FOROS: Fresnel optical propagation code for SPHERE

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ABSTRACT

SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) is VLT instrument for the discovery and study of new extra-solar giant planets orbiting nearby stars by direct imaging of their circumstellar environment. SPHERE is a complex instrument containing more than 50 optical surfaces. The optical imperfections of each of these surfaces might influence the final contrast. SPHERE has several observing modes in Visible and Infrared, and therefore several optical paths.

FOROS is an end-to-end optical propagation code for SPHERE, which includes almost all surfaces of the instrument. It models the instrument by the sequential blocks: VLT, Foreoptics, Corrective Optics, Coronagraph and so on, such that the beam quality can be studied at several selected locations. The Vis and IR paths are separated in the model. It incorporates the real data of surface measurement, according to the availability of this data. Each surface error can be switched on and off; therefore the influence of each surface on the contrast can be studied independently.

FOROS is an IDL-PROPER-based code, the main power of which is Fresnel propagation. Therefore it represents a numerical tool to study the Fresnel diffraction effects in SPHERE. In the paper we describe the structure and philosophy of the code. The phase screens are not yet implemented.

Keywords: high-contrast instrumentation, end-to-end simulation

1. INTRODUCTION

SPHERE[1] (Spectro-Polarimetric High-contrast Exoplanet REsearch) is the second-generation Very-Large – Telescope (VLT) instrument devoted primarily to direct imaging and possible characterization of faint objects very close to a bright star, especially giant exoplanets. The instrument is divided into four subsystems: the Common Path and Infrastructure (CPI), including corrective optics, and three science channels, corresponding to three instruments. The first near-infrared sub-instrument is a differential imaging camera (IRDIS[2], InfraRed Dual Imaging Spectrograph). It provides imaging in two parallel channels over a wide field of view (11"). Second near-infrared sub-instrument is Integral field spectrograph (IFS[3]), low resolution spectrograph (R=30) over a limited, 1.8"x1.8" field of view. The third sub-instrument is visible imaging polarimeter (ZIMPOL[4], Zurich Imaging Polarimeter).

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The purpose of FOROS is end-to-end modeling of SPHERE instrument. It propagates through *all* optical elements of a quite complicates, multi-channel design (Figure 1). This propagation is implemented in PROPER[5] IDL library. Before describing the structure of FOROS, we introduce the main features of PROPER, including Gaussian beam propagation technique.

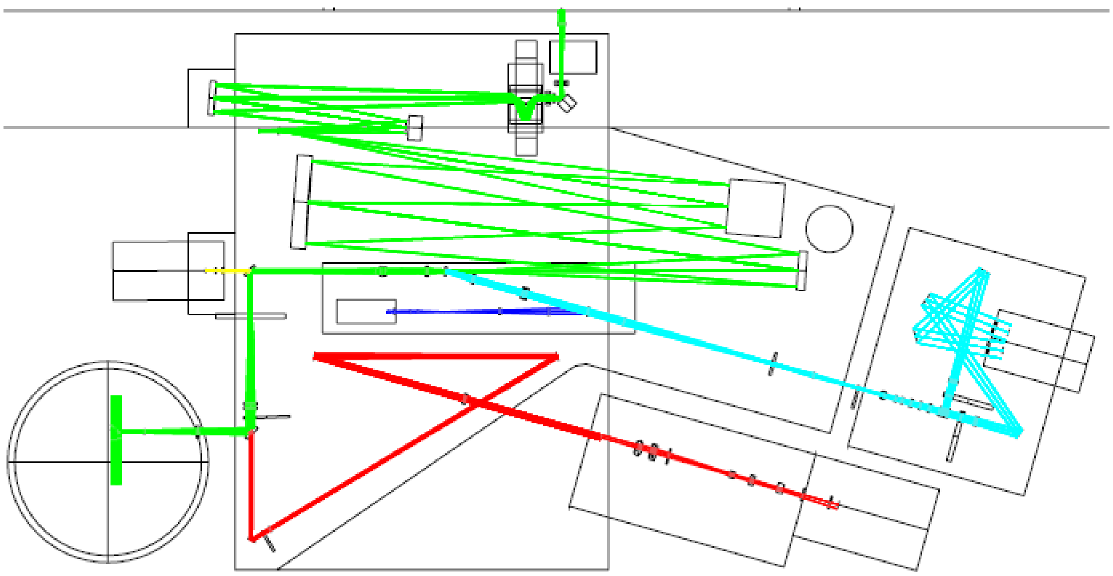

Figure 1. Optical design of SPHERE. Green: common path. Blue: visible channel. Red: near infrared channel.

