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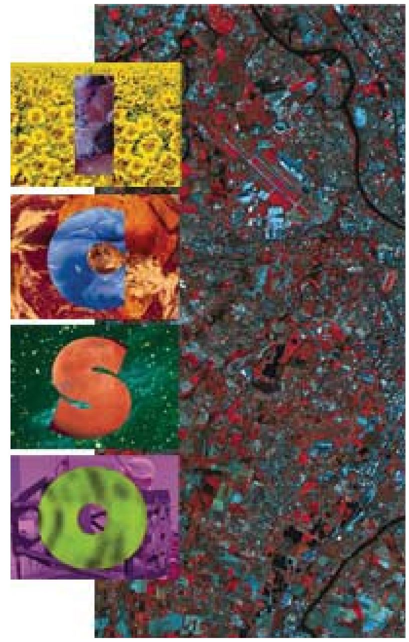

Fast and accurate modeling of stray light in optical systems

Jean-Claude Perrin

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FAST AND ACCURATE MODELING OF STRAY LIGHT IN OPTICAL SYSTEMS

Jean-Claude PERRIN

Consultant

ABSTRACT - *The first problem to be solved in most optical designs with respect to stray light is that of internal reflections on the several surfaces of individual lenses and mirrors, and on the detector itself. The level of stray light ratio can be considerably reduced by taking into account the stray light during the optimization to determine solutions in which the irradiance due to these ghosts is kept to the minimum possible value.*

Unhappily, the routines available in most optical design software's, for example CODE V, do not permit all alone to make exact quantitative calculations of the stray light due to these ghosts. Therefore, the engineer in charge of the optical design is confronted to the problem of using two different software's, one for the design and optimization, for example CODE V, one for stray light analysis, for example ASAP. This makes a complete optimization very complex .

Nevertheless, using special techniques and combinations of the routines available in CODE V, it is possible to have at its disposal a software macro tool to do such an analysis quickly and accurately, including Monte-Carlo ray tracing, or taking into account diffraction effects. This analysis can be done in a few minutes, to be compared to hours with other software's.

1. INTRODUCTION

The problem of stray light is especially important in optical systems for space applications, where it has become an independent discipline, with its own sessions and publications (ref. 1).
It is also more and more considered and specified in other applications, where it is now usual to specify the stray light ratio, i.e the amount of the irradiance due to the ghost images which are created when a source is present in the field of view, with respect to the irradiance on the image of the source itself.

Ratios like 10^{-6} are typical values to guarantee and to justify in the design phase, using exact numerical calculations. It is therefore important to have at disposal effective methods to make these calculations.

Several software's, mainly from the U.S, have been developed to model stray light, and several of them, are commercially available. The more conventional method used is based on geometrical calculation, by tracing a large amount of rays in the opto-mechanical system using the Monte-Carlo technique. At each interface, the rays are split to create the rays which may produce stray light, and each ray is propagated in the optical system by this way up to the detector plane, or extinguish if its energy falls below a specified energy level.

This technique is extremely time consuming, due to the large amount of rays which must be traced before the result is obtained with sufficient accuracy. This problem is of utmost importance, because the optimization process involves a lot of interference's between the design and the expertise.

Moreover, most classic lens design programs do not permit to model scattered light by this way, and two different software's are necessary for a complete analysis, or special software's have to be developed internally (ref. 2).

Also, geometrical analysis do not takes into account diffraction effects, which must be modeled in many applications.

For this reason, we have developed a special software in CODE V macro language, in order to make this simulation in the most effective and accurate manner.

The calculations are done using geometrical analysis, or taking into account the diffraction effect, if necessary.

2. PROBLEM ADDRESSED

The problem addressed is concerning ghost re-imaging due to internal reflections in the lens.
Ghost images can be due to following reasons :

Multiple internal reflections on the surfaces of the individual lenses.
They are the more conventional. If we consider a coefficient of reflection of 1% on each surface, the transmission is about 10^{-4} for two reflections, 10^{-8} for four reflections, etc...

