Using Zemax Programming Language and API as a method to perform parametric ghost analysis, chromatic aberrations and baffle thermal loading on the Litebird Medium and High Frequency Telescopes *

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ABSTRACT

We combine use of the Zemax Programming Language[1] and an API (Application Programme Interface) feature[2] in the Zemax Opticstudio software which allows for rapid ray-tracing computations and maps of intermediate ray distribution intersections with in-house IDL code to produce maps of stray-light distribution and spectral content of ghost images. The calculation of the spectral amplitude of the latter is performed via prior knowledge of spectral transmission of all optical elements involved in a refractor telescope. The results are of generic nature and can be applied to any optical system. For the numerical examples in this case we consider the JAXA *LiteBIRD* CMB Medium and High frequency telescopes[3,4] as a study case and perform a parametric study of the position of its infrared rejecting filters by looking at multiple configurations within a python envelope. By manipulating the resulting intermediate products of ray incidence distribution we determine the optimal position of the filters that will minimize ghost features on the focal plane (or define some competing configurations based on desired outcomes).The resulting analysis is in competition with other aspects of filter positioning (mechanical and thermal) so the results of this optimization is not necessarily a final outcome. Results from such a study can be used to characterize the variation of spectral response across the focal plane caused by the impact angle distribution on the optical coatings and finally the distribution of thermal (out of band) rejected light reflected by the filters on the optical baffles. The first can be obtained with the majority of optical modelling commercial packages, the second are more complex and can also be done in a similar way with packages that perform non-sequential analysis.

Keywords: Ray Tracing, optical aberrations, optical systematics, optical coatings, optical modelling

1. INTRODUCTION

There is a wide range of optical modelling software packages (free and premium) which allow great versatility of modelling of optical systems as well as design optimization. Each has their strengths and weaknesses in providing the optimal output for a given study of a system. In this study we focus on the extraction of intermediate 6D ray distribution (spatial and angular) on given surfaces. This is not a default product of many modelling softwares, but it is needed in order to introduce other physical calculations to such simulations such as Transmission Line

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calculations on multi-layer coatings (especially if these have a non-uniform spatial distribution), or scattering losses of various nature (Lambertian, or more complex bi-directional reflection distribution functions - BRDFs). We find the use of direct ray tracing via API on Zemax Opticstudio (ANSYS)[2] a versatile tool to perform such calculations. Interrupting the ray trace process on a given surface and extracting ray-surface intersection position and angle allows these to be used directly or combined with further calculations and propagated further.

As an example of its usefulness, we adopt this technique to identify:

- The physical position of the most relevant ghost features of a refractive optical system and its parametric nature given the change in position of a given optical element
- The distribution of a given out-of-band stray-light beam within the instrument inner sanctum to identify where a given source of optical loading (considered here as added thermal input) is terminated on the optical baffle.

To showcase this process, we consider a few cases of specific refractive telescopes: the preliminary design of the Litebird Medium and High Frequency Telescopes optimized in the frequency ranges of $89-224$ and $166-448$ GHz with aperture diameters respectively of 300mm and 200mm and constituted of two refracting lenses, 3 filter elements and a detector focal plane where the image is expected. The telescopes in question also present a transmissive half-wave plate (HWP) polarisation modulator positioned close to the aperture stop of the telescope. The nature of this telescope build is in some parts similar to other CMB instrumentation[5,6] so the methodology can be applied to other concepts (and given our coarse assumption of geometrical ray tracing is, to first order, wavelength independent).

The details of the build used are preliminary (as many subsystem performances are not yet measured or known) and are therefore not representative of any design iteration and should not be considered as a predicted performance of systematics of this given experiment.

2. METHODOLOGY

The tool used to perform the points raised above are essentially two. The first is a python-coded API which runs the Zemax Opticstudio kernel on pre-generated zemax files for the various cases considered. The "overhead" of this analysis is in the creation of a number of slightly varying zemax files where the partially reflecting elements are made fully reflective with repetition of intermediate transmissive surfaces (retaining the sequential nature of the raytrace). It is entirely possible that further investigation can remove this additional step replacing it with a multi-configuration file. But as we have not yet explored the possibility of interrogating different configuration within the API, we leave this for future implementation.

The second and third tools are in-house IDL codes to perform in one case a simple interpolation and multiplication of filter transmission profiles to identify, given the transmission and reflection profiles of all surfaces in an optical system, the biggest contributors to ghost spectral content (as shown in Fig 2). In the other, progressing the ray-tracing of rays which would otherwise be lost to the original optical system for the second goal of this study: the location of termination on inner shields of stray light. The latter for the dual purpose of understanding where most of the stray-light is incident and at what angle as well as where the out-of-band light (now maximally reflected due to coating non-efficiency) ends up adding heat-load in the inner sanctum of the telescope.

