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A Technical Report on a dichroic edge filter for Silmaril

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ABSTRACT: In this technical report, we describe the simulation of the effect of a dichroic edge filter that we consider for the edge filter inside the C-RED One camera of Silmaril. For this, we consider two different ways of doing this dichroic edge filter. Both consist in cutting a normal H-band filter in two and trimming the edge to the right angle to reflect one of the bands away. The first way would use an internal reflection of the H-band. The second way would be to have an external reflection of the K-band.

While the first way would be a total reflection of the H-band, hence no flux loss, the accumulation of the extra optical path due to the H-band going through the glass, and the one due to the path added by the reflection will imply a differential of focal length between the H- and the K-band of more than 2 pixels spread of the H-band on the detector.

For the second way, the extra optical path length due to the H-band going through glass would be partially compensated by the extra optical path length of the K-band due to the reflection, bringing the focal difference to a spread of the H-band to slightly less than 1 pixel, however, this external reflection would still allow some of the K-band flux to refract into the glass, losing some of the K-band flux.

1. INTRODUCTION

For Silmaril, to be able to observe both H- and K-band at the same time, we need to use a so-call "edge filter" close to the detector, in order to let the K-band light go on one half of the detector, but filtering it out on the H-band half of the detector in order to reduce the photon noise due to the K-band thermal background. While we already describe the principle of an edge filter with only half of it coated in the TR #105, such an edge filter seems difficult to provide with the specifications needed and is therefore expensive. As an alternative solution, we are considering the use of an H-band filter cut in half, with its edge trimmed to a specific angle that would reflect one of the bands further on the detector, separating the H- and the K-band.

As the trimmed edge will need to reflect the full width of one of the spectral band, the angle of the trimming need to be large enough, but we want to limit this angle as much as possible to avoid sending the reflected band too far.

Then, as the H-band will go through the glass of the filter and not the K-band, this will add some optical length to the H-band, unmatching the focal length of the two spectral bands, making one of the bands not focused (spread) on the detector. The optical length added due to the reflection will also have an effect on the optical path length, adding some path to the spectral band reflected.

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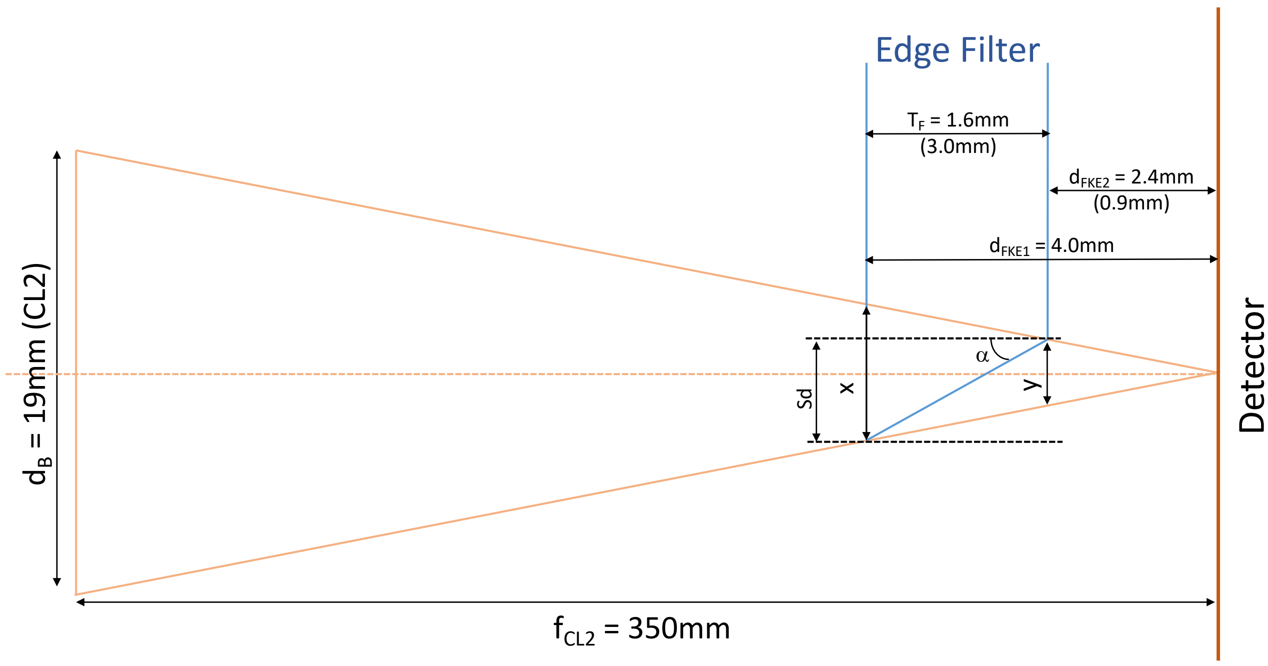