Internal reflection on the detector first, then on the surfaces of the individual lenses.
Usually the coefficient of reflection of the detector itself can be high, near 10% or more.
For one reflection on the detector and one reflection on a surface, the transmission is about 10^{-3}.
For two reflections on the detector and two reflections on surfaces, it is about 10^{-6}, etc...

Internal reflections and diffusion on the mechanical parts of the lens.
To prevent these effects, it is usual to install baffles in the lens, and to use special paintings and coatings.
This is usually the case to prevent stray light from sources which are not in the field of view, or to reduce again stray light ratios below 10^{-10} or less.

In order to quantify the ghost due to the two first reasons, we have developed a specialized software using the CODE V macro language.

The reason to develop this was to have at disposal a very efficient software to make a full quantitative analysis of ghost images, in order to correct it during the optimization process.

3. METHOD

The method can be used with any optical design software on the market, provided this software includes fully optimized routines as described below.

For the discussion, we refer now on the figure I.
On this figure, a typical design for the 3-5 micron band is represented, with two ray path superimposed. The blue rays correspond to the image of a point source of axis. The red rays correspond to a typical ghost path, due to two reflections on two internal surfaces of the lens.

Because this ghost image is near focus, with little vignetting effect, the corresponding ghost will be dangerous and must be analyzed in more detail.

In a lens system like shown, the possible reflections are so numerous, that it is extremely time consuming to examine every of them on a real ray trace basis.
Therefore, the method chosen is to make successive selections of the possible dangerous ghosts, in order to perform a full quantitative analysis only on those of them which may exceed the specification in terms of stray light ratio. By this way, quantitative calculations are done only on the most significant ghost images, using first geometrical analysis by Monte-Carlo ray tracing, then physical analysis using PSF calculations, if necessary.

The first selection is done using first order analysis. This analysis is a very efficient method to sort out the ghost images which can not lead to ghost images exceeding the specification of stray light.
This selection do not takes into account, of course, the aberrations, nor the diameters of the elements and baffles in the lens.

The second selection is done on a real ray trace basis. For each path selected on first selection, an exact file is constructed, based on sequential surfaces only, for reasons of effectiveness in computer time. The vignetting values are then calculated, and an estimate of the stray light ratio is done using simple calculations, and tracing only five reference rays.
By this way, this second selection sorts out from the first selection the ghost images which are below the specification. These calculations are based on a simple but effective ray tracing; It takes into account the diameters of the elements and exact ray tracing. Nevertheless, it doe'nt take into account the caustic effects due to the geometrical aberrations, nor the diffraction effects.

The exact calculations are done only on the results of this second selection.

The first full quantitative calculation done is based on the geometrical analysis only, based on Monte-Carlo technique, in sequential ray tracing. This calculation takes into account :

- The geometrical forms of the elements and baffle,
- The coefficients of reflection and transmission of those elements,
- The shape and position of the source in the field of view, whose ghost images are analyzed,
- The geometrical aberrations and caustic effects.

To complete these results, a physical calculation is done, in order to take into account also the diffraction effects, if necessary.
This analysis is done only on the ghost images whose wavefront error do not exceed a given value, for example one lambda rms. For such ghost images, diffraction effects can be important. This is especially the case for optical systems in the IR band, or also in other wavelength, when an extreme care in ghost images must me taken into account.
These calculations are based on PSF calculations. Most usually, the routines available are using the FFT algorithm. Some special care must be exercised to use the routine in the most convenient manner, and also to transform the result in photometric quantities.

For both geometrical and physical analyses, the results obtained for each individual ghost are combined together in order to represent the full illumination due to stray light in the total field in the image plane.

4. EXAMPLE

In order to illustrate the method, the design in the 3-5 micron band shown on figure I has been analyzed using this software, using a 200 Mhz PC. Results are shown on figure II to V.

Figure II shows the geometrical stray light ratio calculated and represented in pseudo color, in the whole dimension of the detector plane. Values are in Db, i.e, the decimal logarithm of the ratio.

