approach followed in the analysis of the SPIRE instruments (photometer and spectrometer) and CODEV models of the so-called 'reversed' optical systems have been constructed and maintained in order to do this. The term 'reversed' means that the first optical surface (the object surface) is the detector and the last 'image' surface is a surface outside the FIRST telescope, this being the reverse of the normal sequence when analysing the imaging performance of an optical system.

By tracing rays out from the detector through a reversed system, one can follow the footprints of beams that define the geometrical optical view (i.e. ignoring diffraction) that the detector has of the surfaces distributed along the optical path. This technique has been used to generate 'beam sections' and 'beam envelopes' to guide the sizing of mirrors in and structural surfaces surrounding the SPIRE optical system. These beam envelopes are defined by rays traced from various starting points on the detector through points distributed around the edge of a system aperture stop. In the SPIRE photometer, this stop is located between mirrors PM8 and PM9. In the spectrometer, the stop is located between mirrors SM7 and SM6.

For the present study, a modified CODEV model was used which temporarily placed a circular system stop coplanar with and near the physical centre of CM4 (the plane of CM4 is conjugate to the plane of the physical stop). By tracing rays through points on the edge of this stop and by varying the radius of this stop, it was possible to determine the footprints of this small part of the full detector beam envelope at various surfaces between CM4 and space. In this way one could determine what part, if any, this small area on CM4 plays in controlling which surfaces the detectors see through it. Consequently one could then draw conclusions about what size this patch should be in order to maximise the straylight control that its presence might offer.

3. RESULTS

3.1 Photometer

3.1.1 Viewing cryostat surfaces

Figure 1 shows a view that a photometer detector may have of surfaces behind the primary mirror via a 0.8 mm radius patch of CM4 and a small slightly off- centre part of the secondary mirror. The rays shown reflected from the secondary mirror are diverging from a virtual image of the detector approximately 162 mm beyond the pole of the secondary mirror, so the surface viewed will be out of focus. This view was actually found during initial APART analysis of an earlier version of the photometer (PH126b). The present work uses the latest photometer model, PH154B.

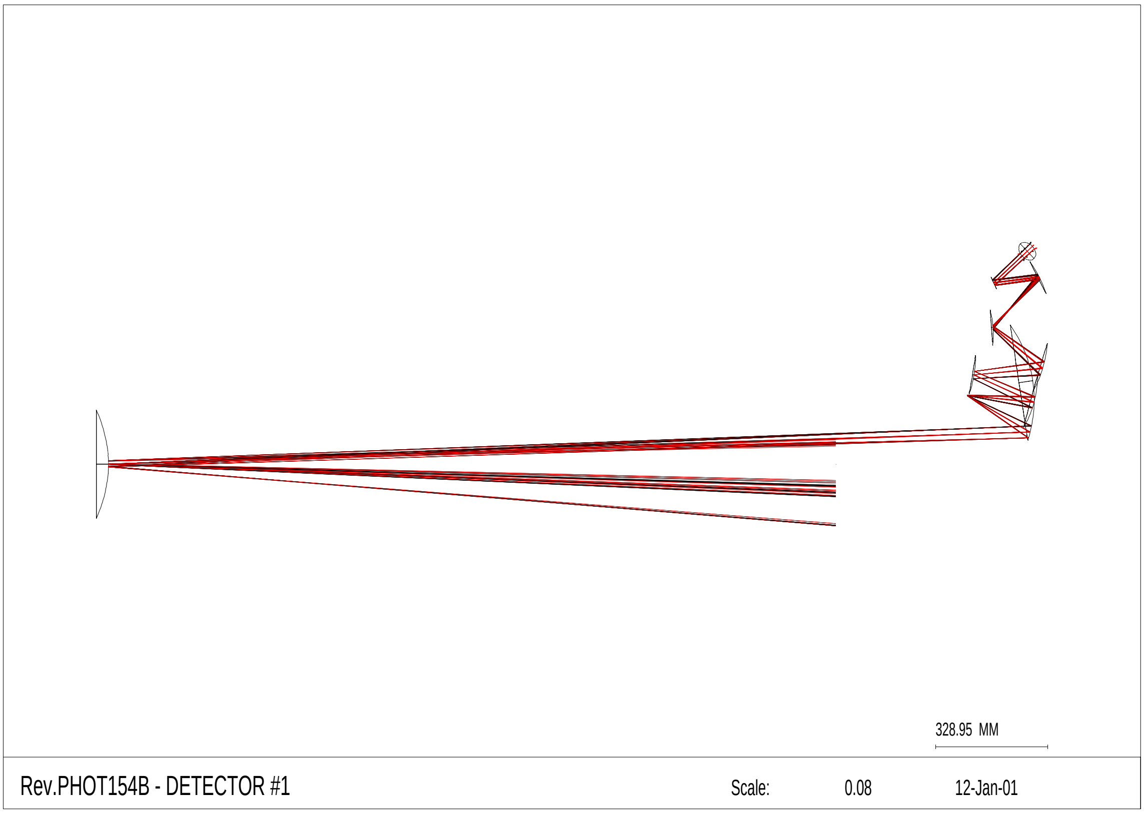

Figure 1 Detector view of the cryostat space

Figure 2 shows the composite beam footprint of this optical arrangement in the plane of the 135-mm radius hole in the primary mirror, with CM4 kept stationary in its untilted position (i.e. no chop or jiggle included yet). It is clear that a 0.8-mm radius 'hole' in CM4 would still permit the detector to view inside the primary hole boundary because of the gap between the boundary of a beam from one point on the detector and the boundary of the primary hole. Figure 2 also shows that there is an area on the composite footprint that is common to all the individual footprints. This common area can be made bigger by increasing the size of the stop or hole located on CM4. Ideally this common area should be made big enough (and be shifted, if necessary, by shifting the centre of the hole or stop at CM4) so as to encompass the primary hole. In this fashion every point on the detector can be prevented from seeing through the primary hole via rays which reflect from CM4 from regions OUTSIDE the hole or stop located there, and thence via CM3 (the SPIRE objective mirror) and M2 (the telescope secondary mirror).

