Virtual MOONS: a focal plane simulator for the MOONS thousand-fiber NIR spectrograph

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ABSTRACT

MOONS will be the next near infrared fiber fed multi-object spectrograph for the Very Large Telescope, that will offer a one thousand multiplexing capability and a simultaneous coverage of the wavelength range from 0.8 to 1.8 µm.

With the aim of quantitatively i) assessing the instrument performances with respect to sensitivity and OH subtraction, ii) blind-testing the 1D spectra extraction and calibration, provided by the data reduction pipeline, and iii) testing the technical solutions adopted for reaching the outstanding instrument requirements, we have developed “Virtual MOONS”, an end-to-end software simulator, which quantitatively computes high fidelity focal plane raw images, emulating the output of the detector electronics.

Starting from an ideal photon image derived from the geometrical optics propagation and Point Spread Function (PSF) variations computed by the ZEMAX optical design, the end-to-end optical budget is introduced along with the stray light contributions, resulting in the expected photon counts impinging the detector pixels. Then the photon image plus photon noise is converted to digital counts by means of a detailed detector simulation, including pixel-to-pixel response variation, dark, bias, read-out noise, cosmetics, charge diffusion, flatness and read-out schemes. Critical points like fiber differential response, PSF haloes and sky emission variations have been also taken into account.

The current status of this work is presented with an example simulated image and numerical results.

Keywords: NIR spectrograph, fiber optics, multi-object, VLT

1. INTRODUCTION

1.1 The MOONS instrument

MOONS[3] will be the next Multi-Object Optical and Near-infrared Spectrograph for the Very Large Telescope, able to simultaneously observe 1024 targets, feeding a bunch of optical fibers which can be placed at user-specified locations on the Nasmyth focal plane.

The sub-fields thus selected are then driven by the fibers into a couple of identical cryogenic spectrographs mounted on the Nasmyth platform, each one hosting 512 fibers arranged in a pseudo-slit at the spectrograph entrance. The light is then split by dichroics in three channels (IZ, YJ and H), dispersed by VPH gratings and imaged on 4k×4k pixel detectors, one for each channel, thus covering the wavelengths from 0.8 to 1.8 µm in the IZ, YJ and H atmospheric windows.

Both low-resolution (LR) and high-resolution (HR) modes are offered: in the LR mode (R~4,000-8,000) the entire 0.8-1.8 µm range is observed simultaneously, while the HR mode covers three selected spectral regions: one around the CaII triplet (at R~8,000) and two regions at R~20,000 (one in each of the J and H bands).
These characteristics demand outstanding requirements for the instrument and the data processing. To test the expected response of the instrument and the Data Reduction Software (DRS)\cite{14} we have developed Virtual MOONS\cite{9}, an end-to-end software simulator, written in Interactive Data Language (IDL\cite{16}), which starting from the source template spectra and the ZEMAX\cite{7} optical design computes high fidelity focal plane raw images emulating the output of the detector electronics.

1.2 The Virtual MOONS simulator stages

The simulation proceeds sequentially in three stages, which compute all the physical effects acting on the incoming light, from the entrance in the atmosphere to the digital image.

The first step (Sec. 2) computes the 2D shapes of the fiber spectra as projected on the detectors. The process starts with directly reading, from the ZEMAX design, the image plane location of a grid of reference fibers and wavelengths. The optical design also provides the space-variant diffraction Point Spread Function (PSF) and the projected diameters of the fiber cores. Diffraction effects, like instrument line shape and diffraction spikes, are also computed at this point.

On second stage (Sec. 3) an ideal photon image is built, summing the flux of each spectral line and continuum emission from all the fibers, suitably scaled to the respective source magnitudes and to the given exposure time, and finally multiplied by the atmospheric absorption. The end-to-end optical budget, consisting of telescope and spectrograph efficiencies, fiber optics transmission, gratings response and so on, together with optical ghosts, are introduced here, resulting in an image of the expected photon counts impinging on each detector pixel.

Finally, the third stage adds the photon noise and the signature of the detectors, converting photon counts to digital counts after considering all the involved physical contributions from detector electronics, i.e. bias, thermal and read out noise, quantum efficiency, pixel cross talks, pixel response variation, bad/hot pixels and clusters and other effects, all relevant for testing the calibration pipeline.