In this design, about 30 ghost have been selected from first order analysis, in about 10 seconds, and 9 after the selection done on a real ray trace basis, in about one minute.
The irradiance in the image plane due to these 9 ghost have been calculated one after the other, and also the irradiance in the direct image of the source, using Monte-Carlo technique. The results are used to construct a matrix which represent the focal plane, in about 100x133 pixels. The duration for this calculation was about five minutes.

Figure III is the curve obtained in the Y axis only, including the position and size of the direct image, in dotted lines.

From the 9 ghost calculated on figure II, 6 of them have a wavefront error below one lambda.

For these ghost only, a physical calculation was done, and the result shown on figure IV and V.
It is important to point out on figure IV that pixels with a stray light ratio below 10^{-9} are represented in the minimum value, i.e 10^{-9}, in blue.
For this reason, the square shape of the matrix created from PSF calculation appears only for the ghost which are above this minimum threshold level chosen for the representation in pseudo color.

Comparing figures IV and V with respect to figure II and III shows the differences due to the diffraction effect only.

5. DETAILS CONCERNING CODE V ROUTINES

The macros have been developed using the possibilities offered by CODE V in the most effective manner.

As a starting file, the standard file resulting from the optimization is used without modifications.

The apertures must be present in the file, and also dummy surfaces in order to simulate the baffles, if they are.
Other informations which are necessary (coefficients of reflection of the surfaces, threshold levels at the different steps, position and size of the source in the optical field of view, parameters for the calculations, etc...) are entered in a simple form in the macro and used for the calculations.

Third order analysis is using the GHO routine. This routine is extremely fast, and, from the result obtained, it is possible to have a first estimate of the stray light ratio due to a point source on axis, and sort out the ghost which are below the threshold level.

For each ghost selected, the file corresponding to the ray path is constructed in sequential, using the standard CODE V possibilities available, like COP. The corresponding entrance pupil and vignetting values are calculated in the most appropriate way (see for example the ORA recommendations concerning pupil and vignetting in ref. 3). CRA option is used, if necessary.

From the information obtained with the five reference rays, a second estimate of the stray light ratio is calculated on a real ray trace basis. This is used for the second selection made.
Also, the rms wavefront error is calculated using WAV, to select from the ghost those which will be also calculated on a physical basis using PSF.

Geometrical calculation with Monte-Carlo ray tracing is then performed for each ghost selected, and the results are accumulated in a convenient way in a buffer to represent the stray light in the whole detector plane. CODE V routine LUM is used for this purpose. The conditions of using this routine are put to the optimum to obtain an accurate result in the most efficient and faster way.

To confirm the calculations and compare geometrical and physical results, another calculation is done for the ghost whose wave front error is below a chosen threshold, for example one lambda.
For this calculation, CODE V routine PSF is used. The conditions and parameters for using the PSF routine correctly are chosen to guarantee the most accurate result. (For PSF calculations, see for example ref. 4).
The result obtained with the PSF routine is a square matrix of points. The values of the matrix are first normalized to be converted in irradiance, and the matrix is used to construct another buffer which represent the whole detector plane.

Extensive use of arrays and buffers is done at different levels in the macro. See for example ref.3 concerning the recommendations for using these in the most efficient way.
For more information's, send a message to the author at jcperrin@compuserve.com

6. PERSPECTIVES

The macros described in this paper are an extremely powerful method to take into account the stray light during the optimisation of optical systems of any kind.

Using the technique described, we are now considering to extend the method to other applications in following directions :

- ✓ Diffractive optics : The method will be used to examine the stray light due to the different orders of diffraction.

- ✓ Diamond turned optics. For such systems, stray light must be considered also, in a manner similar to diffractive optical elements.

- ✓ Stray light due to the narcissus effect : Mixing together stray light calculations and narcissus calculations will help in designing system in a more efficient way.