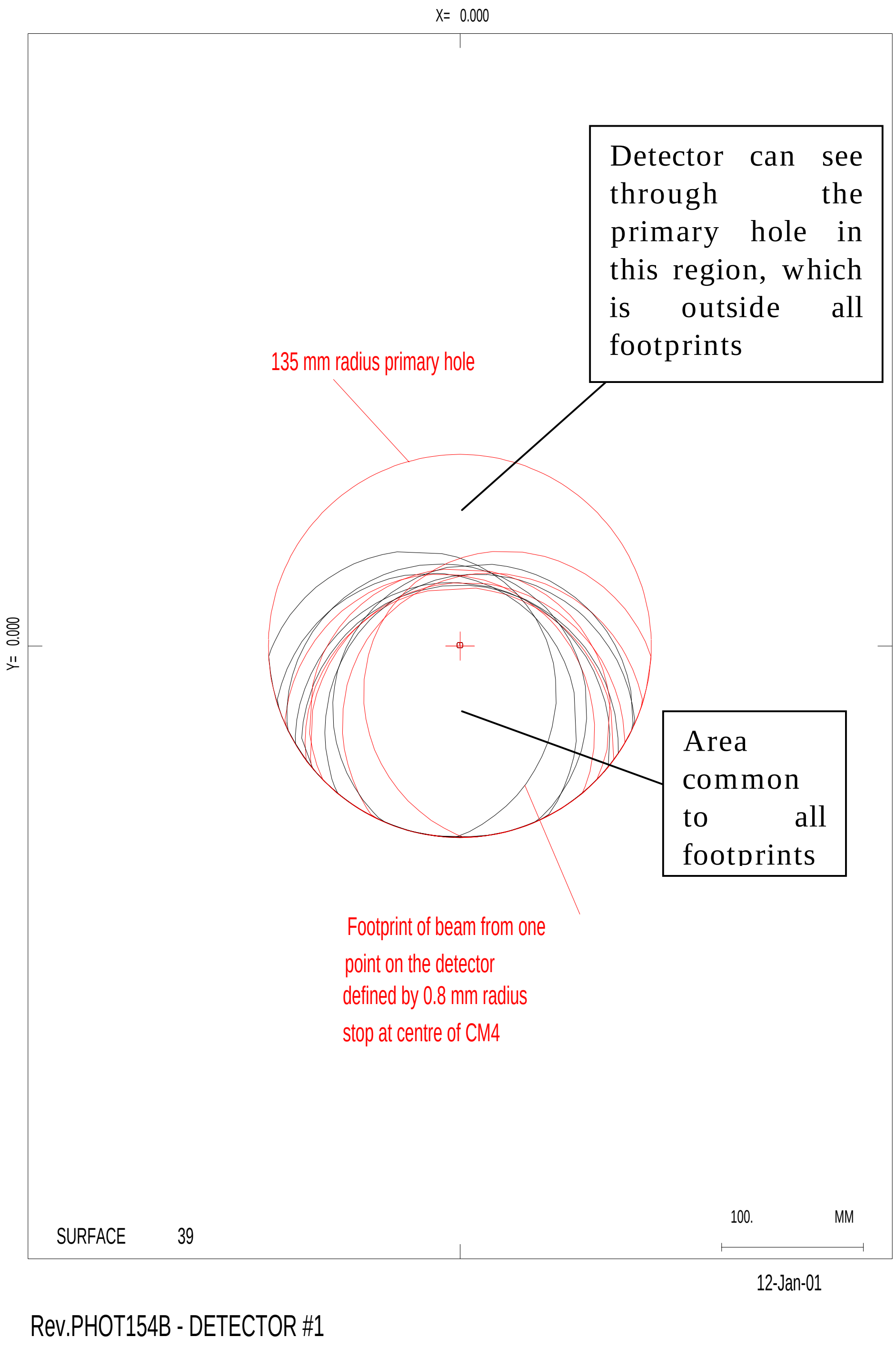

Figure 2 Footprint of CM4 'hole' beam at the front of the hole in the primary

Matters are complicated by the fact that one must first include the effects of chopping and jiggling CM4 over its full ranges of tilt in both directions. Because of imperfect pupil imagery by CM3, inclusion of these tilts spreads out the size of the composite footprint and REDUCES the size of the area common to all footprints. This is illustrated in figure 3, which corresponds to figure 2 but with the full range of CM4 tilts included. The area common to all footprints is indicated.