FIGURE 1. Scheme of the dichroic edge filter. x is the width of the beam at the entrance of the filter, and y is the width of the beam at the exit of the filter. Sd is the height of the edge. T_f id the thickness of the filter, d_{FKE1} is the distance between the entrance of the filter and the detector, d_{FKE2} is the distance between the exit of the filter and the detector. The numbers are the ones for the original design of the filter (flat), and on brackets are the ones for the design that allows the exit of the filter to be closer to the detector (see TR #105). d_B is the diameter of the beam at the second cylindrical mirror (CL2) in the spectral direction. f_{CL2} is the focal length of CL2, hence, the distance between CL2 and the detector.

2. COMPUTATION OF THE EDGE ANGLE

In order to reflect the full width of one of the spectral bands, we need the angled edge to be a certain height. This height, in combination with the thickness of the filter, gives us an angle of the edge with respect to the orthogonal direction of the filter surface (see figure 1).

To obtain the height of the edge (Sd), we need the width of the beam at the entrance of the filter (x) and the width of the beam at the exit of the filter (y). For this, we just use the Thales theorem, using d_B, f_{CL2}, and d_{FKE1} for x, and d_B, f_{CL2}, and d_{FKE2} for y. We get:

$$x = \frac{d_{FKE1} \times d_B}{f_{CL2}} \sim 0.22 \text{ mm} \tag{1}$$

and

$$y = \frac{d_{FKE2} \times d_B}{f_{CL2}} \sim 0.13(0.05) \text{ mm} \tag{2}$$

With x/2 and y/2, to which we need to add the width of the spectral band that we reflect, we can obtain Sd with:

$$Sd(H) = dH + \frac{x+y}{2} \sim 0.32(0.28) \text{ mm} \tag{3}$$

for the reflection of the H-band. with dH being 6 pixels width (1 pix being 24 μm width), and

$$Sd(K) = dK + \frac{x+y}{2} \sim 0.34 \text{ mm} \tag{4}$$

for the reflection of the K-band

Even though we already ruled out the use of the filter's design that would allow us to get the filter closer to the detector in TR #105, we still included this possibility for the H-band reflection part to compare its performance with the original filter design. The number in the bracket is for this closer filter's design.

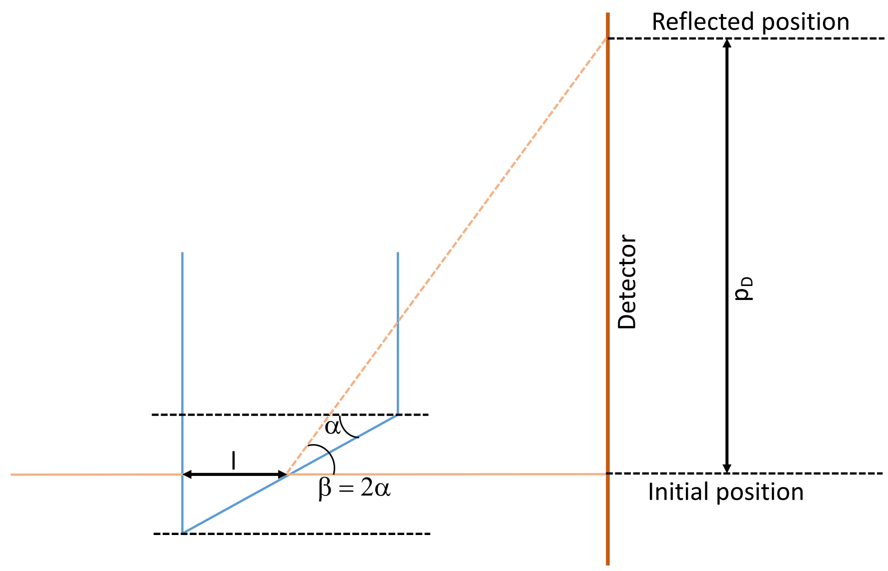

FIGURE 2. Scheme of the path of the beam reflected for the position difference p_D.