7. REFERENCES

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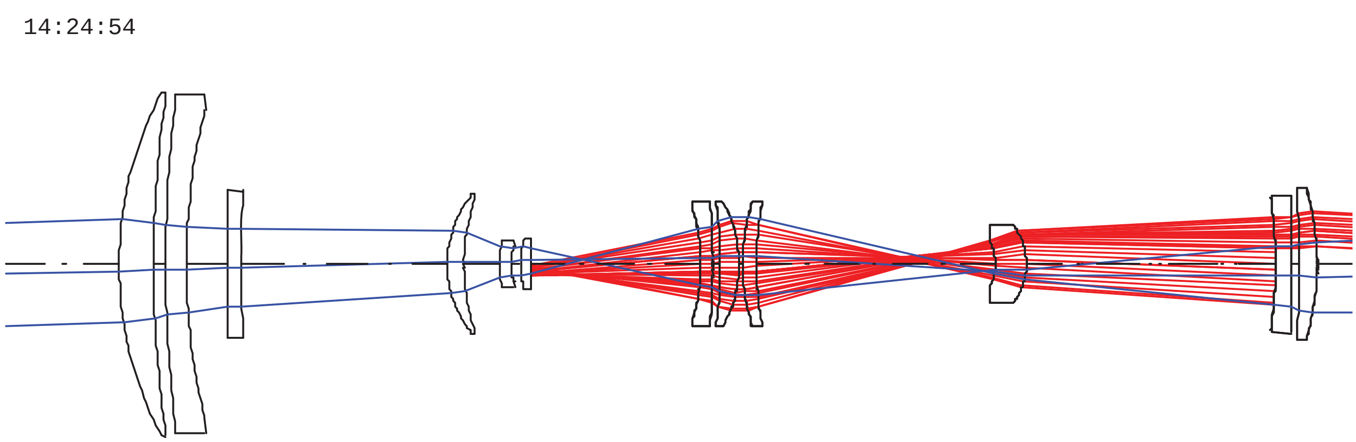