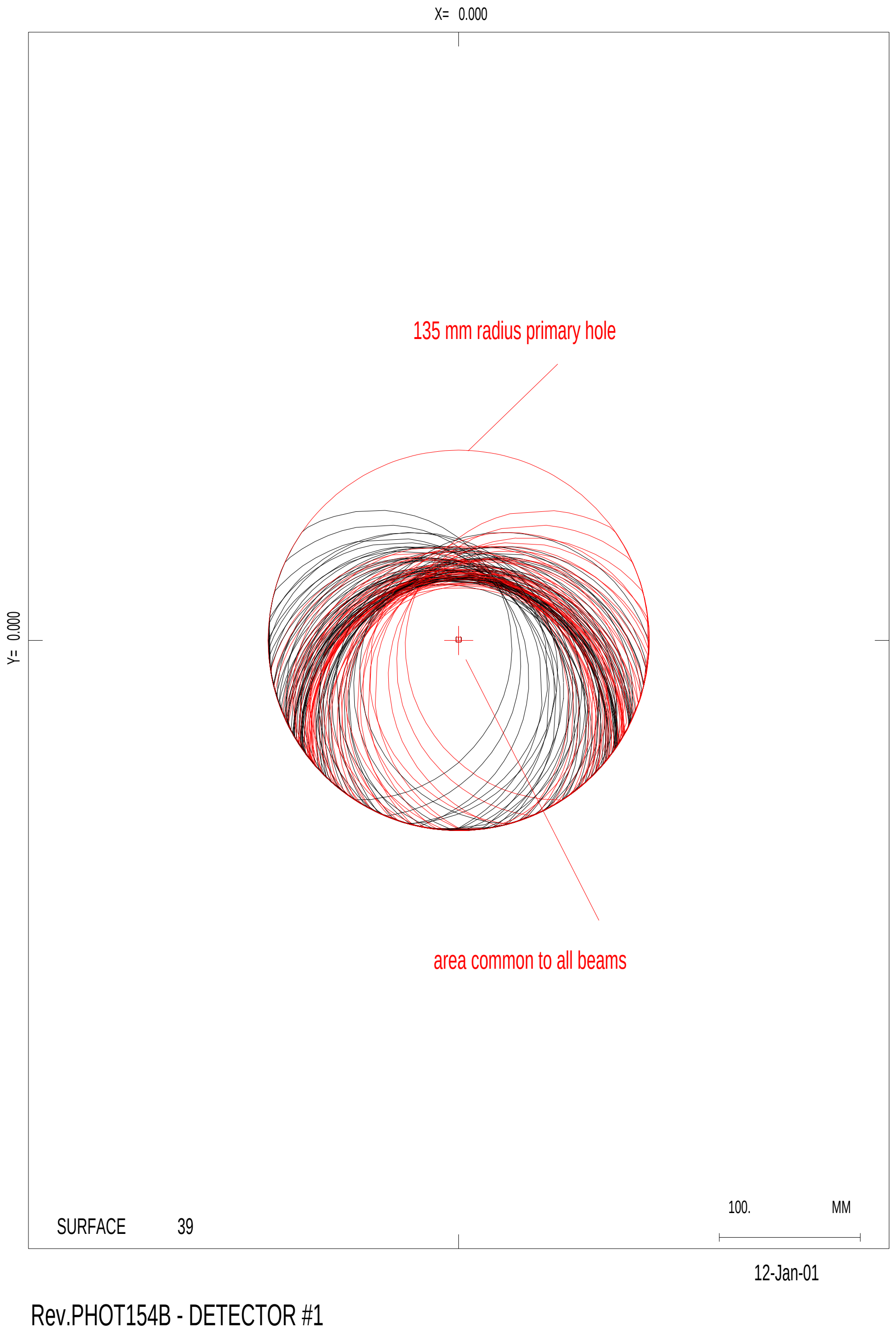

Figure 3 Footprint of CM4 'hole' beam at primary hole with CM4 tilts included

Figure 4 shows the effect of increasing the 'hole' radius to about 1.6 mm. The footprint is presented at the primary mirror as before, but ray tracing was continued out to space so that the clipping effect of the finite 308.3-mm diameter secondary mirror could be included. Figure 4 shows that the size and location chosen for the 'hole' or stop at CM4 results in beams traced from the photometer detector whose composite footprint just clears the 135 mm radius hole in the primary mirror after the first reflection from the secondary mirror.

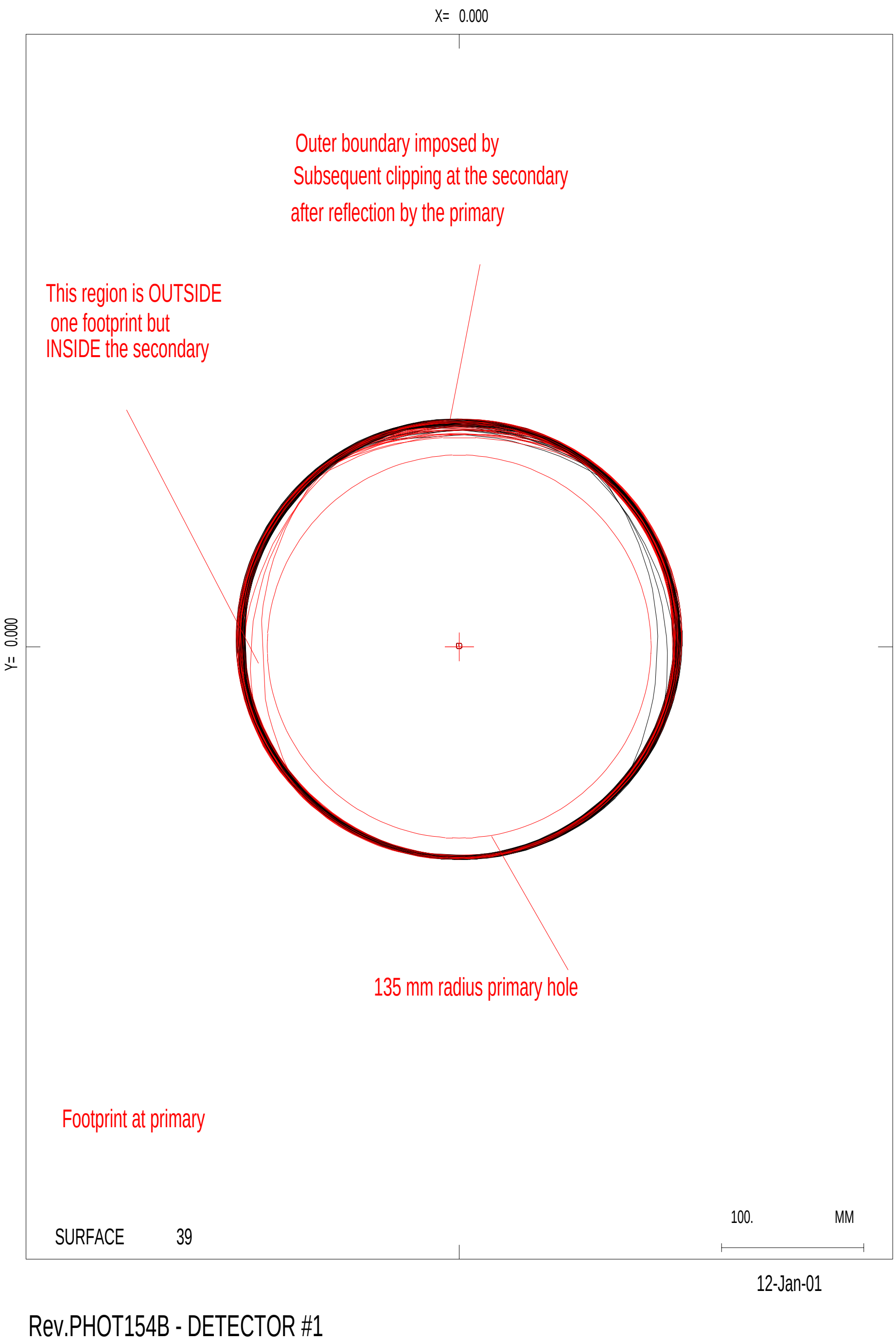

Figure 4 Footprint at M1 of beams defined by a 1.6-mm radius stop on CM4

3.1.2 Avoiding a double-pass through the telescope

An important feature is indicated on figure 4, namely that, for some of the more extreme footprints, (e.g. resulting from tilting CM4 to one of its chopping limits), there is a region just OUTSIDE the footprint which permits some part of the beam from a point or region of the detector view to intersect the secondary mirror a second time. Any ray from a point on a detector which can be traced to the region of the primary shown in figure 4 between the inner primary hole and the outer boundary imposed by secondary clipping, will hit the secondary a second time. This means that it is therefore possible for part of the unobscured detector beam (that using parts of CM4 OUTSIDE the proposed 1.6 mm radius hole obstruction) to view space after making TWO passes through the telescope.