Now that we have Sd, we can determine α with T_F, with:

$$\alpha = tan^{-1}(Sd/T_F) \tag{5}$$

which gives us $\alpha(H) \sim$ **11.23 (5.11)**° and $\alpha(K) \sim$ **12.06**°.

3. COMPUTATION OF THE EFFECT OF THE REFLECTION

Now that we computed the optimal angle α, we can calculate the effect of the reflection on different aspects of the beam, such as the total optical path difference between the H- and K-band beams, due first to the extra path induced by the reflection, and second by the fact that one beam will go through glass and not the other. This difference in the optical path will bring a difference in focus on the detector between the two beams. Another effect of the reflection is a difference in the number of pixels the reflected beam will spread on because the beam will not arrive in an orthogonal direction in the spectral direction.

3.1. Position on the detector

The initial gap between the H- and the K-band for our spectral resolution (see TR #105) is 6 pixels on the detector. As the dichroic edge filter will reflect one of the beams, this will bring it further on the detector, increasing this gap (see figure 2). Due to the reflection, the spectral band will also be reversed. The position of a certain spectral channel will depend as well as the initial position of the spectral channel.

To calculate the position of the reflected beam we first compute the distance for which the beam will be reflected, with respect to the entrance of the filter (l), as a function of the initial position of the beam on the detector. We then compute the distance between the initial position on the detector and the reflected position (p_D) with:

$$p_D = (d_{FKE1} - l) \times tan(\beta) \tag{6}$$

with $\beta = 2\alpha$

3.2. Optical path difference due to the reflection

As you can see in Figure 3, the path followed by the reflected beam is longer than the one it would have been without the reflection. To compute the difference in the path due to

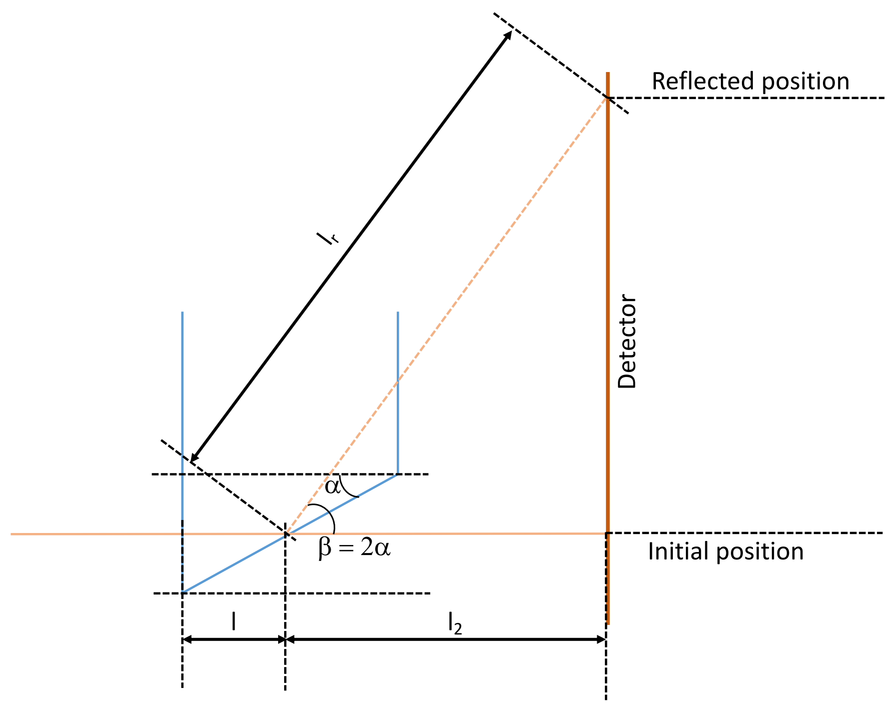

FIGURE 3. Scheme of the path of the beam reflected for the computation of l_r.

this reflection, we first calculate the distance the beam would travel if not reflected from the position it is reflected:

$$l_2 = d_{FKE1} - l. \tag{7}$$

We then compute the distance the reflected beam travel to reach the detector, from the same position:

$$l_r = l_2/cos(\beta). \tag{8}$$

the path difference between the reflected and the straight beams is $l_r - l_2$.