Fig. I : Example of stray light (in red) corresponding to a direct image

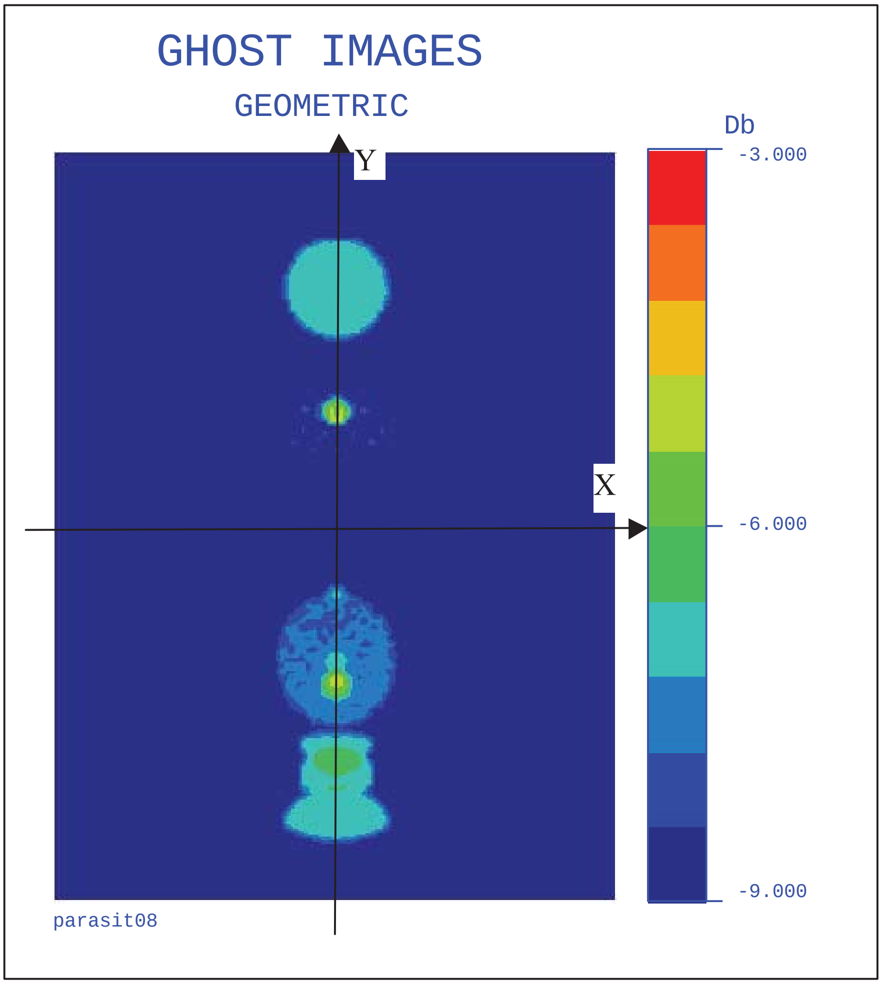

Fig. II : Geometric analysis of the GHOST images corresponding to Fig. I.

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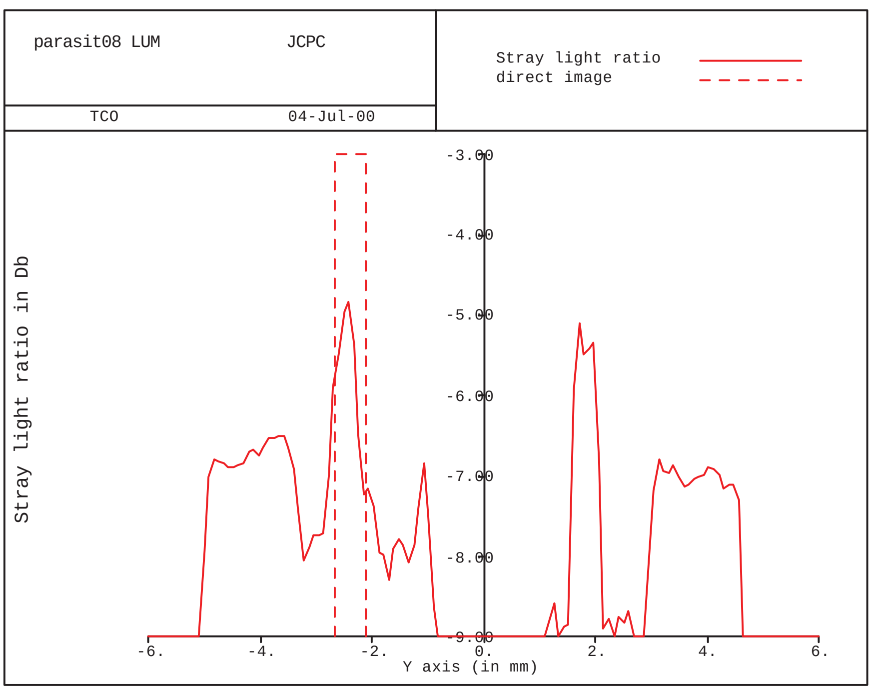