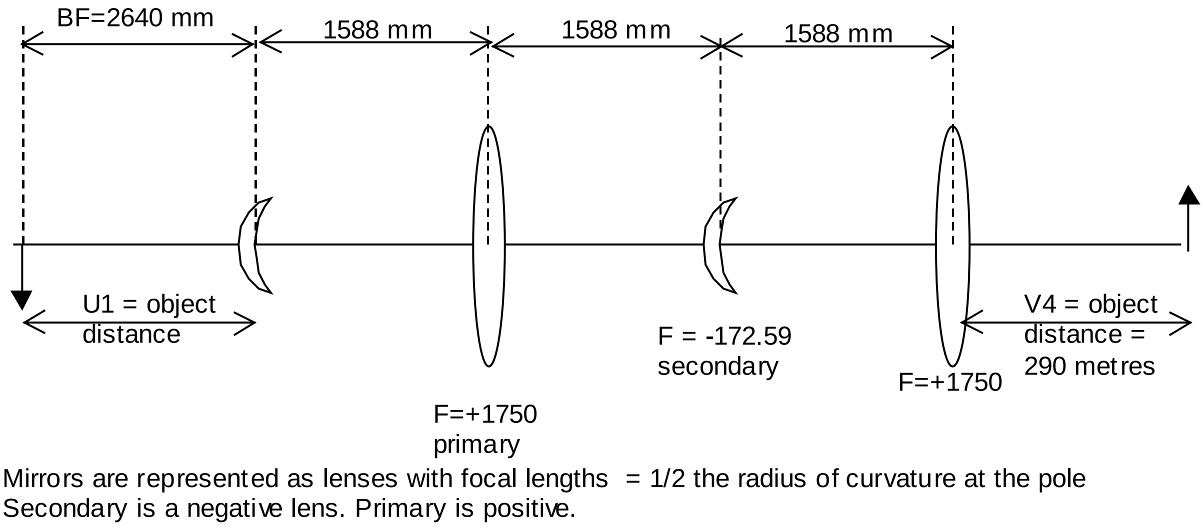

Figure 5 Paraxial representation of two-pass telescope

A simple paraxial analysis of an optical system consisting of secondary-primary-secondary-primary (see figure 5) shows that for an object located at the back-focus of the telescope, we should expect a real –1.0 magnification image located in space at about 290 metres in front of the primary mirror. A CODEV analysis confirms moderate imagery at a distance of 284 metres. Figure 6 shows rays converging on this image from the primary. Figure 7 shows the boundaries of spot-diagrams for points at the centre and on the edge of the photometer detector (no vignetting by primary hole or secondary edge has been included in those ray traces, which are for illustration only).

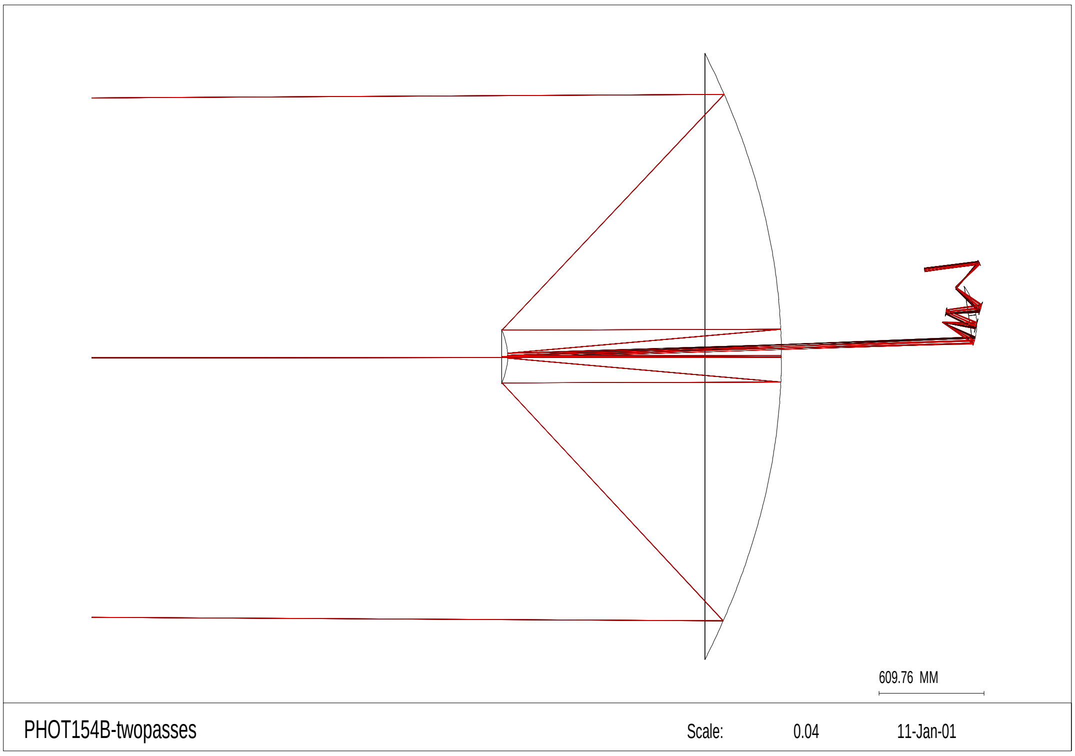

Figure 6 Rays converging on detector image at 290 metres after two passes through the telescope