3.3. Optical path difference due to the index of the glass

As the H-band will go through a certain thickness of the glass due to the filter, and the K-band will not, the difference in the optical index of the glass will induce a difference in the optical path between the two beams. To compute this, we first compute the physical distance that the H-band will travel through the glass. For the version where the K band is reflected, this distance is just the thickness of the filter. For the version where the H-band is reflected, we need to add the distance the beam travels before the reflection and the distance it travels after the reflection, in the filter (see Figure 4).

$$l_g = (d_{FKE1} - d_{FKE2} - l)/cos(\beta) \tag{9}$$

And so, we get the total optical path induced by the glass:

$$l_{gn} = (n \times (l + l_g)) - (l + l_g) \tag{10}$$

where n is the optical index of the glass. For the company we are considering manufacturing the filter, this index in the center of the H-band is $n = 1.44$.

3.4. Defocus due to optical path difference

The main effect of the optical path difference is that the focus of the two beams will not happen at the same distance from the second cylindrical mirror, meaning that one of the beams will not be focused on the detector. To simulate this effect, we compute first the total optical path difference. For the version with the H-band reflected, we have:

$$P_D(H) = l_{gn} + l_r - l_2, \tag{11}$$

as both optical path difference is added to the H-band, and for the version with the K-band reflected we have:

$$P_D(K) = l_{gn} - (l_r - l_2), \tag{12}$$

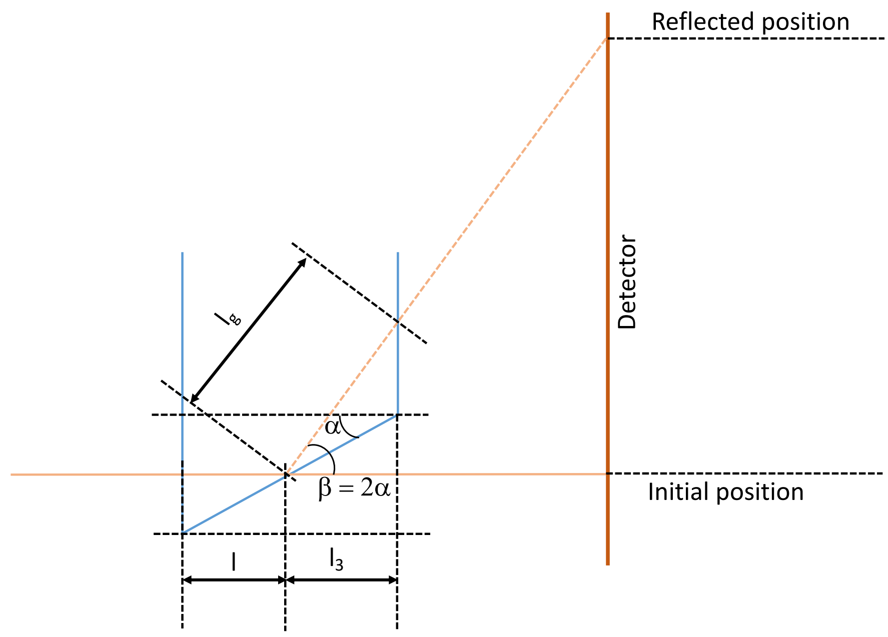

FIGURE 4. Scheme of the path of the beam reflected for the computation of l_r.

as the path difference due to the reflection is added to the K-band and the one due to the glass is added to the H-band. In this case, we assume we will focus the K-band and the detector.

To simulate the defocus, we then apply the Thales theorem to compute the spread of the beam at the distance between the focal point (at the focal distance of CL2) and the detector:

$$\text{defocus} = d_B \times P_D / f_{CL2} \tag{13}$$

4. RESULTS OF THE SIMULATIONS

In this section, we present the different results first for the internal reflection of the H-band and then for the external reflection of the K-band.

4.1. H-band reflected

The internal H-band reflection induces that both the reflection and the travel in the glass of the filter will add optical length to this spectral band.

Figure 5 summarizes the results for the H-band. For the top-left plot, we can see that the H-band is reflected between pixels 62 and 69 away from the point of origin taken as pixel 0, where the H-band would fall on the detector without a reflection. It also means that the H-band would be spread over 7 pixels, instead of 6 without reflection, increasing slightly the spectral resolution.

The top-right and bottom-left show that the path difference induced by the glass is around 7mm and in total between 1.0 and 1.1mm in total, meaning that the reflection induces an optical path difference of 0.3 to 0.4mm. We can conclude then that the travel through the glass is the one that dominates the difference in optical path length with twice the effect of the reflection.