In the following sections we describe these stages in more detail.

2. FIRST STAGE: FROM OPTICAL DESIGN TO SPOT SHAPE AND POSITION

2.1 Spectrographs and detectors

MOONS optical design consists in two identical three-arms spectrographs, as depicted in in Figure 1, with one arm providing the visible channel, and the other two simultaneously imaging two near infrared bands. The former is sensed by an e2V 4K×4K CCD231-84 detector, while the latters are imaged by two identical HgCdTe Teledyne 4K×4K Hawaii-4RG-15 NIR array\cite{17}.

The interested reader can find the general description of the instrument and the detailed spectrometer design in two dedicated proceedings of this SPIE conference (Cirasuolo et al. 2014\cite{4} and Oliva et al. 2014\cite{11}, respectively).

![Figure 1: Preliminary layout of the spectrograph in the MR configuration.](image-url)
2.2 PSF and fiber images

For each spectral mode, the code must compute the projected shape of the fiber core and its location on the array, as produced by the optics for each fiber position along the pseudo-slit and for each wavelength of the spectral range.

This task is accomplished by directly querying the ZEMAX optical design from inside IDL through the DDE protocol of the Windows™ operating system, a task done by the ZEMAXMODULE code, provided to us by L. Busoni [1]. The basic mechanism of this communication consists in sending string commands to ZEMAX (among the ones listed in the ZEMAX EXTENSIONS section of the ZEMAX manual) and receiving back a string answer containing either numeric values or a confirmation that a data file has been written.

Hence, for the chosen optical design, Virtual MOONS starts by generating a set of diffraction images and a set of projected x-y fiber diameters, for a grid of selected fibers and wavelengths. As diffraction figures we adopt the ZEMAX “Huygens PSF”, which includes the optical aberrations (Figure 2, left), while the fiber diameters are computed by displacing each field center to the x-y diameter edges of the fiber cores. An elliptical shape (for simplicity parallel to x-y detector axes) is assumed for the optically distorted image of the 150µm fiber core, covering an area of about 3×3 pixels. Finally the true fiber core image is generated by convolving the diffraction PSF with the corresponding ellipse image (Figure 2, right).

The actual spectral traces, i.e. the x-y position of the chief ray for each wavelength and fiber slit position, are then computed by means of a minimum curvature interpolation of the stored fiber image grid.

Figure 2: Huygens PSF (left) and fiber image (right) for the LR-H spectral mode (logarithmic grayscale, 64 and 150 µm side respectively). FIELD positions correspond to 0, 25.6, 51.2, 102.4 mm along the fiber slit. WAVE positions correspond to wavelengths of 1.448, 1.64, 1.812 µm.
2.3 PSF halo

The Huygens PSF images shown in Figure 2, left panel, only accounts for the diffraction figure and optical aberrations closely around the central peak, but do not describe the PSF wings at large scale, whose flux causes the well known halo aside the bright OH sky lines, partially responsible for the sky continuum emission seen among these lines.

The intensity profile of this halo can depend on many factors, like imperfections on grating ruling, diffuse scattering on the surfaces of optical elements or within the optical materials, diffraction spikes extending towards dispersion direction, and often shows a lorentzian profile, as e.g. in FIRE/Magellan\cite{16} and APOGEE\cite{19} spectrographs (see Figure 3).

![Figure 3: Lorentzian PSF profiles, along spectral direction, for the FIRE/Magellan spectrograph (left) and the APOGEE spectrograph (right), from Sullivan et al. 2012\cite{16} and Wilson J.C., et al.\cite{19}, respectively.](image)

So to accurately simulate the PSF in *Virtual MOONS*, we need a quantitative model to compute what the full PSF will be for the MOONS spectrograph, considering both the diffraction and optical aberrations at small scales (Sec. 2.2), the diffraction spikes (Sec. 2.4), and the large scale PSF halo.

A preliminary ongoing study suggests that the halo will have a circular Bessel profile which, if the horizontal diffraction spike is removed (see Sec. 2.4), asymptotically decreases like $r^{-3}$ in both spatial and spectral directions, thus spreading the light much less than the $r^{-2}$ behavior of a lorentzian tail.