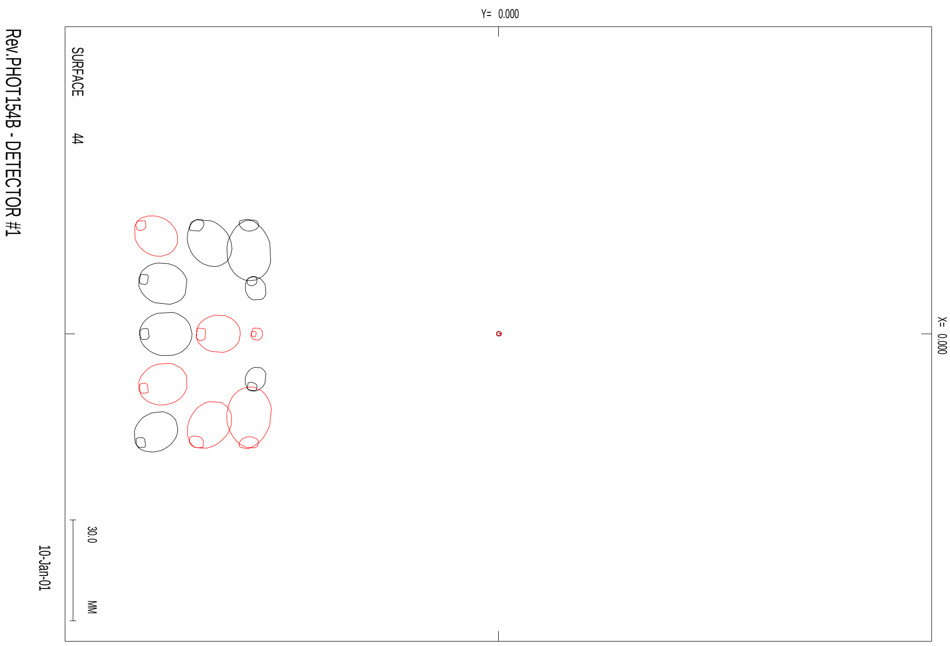

Figure 7 Spot boundaries of two-pass detector image

The central spot in figure 7 is located in a direction about 0.0186 degrees from the telescope axis. The SPIRE boresight is 0.183 degrees off axis. This is the direction that the beam traced from the SPIRE detector exits the telescope on the first pass through it. As expected, given the telescope's angular magnification of about 10 (angular de-magnification of 0.1 when used in the reverse direction), the second pass changes the object direction to about 0.1*0.183 degrees. So a second pass through the telescope will permit the detector to see a defocused region of the sky centred about 0.9*0.183 degrees = 10 arc minutes away from the region being observed by SPIRE. The part of the beam which can make these two passes also permits the detector to see telescope emission twice.

It is possible to avoid this situation by increasing the size of the hole / spot at CM4 until the common area of the overlapping footprint boundaries produced by tracing the CM4 hole to the primary and then onwards to the secondary mirror again CLEARS THE EDGE OF THE SECONDARY MIRROR. This situation was achieved by increasing the radius of the stop at CM4 to 1.8 mm and adding a small +0.1-mm Y-shift of its centre at the same time, the results being shown in figure 8. A slight change in presentation has been made to enable the clearance over the secondary radius on exiting the telescope to be clearly shown (the radius of the 'second' secondary was increased by 50% to enable some rays to be traced to it and to permit the footprint boundaries to be shown).

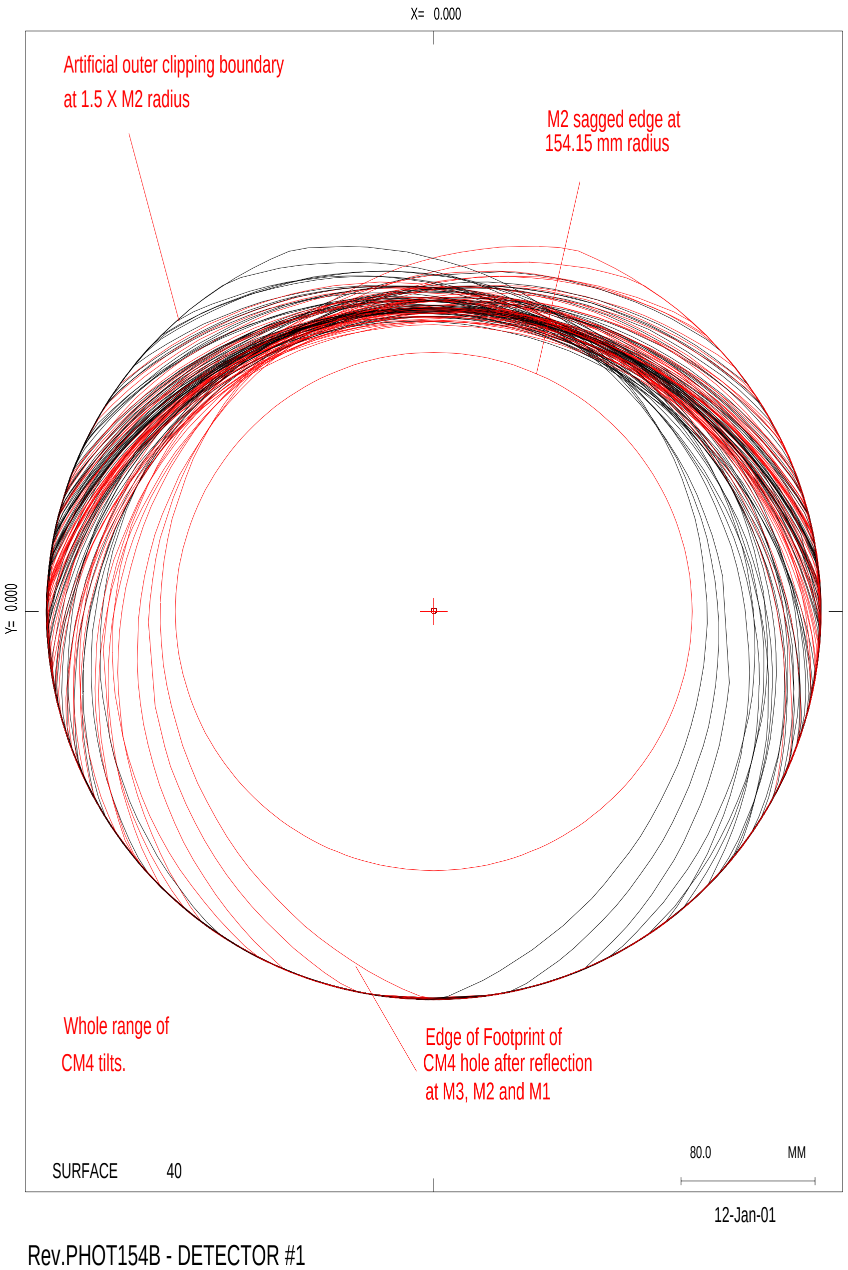

Figure 8 Composite footprint of photometer beams defined by a 1.8-mm radius stop at CM4 clearing M2 as they exit the telescope.