The bottom-right plot shows the defocus, in pixels of the H-band if we focus the K-band on the detector. The defocus is defined here as how many pixels a beam would be spread on the detector, due to the focus of the beam being reached before the detector, due to the additional optical length. We can see that for the initial filter position, the defocus would be between **2.3 and 2.5 pixels**. For the filter that would be closer to the detector, inducing a thicker filter, the defocus would be even worse, as the dominant factor adding optical length is the travel in the glass, which would be longer in this case, compared to the use of a smaller angle of reflection that reduce the amount of optical path added by the reflection. Even if the idea of getting the filter closer to the detector because of the risk

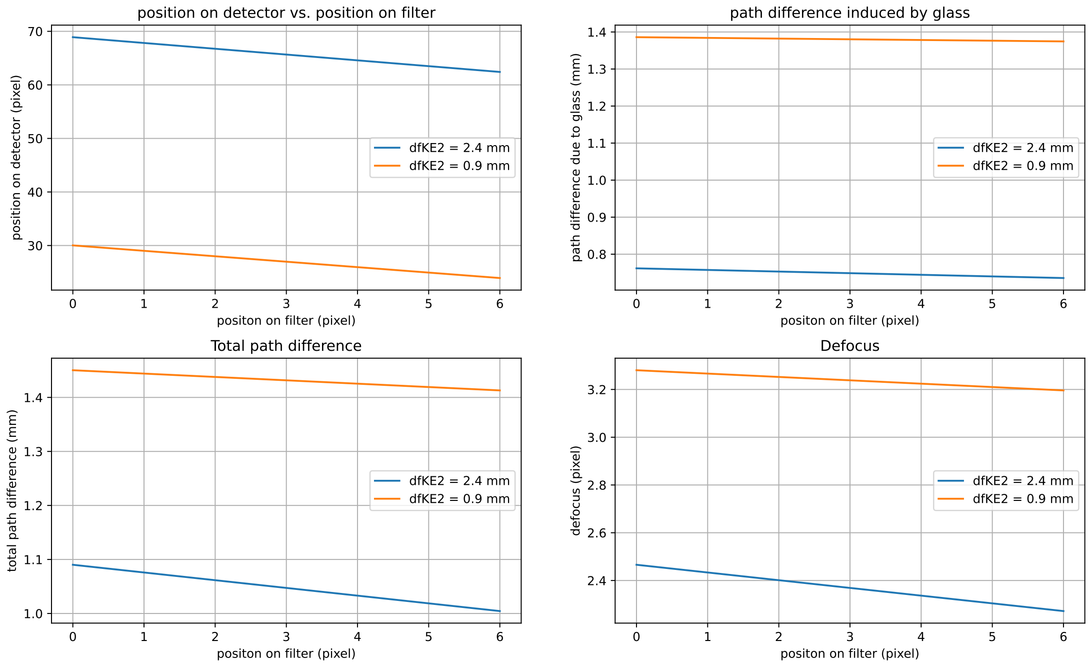

FIGURE 5. Results of the computation of the effect of the reflection for the H-band. Top-left: Position of the light on the detector as a function of its position if there is no reflection. Top-right: The optical path difference induced by the travel through the glass only. Bottom-left: Total optical path difference, taking into account both the one induced by the reflection and the travel through the glass of the H-band. Bottom-right: Defocus as a function of the position on the detector if no reflection. In blue, the normal distance between the end of the filter and the detected, in orange, if we get the filter closer to the detector.

to damage the camera for a small gain, this concludes that this solution would actually be worse in the case of a dichroic edge filter.

4.2. K-band reflected

The K-band reflection induces that some optical length is added to the H-band from its travel through the glass of the filter and that the K-band would have some optical length added because of its reflection.

Figure 6 summarizes the results for the K-band. For the top-left plot, we can see that the H-band is reflected between pixels 67 and 74.5 away from the point of origin taken as pixel 0, where the K-band would fall on the detector without a reflection. It also means that the K-band would be spread over 7.5 pixels, instead of 7 without a reflection, increasing slightly the spectral resolution.

The top-right figure shows that the reflection will add between 0.31 and 0.38mm to the K-band's optical path, which is less than the optical path added to the H-band by its travel through the glass. In this case, as the H band is not reflected, the whole H-band travels the same thickness of glass, adding 0.7mm to its optical path. Note that in reality due to the change of index of the glass with the wavelength, the glass will not add exactly the same optical path throughout the whole H-band, but we make this approximation as it won't affect the results of this study.