The true fiber image thus is to be computed by convolution of the fiber ellipse with an high resolution PSF model involving all the small scale and large scale features, but this task would be computationally unfeasible, due to the huge dimension of a similar PSF image. So that, we separate the two scales by still using the approximated images of Figure 2, right panel, but slightly modified to smoothly match the PSF halo above a threshold radius, and convolving the outside halo only at detector pixel resolution as last step of the first simulation stage.

2.4 Diffraction spikes

A further effect involved in shaping the PSF is due to the diffraction spikes, which are caused by the optical elements which obstruct the beam in optical layouts with on-axis collimator and/or reflective cameras\cite{11}. These elements are i) the fiber slit assembly and ii) the detector box and its spider arms (see Figure 5, case 1), whose presence modifies the ideal diffraction image and generates three different spikes:

- an horizontal spike, due to the vertical fiber slit and to the vertical edges of detector box
- a vertical spike, due to the horizontal edges of detector box
- three inclined spikes at orthogonal directions with respect to the three spider arms

which affect the focal plane image associating a star-like figure to every bright OH line and spectral feature. This produces a localized stray light effect, as shown in the simulation of Figure 4 where we clearly see that a pure OH line spectrum shows a considerable flux in between the lines.
Figure 4: Focal plane simulation considering diffraction spikes (and no other effects): top spectrum is made by OH lines only; bottom spectrum is made by OH emission plus sky continuum.

The most disturbing diffraction spikes are the horizontal ones, which spread the light to either side of the bright OH lines along the spectral direction, thus increasing the continuum background, in a similar way as the lorentzian wings profile. This is illustrated in Figure 5, case 1, while the vertical spike is not an issue, because it overlaps to the same OH emission on the adjacent fibers. Any inclined spike is also problem for the cross talk that it produces at different wavelengths on the adjacent fibers. This is why we propose a different obstruction profile where both the fiber slit, the vertical spider arm and the vertical sides of the detector box are profiled with a triangular wave border, whose effect is to split the horizontal diffraction spike into a couple of slightly inclined ones, avoiding the overlap with the fiber spectrum and thus highly decreasing the OH wings intensity (Figure 5, case 2).

<table>
<thead>
<tr>
<th>Obstruction</th>
<th>Diffraction</th>
<th>X and Y profiles</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td><img src="image1.jpg" alt="Obstruction" /></td>
<td><img src="image2.jpg" alt="Diffraction" /></td>
</tr>
<tr>
<td>2</td>
<td><img src="image4.jpg" alt="Obstruction" /></td>
<td><img src="image5.jpg" alt="Diffraction" /></td>
</tr>
<tr>
<td>3x exagerated angles</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: Different obstruction shapes (left) and corresponding diffraction images (center) and intensity profiles (right; white: horizontal profile, red: vertical profile). Same scales for all the plots, and logarithmic grayscale for diffraction images.

3. SECOND STAGE: FROM SPECTRAL TEMPLATES TO PHOTON IMAGE

3.1 Sources

A Virtual MOONS simulation starts with the preparation of two textual files describing the spectrum of the input light sources feeding the selected fibers. We distinguish the sources in four categories, FLAT, THERMAL, ARC, SCIENCE or BACKGROUND, and in two types: i) Line Spectrum, used for unresolved spectral lines, in emission or absorption, and consisting in a list of integral line intensities given in $\gamma/\sec/m^2$ or $\gamma/\sec/m^2/arcsec^2$ for point-like and extended sources, respectively, and ii) Continuum Spectrum, used for continuum or resolved spectral lines and consisting in a list
of punctual flux densities at various wavelengths and given in arbitrary units, then rescaled to the given magnitude in the
given band, or directly given in $\gamma/sec/m^2/\mu m$, or $\gamma/sec/m^2/\mu m/arcsec^2$, for point-like and extended sources respectively, in
case a magnitude value is not provided.
Multiple source types can be mixed for each fiber, e.g. for sources where the line spectrum of the extended OH emission
is added to the continuum spectrum of the astronomical source and to sky continuum.

3.2 Sky emission source

A special source is the sky emission, modeled as the sum of the OH emission line and the background continuum.