3.2 Spectrometer

3.2.1 Avoiding cryostat views and a double-pass through the telescope

An analysis similar to that described above for the photometer was carried out for the spectrometer, model SP501E. This again involved slightly adjusting the radius and X-Y position of a 'hole' in CM4 in order to provide a composite beam footprint at M2 which had a common area large enough to circumscribe M2. The major differences here are

- The amplitude of the tilt of CM4 in the 'chop' direction was reduced to +- 30 arc seconds,
- Two extremes of corner-cube shift in the FTS path were modelled, in order to cover the cases of different optical path lengths from the detector through both arms of the FTS.

The main result of this analysis was that the use of the same 'hole' at CM4 as that defined for the photometer produces a spectrometer-viewed footprint at M2 which fails, in places, to clear the edge of M2. Figure 9 shows this effect.

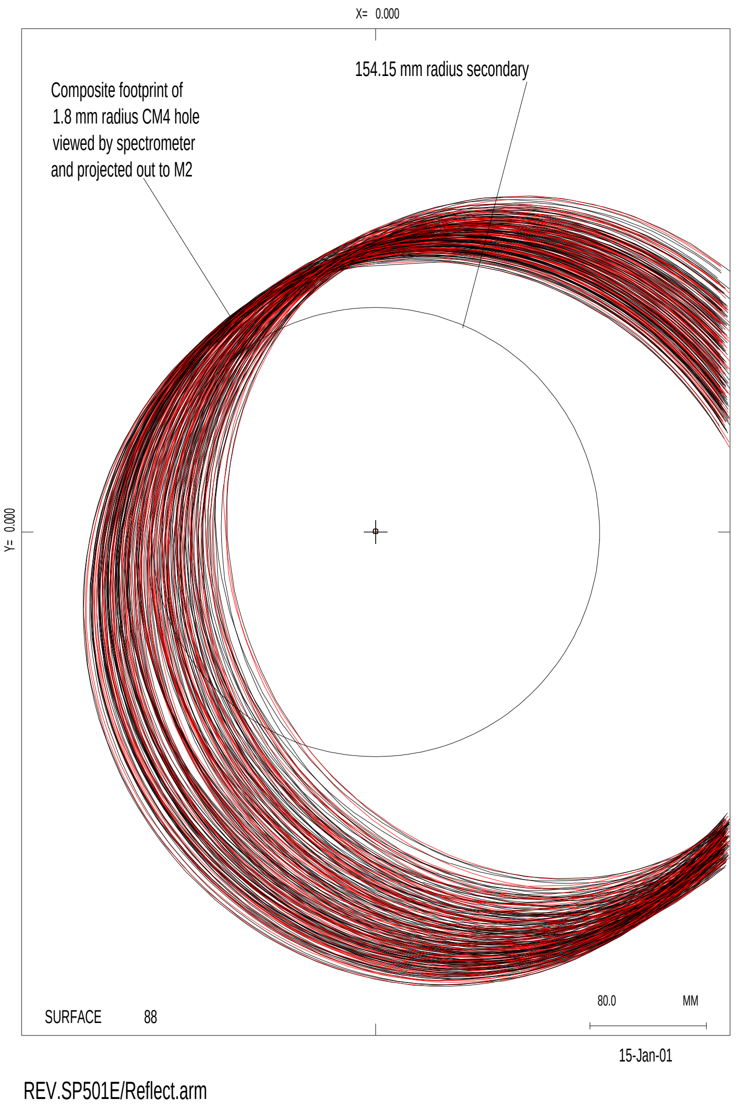

Figure 9 Composite footprint of spectrometer beams defined by a 1.8-mm radius stop, centred at CM4, clearing M2 as they exit the telescope.

In order to produce a spectrometer footprint which clears M2, as in figure 8, it was necessary to shift the 'hole' in CM4 by +0.65 in the X direction. A radius 1.7-mm for the hole sufficed in this case. Figure 10 shows the result.

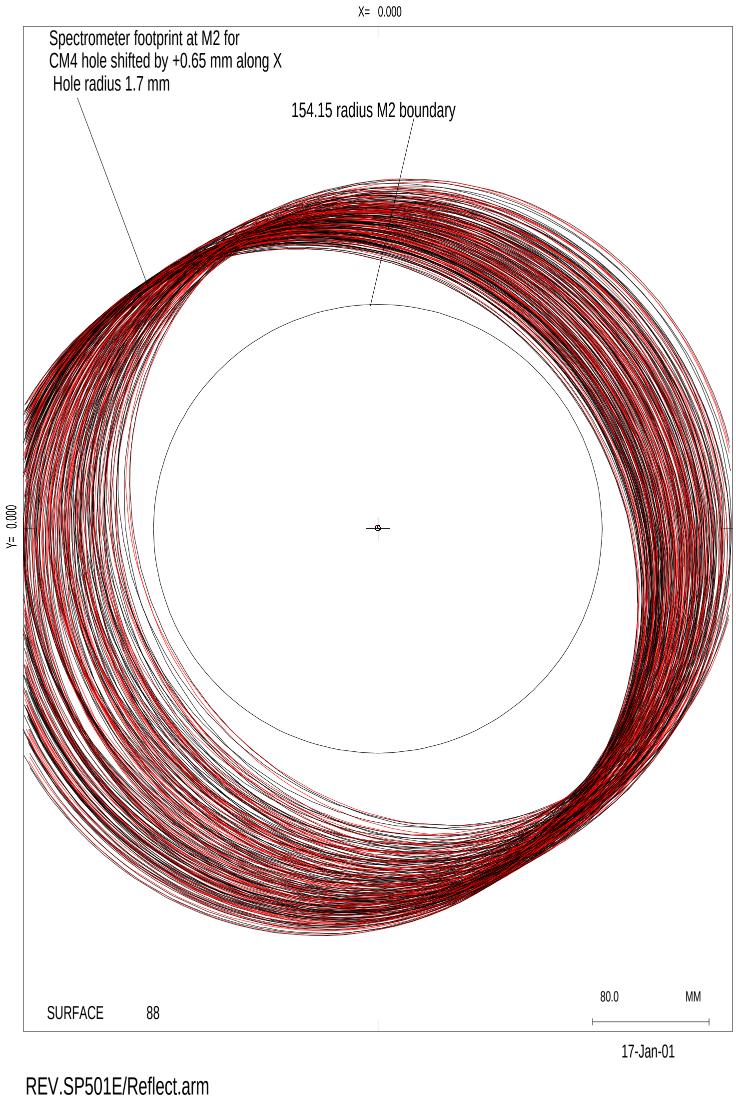

Figure 10 Composite footprint of spectrometer beams at M2, defined by a 1.7-mm radius stop at CM4 shifted by +0.65 mm along X

4. THROUGHPUT CONSIDERATIONS

The effective aperture of the FIRST telescope is 3283 mm, based on the aperture stop being located at the secondary, diameter 308.3 mm. The percentage of the total entrance pupil area obscured by the secondary is therefore 100*(308.3/3283)**2= 0.88 percent. The creation of a 'hole' in CM4 of a certain size exceeding that needed to cover the central obscuration formed by the secondary obviously reduces the throughput of the system. The reduction can be estimated, for both instruments, as follows.