The bottom-left then shows the difference in optical length between the H-band and the K-band. We see that because the effect of the glass is more important than the effect of the reflection, the H-band will have more optical length added to its path, meaning that it will reach its focus before the K-band.

The bottom-right figure shows the same information as for the H-band reflection's results. However, as the optical path difference between the H- and the K-band is lesser, the defocus of the H-band, if we focus the K-band on the detector, is only between **0.72 and 0.9 pixels**, which is around 3 times less than for the H-band reflection.

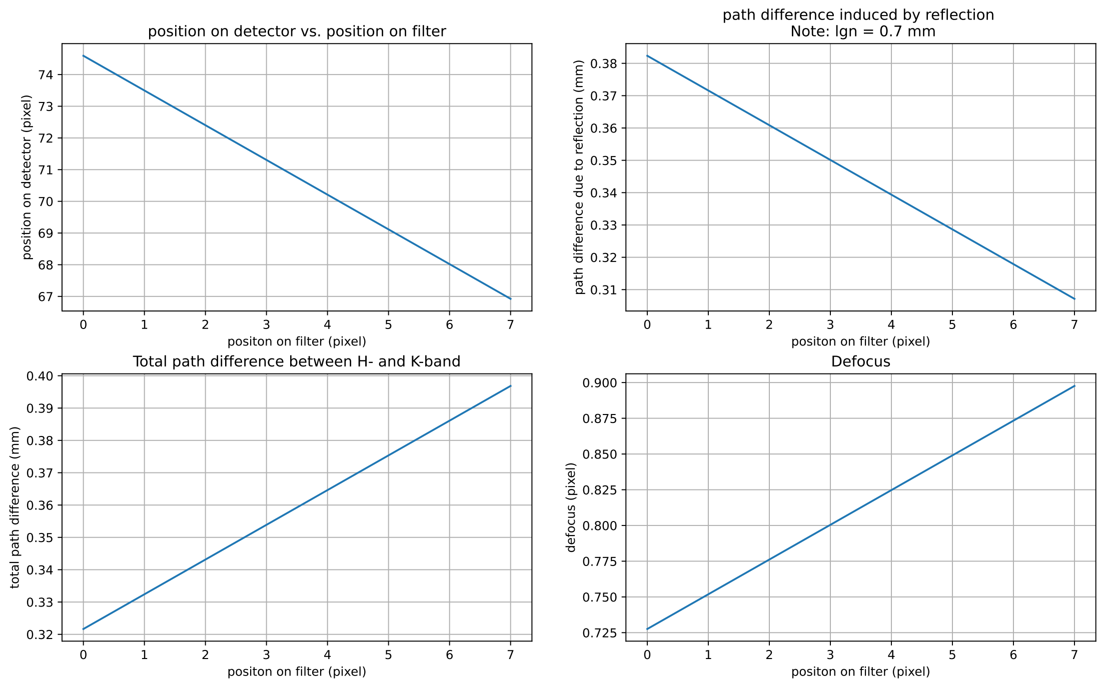

FIGURE 6. Results of the computation of the effect of the reflection for the K-band. Top-left: Position of the light on the detector as a function of its position if there is no reflection. Top-right: The optical path difference induced by the reflection only. Bottom-left: Total optical path difference, taking into account both the one induced by the reflection of the K-band and the travel through the glass of the H-band. Bottom-right: Defocus as a function of the position on the detector if no reflection.

5. SUMMARY

In this technical report, we simulated the effect of a dichroic edge filter, reflecting one of the spectral bands (H or K), thanks to an angle introduced on the flat edge of the filter.

Table 1 shows the results on the angle we need to give to the edge and the defocus that it will induce, comparing the internal reflection of the H-band and the external reflection of the K-band.

TABLE 1. Results of the simulations. The first column is the different characteristics. The second column is the results of the internal reflection of the H-band. The third column is the results of the external reflection of the K-band.

Characteristic	H-band	K-band
minimum edge angle (degree)	11.23	12.06
Defocus (pixel)	2.3 – 2.5	0.72 – 0.9

We can see that the angle for the edge is similar for both cases. Note that for safety, it would be better to give the edge a slightly bigger angle, for instance, **12° and 13°** for the internal H-band and the external K-band reflections respectively. For the defocus, we can see that the K-band external reflection will have an effect between **2 to 3 times better** than the internal H-band reflection.