For the OH lines we use the rich catalog from Rousselot et al. 2000[13], whose theoretical intensities, given in arbitrary
units, have been calibrated by normalization to the observational catalog of Mahiara et al. 1993[10], also considering the
atmospheric transmission, as Figure 6 shows (wavelengths are in vacuum). We have also performed new high resolution
measurements of the sky emission, with the spectrograph GIANO[12], that will be used to improve this model.

![Figure 6: Adopted OH line spectrum from Rousselot 2000[13] (black) within the MOONS spectral range; in red is Mahiara 1993[10]; in green the (rescaled) atmospheric transmission.](image)

For the sky continuum, we follow the study of Sullivan et al. 2012[16], which fit the variation of the sky background
between the OH lines versus both Moon’s distance, Moon’s elevation, local time and OH flux, thus being able to
extrapolate the true continuum level for dark time disentangled from OH contamination: the reported values amount to
0.0312, 0.0543 and 0.0619 mJy/arcsec^2 in the Y, J and H band respectively (corresponding to 460, 670 and 570
$\gamma/sec/m^2/\mu m/arcsec^2$).
3.3 Optical budget

The input spectral templates are trimmed to the wavelength range of the selected mode and interpolated to each pixel, or to a finer sub-pixels grid, integrating the spectrum over the corresponding pixel’s wavelength interval.

Then the spectra are scaled to the given Vega or AB magnitudes, multiplied by the atmospheric transmission and finally converted into photon counts, considering the exposure time and the fraction of source light entering the fibers (less than unity because of the seeing disc and the finite size of the source).

Finally they are multiplied by the optical absorption of the telescope and the spectrograph optics, the fused silica field corrector, the fiber-to-fiber relative efficiencies, the blaze function of the VPH disperser, and the fiber assembly transmission (Figure 7 and Table 1).

![Graphs and charts showing optical budget breakdown and fiber assembly efficiencies.](https://www.example.com/graphs)

**Table 1**: Left: efficiencies of the fiber assembly\(^5\). Right: simulated distribution of fiber-to-fiber transmission.

<table>
<thead>
<tr>
<th>Contributors</th>
<th>Mean throughput (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decentration and/or tilt of telescope</td>
<td>93</td>
</tr>
<tr>
<td>pupil/fibre</td>
<td></td>
</tr>
<tr>
<td>Microlens surface transmission</td>
<td>99</td>
</tr>
<tr>
<td>Fresnel losses</td>
<td>95</td>
</tr>
<tr>
<td>Transmission of the fibre</td>
<td>96</td>
</tr>
<tr>
<td>Connector</td>
<td>99</td>
</tr>
<tr>
<td>Parallelism of fibre optical axis</td>
<td>99</td>
</tr>
<tr>
<td>FRD effect</td>
<td>97</td>
</tr>
<tr>
<td>TOTAL</td>
<td>80</td>
</tr>
</tbody>
</table>

3.4 2D spectral image

Once the 1D spectra, in photon counts per (sub-)pixel, are computed, the 2D photon count image is built, via a double cycle spanning all the fibers and wavelengths, by interpolating the grid of reference fiber images (Sec. 2.2) to each spectral point. The interpolated fiber image is then projected on the detector pixels grid, where the pixel intensity is given by the integral of the fiber image on the pixel area.

The full image is thus constructed point by point summing the spot shape scaled by the local spectral flux, and further convolved with secondary effects, e.g. the spatially variant defocus caused by a peak-to-valley flatness deviation of the detector surface of \(\sim 20\ \mu\text{m}\) (as reported by H4RG data sheet\(^{[17]}\)), that with a pixel size of 15 \(\mu\text{m}\) and a camera as fast as F/1.04 is not negligible.
3.5 Optical ghosts

Finally, all the stray light effects are added, i.e. the PSF halo (as said in Sec. 2.3) and the diffraction spikes (Sec. 2.3), plus the optical ghost, which are combinations of defocused replicas of the focal plane produced by multiple reflections within the optical surfaces.

We compute the ghosts by converting the sequential ZEMAX design to Non-Sequential Component mode, which produces the image shown in Figure 8, on the right. This ghost contains a total flux amounting to 0.47% of the input light.

The ghost image is thus convolved with the simulated ideal spectral image, either via a quick fixed-kernel convolution, computed by an FFT overlap-and-add method[^15], or via a rigorous variable-kernel convolution, computed through sparse matrix coding[^18]. Figure 8, on the left, shows a full simulation for a single fiber, fed by a very bright source (a galaxy with $H_{AB}=10$) imaged in a 1 hour exposure.