4.1 Photometer throughput reduction due to a central hole in CM4

Figure 11 shows the footprint of the SPIRE photometer stop re-imaged at CM4 in the direction from the centre of the detector. It is almost circular, radius approximately 12.2 mm. A hole radius 1.8 mm displaced by +0.1 mm in the Y-direction will therefore obscure 100*(1.8 / 12.2)**2= 2.2 percent of the beam, for this particular view direction. Thus, the hole in CM4 will subtract a further 1.32 percent throughput, over and above the 0.88 percent reduction that the secondary will produce.

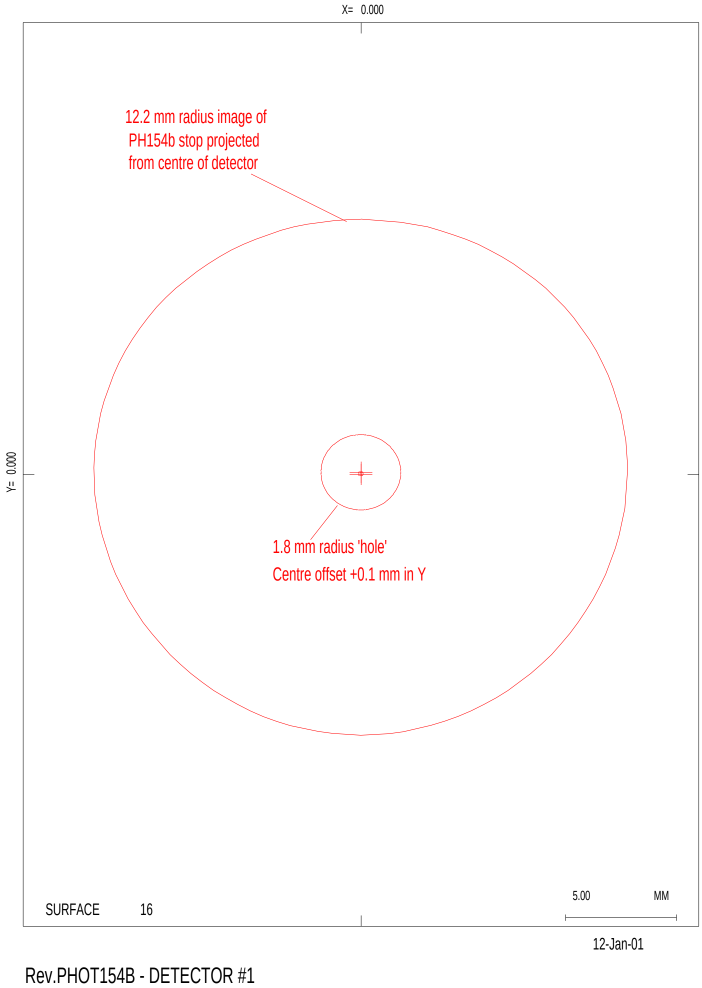

Figure 11 Proposed 'hole' in CM4 compared to total photometer beam area

4.2 Spectrometer throughput reduction due to an off-centre hole in CM4

Figure 12 shows the footprint of the SPIRE Spectrometer stop re-imaged at CM4 in the direction from the centre of the detector. It is almost elliptical, with semi-major and semi-minor axes lengths 12.2 mm and 12.98 mm respectively. The footprint area is therefore π*12.2*12.98 square mm. A hole radius 1.7 mm displaced by +0.65 mm in the X-direction will obscure 100*(1.7**2 / (12.2*12.98))= 1.83 percent of the beam, for this particular view direction. Thus, the hole in CM4 will subtract a further 0.95 percent throughput, over and above the 0.88 percent reduction that the secondary will produce in any case.