We first identify meaningful terms to this particular optical system, choose one such contribution and parameterize one of the optical elements involved. We then explore the outputs as a result of the parametrization and finally take a look at a different case where rays which are generally lost through unwanted reflections are tracked on to absorber screens.

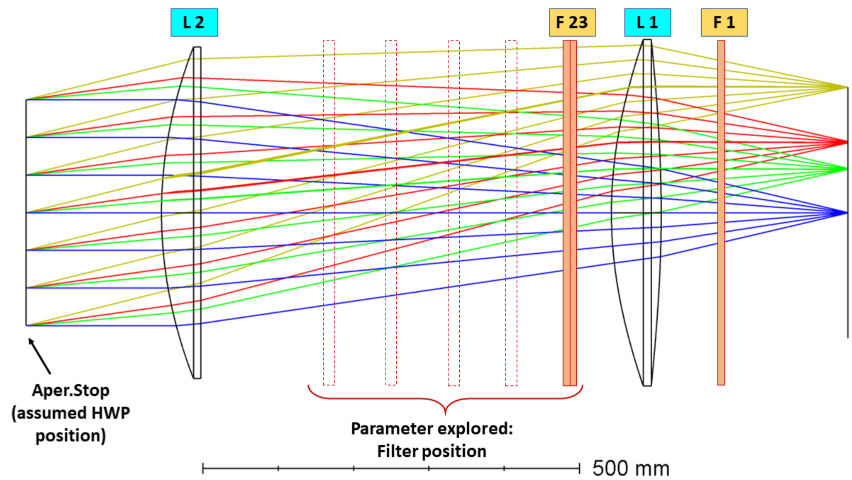

Figure 1. Preliminary optical design of the Litebird MFT telescope showing the two refractive lenses and a hypothetical position of three filters.

2.1 Out of band filter contributions

To identify which elements are the primary cause of any ghost features and therefore which elements require the use of the combined API-code to establish ghost distributions and thermal dumps we consider the optical design in Figure 1. There are in principle 9 surfaces which can be considered for reflection, under the following assumptions: that filters do not possess thickness (which is de facto incorrect as thicknesses will vary between 1 and a few (< 10) millimetres), that we consider only the back surface of the HWP positioned at the aperture stop and that the focal plane is for this purpose, flat. This last assumption is quite strong (weakening part of our results) as the true focal plane is generally constituted of either lenslets or hornlet plates and at any rate does not present a perfectly flat partially reflective surface in millimetre wavelength experiments.

As such, we will consider the transmission and reflection profiles known of appropriate low pass filters[7] (suppressing all out-of-band higher frequency rays) and similarly for the HWP and for the coated lenses as inputs to our ghost spectral content. For the purpose of in-band calculation, most optical elements have in-band average transmission $> 95\%$ and it is the focal plane (FP) followed by the HWP and filters which have higher residual reflection raising the potential question of ghost presence (Fig.2). For this reason, only ghosts generated by two reflections have been considered as all others are likely to be smaller by more than one order of magnitude. Likewise if we consider out-of-band contributions, a single reflection off one such element is sufficient to be noteworthy of its directional output (due to the band-tuning of anti-reflection coatings).

2.2 The Zemax API

The API code uses basic Zemax Programming Language (ZPL) to extract, given a set of input 6D coordinates (position/angle) of optical rays at the aperture of the system. The code then extracts 3D coordinates and cosine vectors at the desired intersection with the n^{th} surface and saves the output to a .csv file for subsequent usage. As ZPL allows to also extract the normal to that surface in the point of impact, the reflected rays (from a partially transmissive surface) are also immediately obtained given the knowledge of the latter and the ray's cosine vectors.

The potential usefulness of this is shown in Figure4 where we map the undesired straylight on the internal optics baffle (or simply the black surface of the optics assembly).

In Figure 3 a custom code visualizes (unnecessarily and for the purpose of this paper only) two separate sets of rays (which are reflected after their intersection with the aft surface of the first lens. In the following figure integrating for all phases of that particular off-axis angle, we show the distribution of rays seen from above of