This kind of images will be used by the DRS to test the same sparse matrix coding[^18] as a reconstruction algorithm for removing the ghost stray light during data reduction.

![Figure 8: Right: image of the optical ghosts for the preliminary reflective design. Left: ghost effect for a single fiber spectrum (black arrow) of a very bright $H_{AB}=10$ galaxy in 1 hour exposure.](image)

4. THIRD STAGE: NOISES AND PHYSICAL DETECTOR

Photon noise is introduced at this point by generating a random image with Poisson distribution, centered to the integer photon counts per pixel.

The photon counts are then first converted to electrons and then to digital counts, taking into consideration all the involved physical responses and noises of the detectors: electronic biases, thermal dark, amplifier gains, read out noise, quantum efficiency, pixel cross talk, non-linear response, pixel variation, hot/dead pixels and clusters, dust, cosmic rays, pixel saturation and digitization.

4.1 Quantum efficiency and dark image

We adopt for the infrared H4RG-15 2.5µm detector a uniform quantum efficiency of 0.95 $e^-/\gamma$ along all the MOONS wavelength range, as the measured values only varies among 0.9 and 1.0 with a different shape for different detectors (see Figure 9, left).
The correction of the pixel-to-pixel variation in this quantum efficiency, also known as micro-flat or high frequency-flat, is one of the major issues for a correct data reduction. We simulate this variation as a static random Gaussian distribution with a standard deviation of 4%, plus Cauchy distributed outliers, to which we add a static random 4-th order polynomial variation at large scale across the detector area, to simulate a possible low-frequency flat deviation.

The dark image is computed considering that each pixel of the infrared array has its own average dark level, simulated via a static random Gaussian distribution centered on 0.05 e⁻/sec/pixel, as from the H4RG-15 data sheet, and a standard deviation of 5% (Figure 9, right). Cauchy distributed outliers are also introduced, and for each pixel a Poisson random distribution is produced, after conversion to integer electrons, to generate the final dark image. The dark image has assumed to have a smooth structure and to be linearly increasing with elemental integration time.

### 4.2 Read-Out noise

Read Out Noise (RON) is the Gaussian electronic noise due to the reading process, which in CMOS arrays has a different standard deviation for each pixel.

We simulate the RON, for each elemental integration, as a variable random Gaussian distribution, whose standard deviation $\sigma_{\text{RON}}$ does follow on its turn a static random Gaussian distribution, centered to an average value of 13.4 e⁻ /pixels, or to a lower value if multiple sampling readout is used (see Figure 10, left panel); the standard deviation is assumed 66% of the mean, as shown in Figure 10, right panel. Cauchy distributed outliers are also simulated. The RON image has assumed to have no large scale structure.

The actual RON value depends on the particular adopted reading scheme, among “SINGLE READ”, Fowler “CDS”, or “LINEAR RAMP” i.e. non-destructive multiple readouts for which a straight line is fitted to each pixel growth ramp.
4.3 Bias, gain and pixel cross talk

The H4RG detector will be read by 64 channels, each one having its own amplification gain, which yield a column-like pattern in the Bias image (for the SINGLE READ mode).

The Bias is thus an image made of uniform columns, to which we add a variable random gaussian horizontal banding, due to random electromagnetic disturbances on the electronic masses during detector reading, with standard deviation equals to the average RON times the average gain (Figure 11, left). The same column-band pattern is used for the Gain image, that we use to convert from e/pixels to ADU/pixels. An average gain of 0.5 ADU/e⁻ has been adopted, with a static random Gaussian distribution with 1% standard deviation.

Each detector pixel has a cross-talk to neighboring pixels, due to both charge diffusion and inter-pixel capacitance, whose effect can be simulated via a convolution with a Gaussian kernel, as depicted in Figure 11, right, resulting in a further defocusing of the fiber images. We adopt the H4RG-15 data sheet value of 2.42% diffusion into the adjacent pixels.