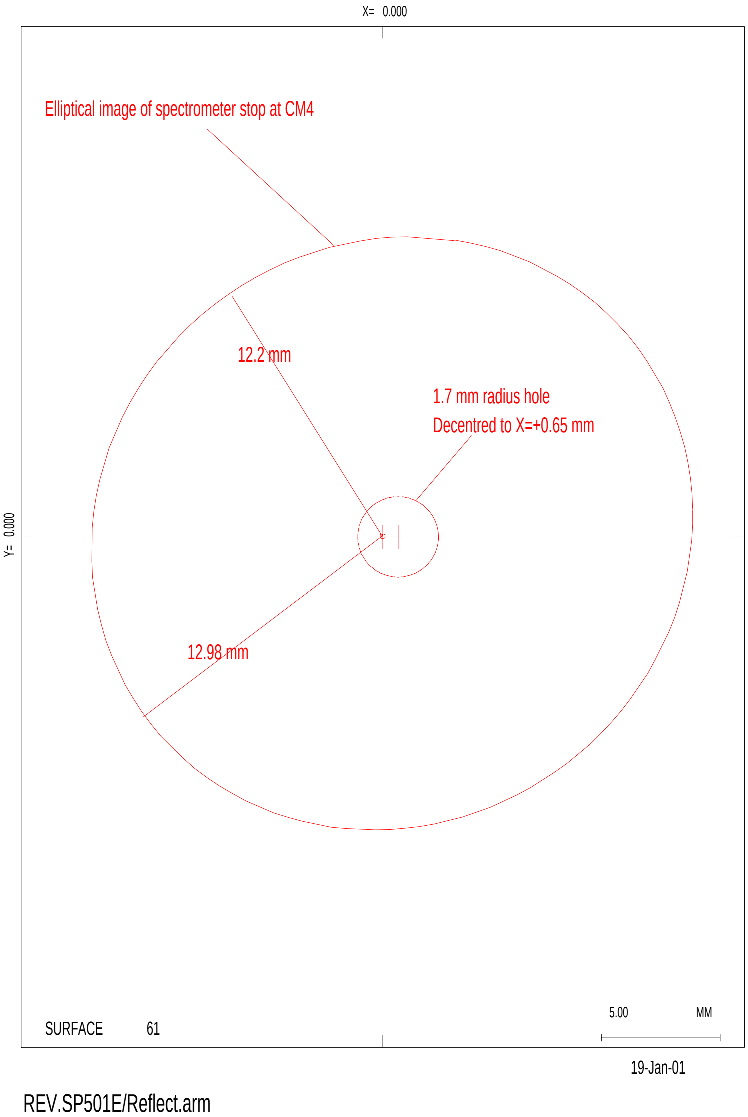

Figure 12 Proposed hole in CM4 compared to total spectrometer beam area

4.3 Throughput reductions due to a single, central hole in CM4

Figures 11 and 12 show that a single, central hole in CM4 must have minimum radius 1.9 mm in order to enclose the photometer's 0.1 mm decentred hole, or a minimum 2.35 mm radius in order to enclose both the photometer's and the spectrometer's decentred holes. A 2.35 mm radius hole will incur throughput losses of the following magnitude:

- Photometer - 100*(2.35 / 12.2)**2= 3.7 percent
- Spectrometer - 100*(2.35**2 / (12.2*12.98))= 3.5 percent

When the loss of throughput (0.88%) resulting from the secondary obscuration is subtracted, the incremental throughput losses become 2.82% and 2.62% respectively.

4.4 Throughput reductions due to imperfect pupil imagery at M2

The present policy for sizing and locating the stop inside each instrument is to make the image of each stop at M2 concentric with and equal to the size of M2, for the central field direction of each instrument and with CM4 untilted. Because of unavoidable residual aberrations in each instrument, for all other field points the image of each stop at M2 deviates by more or less amounts from this central image. Since the telescope beam from a direction in space is limited by the boundary of M2 then, for directions other than the central field point, there may be a drop in throughput caused by a mismatch between the image of each stop at M2 and the M2 boundary. Figure 13 shows the expected loss of overlap area, for each 1.54 mm shift of a pupil image that is otherwise perfectly matched to M2 in shape and size. This shift increment is just 1 percent of the M2 radius (154.15 mm). A total 3.5 % loss of throughput requires a 5.5 % shift of the stop image relative to M2.

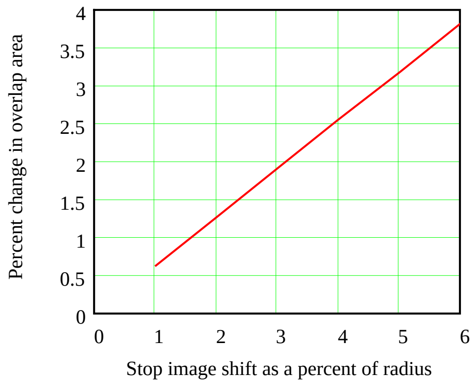

Figure 13 Percentage throughput loss as stop image is shifted

Another result of mismatch is a change in shape and/or size of the stop image, with no shift. For the case where the shape remains circular but the radius changes, the rate of throughput loss is shown in figure 14.

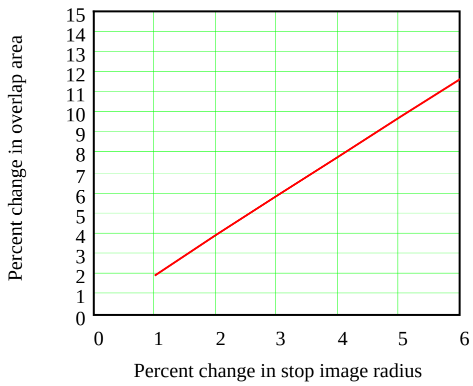

Figure 14 Percentage throughput loss as stop image radius changes

In this case, a 3.5 percent loss in throughput results from a little under 2 percent change in image radius. In practise, the aberrations result in a combination of shift and shape/size change in the stop image, and the computation of throughput variations is complicated. However, estimates for these effects are given as totalling about 8 percent for the photometer in the 'FIRST SPIRE Optical Error Budgets' document[1]. Complications are further increased by the effect on the stop image location of tilting CM4 over its range of 'chop' and 'jiggle' ranges.

5. RECOMMENDATIONS

It is clear that a hole should be implemented in the design of CM4. A set of minimum hole sizes is given in table 1. The ultimate recommended shape, size and location of the hole will have to be decided according to the importance (and cost, in terms of lost photometer throughput) attached to controlling the view that the **spectrometer** has of out-of-fov surfaces.

Instrument (offsets relative to centre of CM4)	Radius mm	X offset mm	Y offset mm
Photometer PH154B	1.8	0.0	+0.1
Spectrometer SP501E	1.7	+0.65	0.0
Both	2.35	0.0	0.0

Table 1 Size and location of minimum hole required in CM4 for each instrument

The minimum circular hole recommended as necessary to stabilise the view that the **photometer** has of out-of-fov surfaces has radius 1.8 mm and should be offset by +0.1 mm along Y from the physical centre of CM4 (where the photometer boresight intersects CM4, with CM4 in its untilted position). The extra 1.32% loss of throughput that it will cause will be compensated for by the removal of two straylight paths, namely from inside the primary hole and the cryostat and a double view of the telescope emission. If a centred circular hole is used, its radius must be increased to 1.9 mm, increasing the loss of throughput to about 1.47%.

The analysis carried out here shows that this minimum-size circular hole would not be located in the optimum position to control the view that the spectrometer has of the same out-of-fov surfaces. A centred, circular hole which covers the area of CM4 relevant to the spectrometer will have to be nearly 30% bigger in radius (2.35mm) and will contribute an extra 1.5 – 2 % loss in throughput (depending on the instrument), over and above that resulting from using a minimum-size hole. The alternative to this 'oversized' circular hole is an elongated, non-centred, non-circular hole just covering the combined patch made by overlaying the spectrometer and photometer 'hole' outlines.

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[1] LOOM.KD.SPIRE.2000.002-2, author Kjetil Dohlen, LAM, 5 December, 2000

The magnitudes of the incremental throughput losses expected to be caused by the loss of reflectivity at CM4 over the area of a hole appear to be of the same order as the variations in throughput over the whole field of view of each instrument and they also appear to be of the same order as the variations in throughput to be expected by tilting CM4. This would appear to make it hard to ignore these 'hole' losses and hence more difficult to justify the 30% 'oversized' hole.