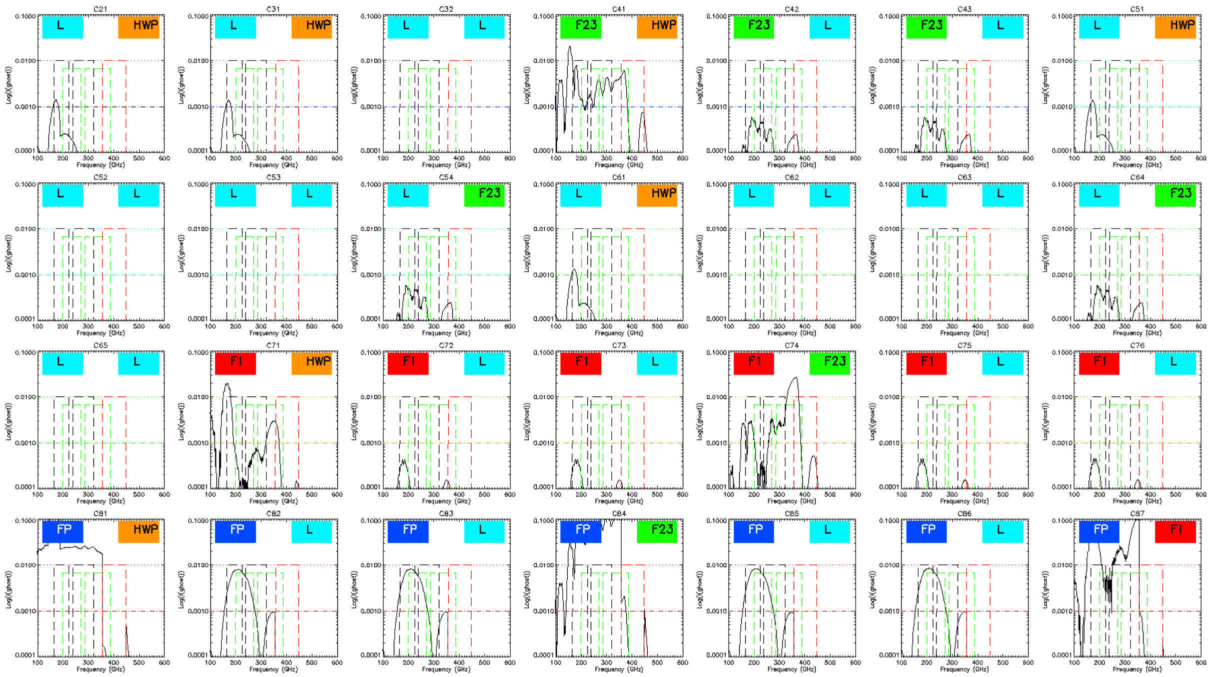

Figure 2. Spectral transmission profile resulting from the triangular matrix of each pair of 9 surfaces (without diagonal) that can cause a first order ghost. The left and right boxes identify elements generating it as first and second reflection respectively. The three spectral bands relevant to the detectors are highlighted as dashed boxes.

the rays off axis and as a result of angle symmetry, the "heat-map" of impact of rays observed at the internal conical baffle for all off-axis angles of 10 degrees.

2.3 Multiple (parametric) system build

One of the uses of these scripts is to allow to perform parametric analysis of a given derived feature of the optical model. To do this, the pedantic part is to create a number (few) of separate zemax files, one for each pair of reflecting surfaces that contributed to the ghost. In each file the sequential nature is maintained but the reflecting elements are considered twice (once in reflection and once in transmission) and elements in between three times in trasmission.

Figure 5 shows the resulting back reflections for a beam placed at 0,5 and 10 deg w.r.t. the line of sight as a function of the distance of the last filter from the focal plane.

This particular reflection is not only chosen as it is a potential non-negligible contribution to the "ghost population", but also because it is possibly the most intuitively agreeable expected outcome which can be agreed with as a validation given that as the filter approaches the image plane, a planar reflection which is back reflected from a pupil plane will still refocus back on the focal plane (in a different position if off-axis).

3. RESULTS

This paper highlights the capability of this framework which uses intermediate ray-tracing coordinate products to perform further calculations on ray distributions (with knowledge of their spectral content) which have potential for characterizing a range of systematics including:

- Ghost analysis from double reflections within optics
- Allowing parametric study of ghost variation with the position (or spectral performance) of different elements

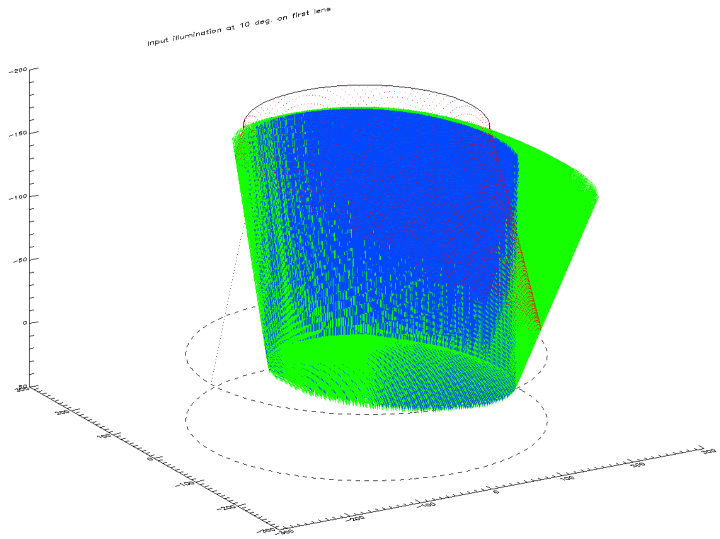

Figure 3. The output showing the extrapolated rays on follow-on raytracing from the intermediate intersection on the first surface of the lens encountered for on-axis (blue) and 10 deg off-axis (limit of the FoV) (green) rays. The silhouette of the internal baffle can be seen as a truncated cone.