4.4 Hot and Dead pixels and dust on detector

Fully blind (dead) and saturated (hot) detector pixels are scattered across the array surface and also clustered in contiguous pixels, for which simulation we used the values reported in the detector data sheet. Single bad pixels are just placed in static uniform random positions, while clusters are built by placing points in static and narrow Gaussian random locations around cluster centers distributed uniformly. Then the thinning and closing
morphological operators are used to qualitatively simulate the clusters, by transforming these groups of pixels in closed regions (Figure 12, left).

Finally, dust can deposit on the detector surface after possible opening of the cryostat for technical reasons. Thus we simulate the dust too, using morphological image operators and considering defocusing due to the fast beam F/1.04 of the camera, in order to give a fully realistic raw image to the DRS (Figure 14, right).

![Figure 12: Left: simulation of saturated (white) and blind (black) pixels and clusters. Right: simulation of dust image via morphological operations, defocused for an F/1.04 camera beam.](image)

4.5 Cosmic rays

Cosmic ray events leave random and intense tracks on the detector, whose length and direction depends on the orientation of the detector surface w.r.t. the horizon, as shown in a study for the LSST telescope\(^8\) (Figure 13). This part of the simulation is still TBD, but will be implemented in order to test cosmic rays rejection by the DRS.

![Figure 13: Simulation of cosmic rays for LSST\(^8\) showing the detector orientation (blue rectangle) w.r.t. the mainly vertical cosmic rays direction (black lines).](image)

5. SIMULATION RESULTS

We finally show a detailed MR-H simulation of a set of galaxies, of early, intermediate and late type respectively, whose spectra have been taken from the K20 Galaxy Survey and scaled to different brightness in the range of H\(_{AB}\) from 13 to 23, and to red-shift 1.66 in order to have the H\(_\alpha\) line in a convenient position. Fibers with only sky background are added for comparison.

We introduced all the described optical and detector effects, adopted 128 readings in a multiple non-destructive read out scheme, and considered the light loss due to both the intrinsic size of the galaxy (0.8 arcsec FWHM) and the seeing (0.7 arcsec FWHM), assuming a gaussian profile for both: the resulting raw Focal Plane Image, corresponding to an exposure time of 1 hour, is shown in Figure 14. Some effects are clearly visible in the simulated image, like the bad pixels, the PSF halo, the gain channeled structure, and the OH lines, which are the most evident spots on the spectra.
In parallel to the Focal Plane Image, the simulator also computes two other outputs (not shown), namely the Signal Image and the Variance Image, the former giving the digital counts per pixel from the SCIENCE sources only and without any noise contribution, while the latter giving the total variance due to all the intervening noises.

Thus, by extracting the 1D spectrum of a fiber in the Signal and Variance images separately, we can compute the Signal to Noise Ratio (SNR) per wavelength, as expected for the given source and observation setup in the ideal case of a perfect calibration (i.e. perfect OH subtraction, flat fielding, flux calibration, stray light removal, etc.). Figure 15 shows this SNR spectrum for an H\textsubscript{AB}=21 galaxy in 1h exposure, showing that its continuum is below the detection threshold of SNR=5, while its H\textalpha line is well detectable at a peak SNR of 9, though slightly damaged by the OH residuals (which are the numerous deeps across the SNR spectrum, where the high photon noise of the OH lines decreases the SNR).

Figure 14: Piece of a raw Focal Plane Image simulating galaxies of H\textsubscript{AB} 13 to 23 in 1h exposure time (asinh color scale)

Figure 15: SNR along the spectrum of the H\textsubscript{AB} 21 mag galaxy
6. CONCLUSIONS

The Virtual MOONS simulator quantitatively computes the MOONS raw image output from a given set of template spectra and exposure time, directly starting from the ZEMAX optical design and adding all the various optic and electronic effects thus performing a full end-to-end simulation.

This output is thought with two main scopes, the first of which is to input the simulated frames to the DRS, in order to blind test the optimal extraction algorithms which computes the 1D spectra and to evaluate the accuracy of critical calibration stages, as micro-flat, stray light recovery and OH subtraction. This will be done by directly comparing the science and calibration outputs of the DRS with the input spectra and instrumental signatures used to build the synthetic images.

The second scope is to aid evaluating new strategies to mitigate the influence of instrumental signatures, as we have done e.g. in Sec.2.4 with the study of the diffraction spikes, or new algorithms to subtract them, as envisaged in Sec.3.5 for the optical ghosts.

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