Fig. III : Stray light ratio along Y axis corresponding to Fig. II

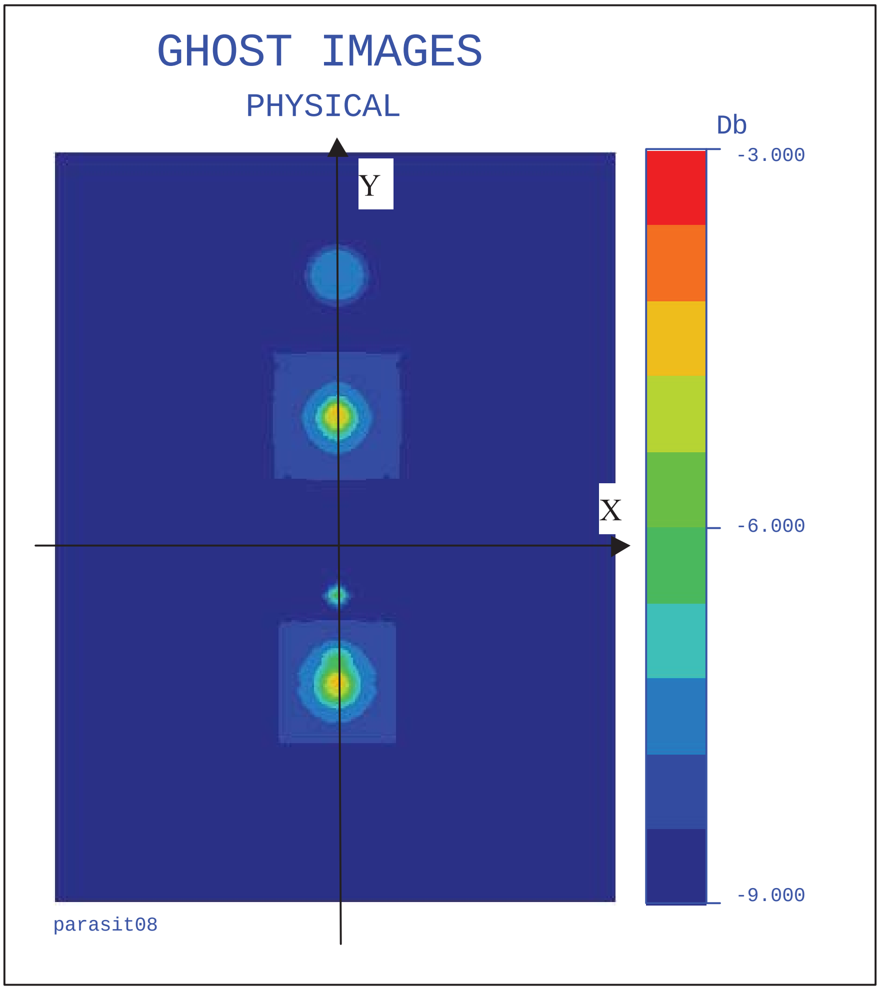

Fig. IV : Physical analysis (PSF) of the ghost images of Fig I.

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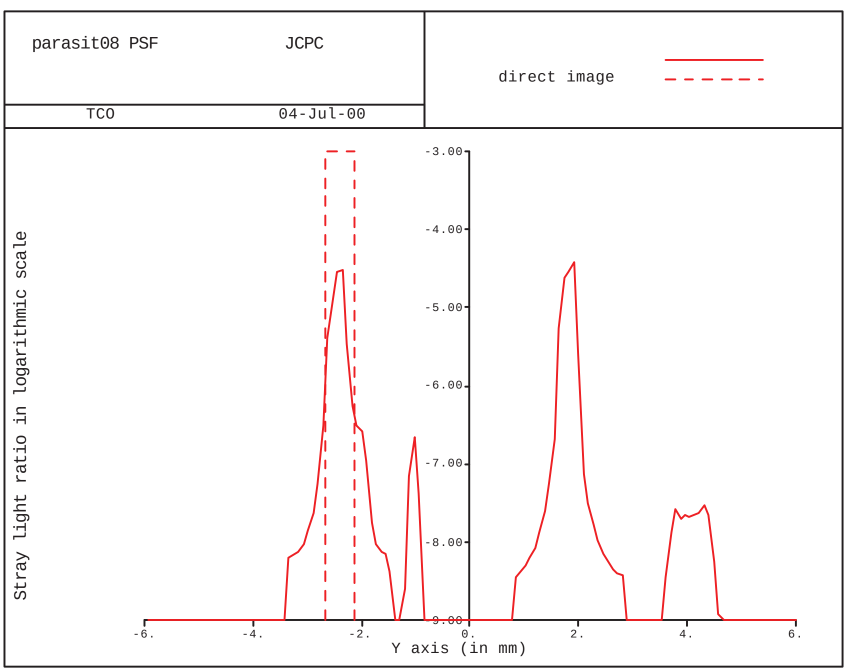

Fig. V : Stray light ratio along Y axis corresponding to Fig. IV