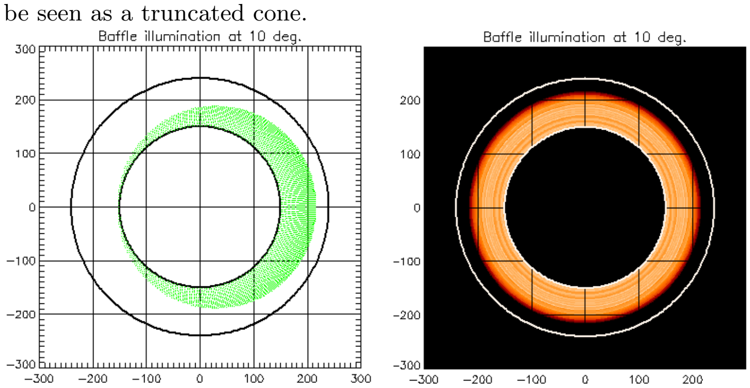

Figure 4. Left shows the top view of the ray tracing output for a 10 deg off axis source being reflected from the top surface of the lens on the internal baffle. Right: the extrapolated "heat map" for a ring of similarly off-axis sources. This gives the inherent location of where rays reflected by the first lens surface will be contained.

- Knowledge of internal baffle absorption distribution item as well as
- Preliminary estimation of optical chromatic aberration

the latter is only and mostly relevant for shorter wavelength studies given the less physically accurate results in our cases due to geometric optics approximation.

The example of the parametric study shown above is just a first of intended combinations, and shows the expected fact that, as the filter is moved away from the image plane, it's reflection combines with that of the HWP to produce a more diffuse image, which could be considered more beneficial (due to dilution) than a refocused ghost image in a different position of the focal plane.

The third point was shown as a particular case of following reflections which are usually lost to standard ray-tracing, but the applications are both for the purpose of determining the distribution of positions and angles at which the internal baffles are hit by in-band stray-light from reflections as well as (for substantially out-of-band

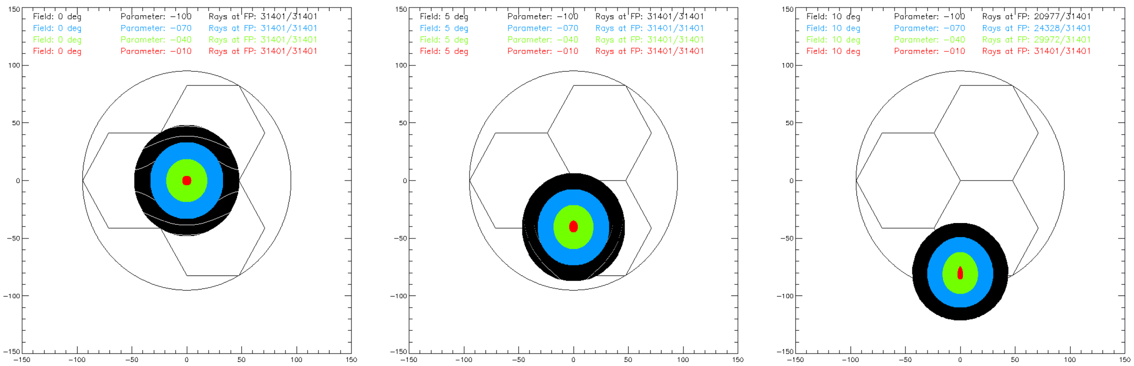

Figure 5. From left to right the geometrical ghost distribution for rays incoming respectively at 0, 5 and 10 degrees off axis. Each contour shows in the backdrop the footprint of the detector arrays, the parametric outcome is given by the different colour spots (black/blue/green/red) respecitvely for the filter F1 (in Fig.1 position of (100/70/40/10 mm) from the Focal Plane.

higher frequencies, where reflections will be higher) to monitor potential optical heat loading spots on the same internal baffle.

Future work will entail producing focal plane maps of all the larger contributions for the ghost reflections as well as a more accurate characterisation of the spectral transmissions once all relevant items are known.

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