2. PROPAGATION WITH PROPER

The PROPER routines implement common Fourier transform algorithms (angular spectrum and Fresnel approximation) to propagate a wavefront in near-field and far-field. The procedure determines which algorithm to implement depending on the properties of on-axis Gaussian beam (Figure 2). For a Gaussian beam propagating in free space, the spot size $w(z)$ will be at a minimum value w_0 at one place along the beam axis, known as the *beam waist*. For a beam of wavelength λ at a distance *z* along the beam from the beam waist, the variation of the spot size is given by

$$w(z) = w_0 \sqrt{1 + (z/z_R)^2} \tag{1}$$

where the origin of the z-axis is defined to coincide with the beam waist, and where

$$z_R = \pi w_0^2 / \lambda \tag{2}$$

is called the Rayleigh distance. The radius of curvature of the Gaussian beam is

$$R(z) = z\left[1 + (z_R/z)^2\right] \tag{3}$$

The divergence angle θ is related to the waist as

$$\theta = 2\lambda / \pi w_0 \, . \tag{4}$$

In an unaberrated system the wavefront is planar at the waist of the beam, which is at the pupil when the beam is collimated or at the focus when the beam is converging or diverging. Within the Rayleigh distance near the waist (the near field) the amount of wavefront curvature is low and the phase can be represented relative to a plane without significant aliasing. Away from the waist (into the far field), the wavefront gains curvature. At some point, it cannot be sampled on a planar grid without aliasing. When propagating from one location to another within the near field (within Rayleigh distance), PROPER utilizes the angular spectrum algorithm (plane-to-plane, PTP transform). To propagate from the beam waist in near field to a location in the far, or vice-versa, the Fresnel method is used. Propagation between two points in the far field is done by first propagating to the beam waist and then to the new location. The scale between sample points varies during propagation through a multi-element system.

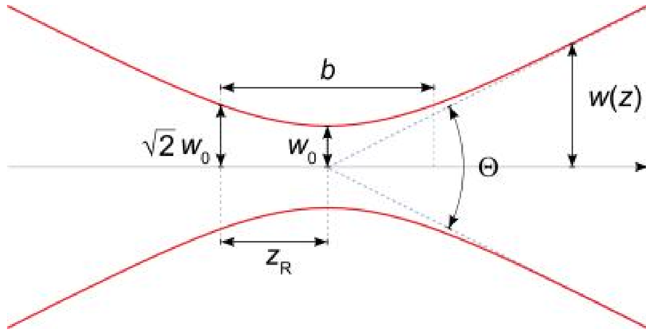

Figure 2. Gaussian beam with parameters: w_0 – radius of the waist, z_R – Rayleigh distance, $b=2z_R$ – depth of focus, θ - divergence angle

While propagating through SPHERE elements we cross-check the beam diameter with the foot prints reported in the SPHERE CPI Optical design Description document[6]. Notice that to calculate the beam diameter we use function **prop_get_beamradius()** which returns the radius of a pilot Gaussian beam, $w(z)$. Let us compare the radius of Gaussian beam in waist for the focused beam with the Airy disk. Let F be focal ratio of the beam. It is the inverse of the divergence angle $F=\theta^{-1}=\pi w_0/2\lambda$, so the beam radius in the waist is $w_0=2\lambda F/\pi\approx 0.64\lambda F$. The first zero of the Airy pattern is $1.22\lambda F$, and the position of half-maximum intensity is $0.51\lambda F$. Therefore the diameter of the Gaussian beam in the focus is intermediate between the full-width-half maxima and the diameter of the Airy disk.

3. CODE STRUCTURE

All PROPER's procedures names start with PROP_ (example PROP_LENS). All name of procedures in our code, which use PROPER procedures inside, start with SPHERE_ (example SPHERE_CORONAGRAPH).

3.1. Main prescription

The main program is executed as prescription called **SPHERE_Common_Path.** Any user who wants to run FOROS types the following in user's routine:

```
PARS ={PATH: 'IRDIS CHANNEL 1', DtoF: 'TEXT'}
prop_run, 'SPHERE_Common_Path', psf, 0.5, 512, dx, PASSVALUE=PARS
```

In this particular example the wavefront intensity in IRDIS CHANNEL 1 focus is returned in the variable psf. The wavelength is set to 0.5 microns, the wavefront grid – to 512 by 512 pixels, the sampling in meters is returned in dx.

PROPER prescription has one PASSVALUE. It allows passing parameters into inside the code and returning internal parameters. We made the PASSVALUE to be a structure of two strings. First string **PARS.PATH** is the name of the optical path. It passes the name of the path to **SPHERE_Common_Path and** defines the optical path to follow. Seconds string **PARS.DtoF** is optional. It is created if we want to extract some internal parameter, for example Distance to Focus at the position of a camera, or beam diameter at a chosen location (see section 4).

The initial wavefront is created in VLT entrance pupil by calling PROP_BEGIN. Procedure PROP_CIRCULAR_APERTURE sets a circular aperture 8m diameter. Afterward the beam follows an optical path defined by **PARS.PATH**. The corresponding procedure has name starting with SPHERE_PATH_, for example **SPHERE_PATH_VLTIMAGE** or **SPHERE_PATH_IFS**.

Prescription creates and propagates a structure *wavefront* – complex amplitude. But PROP_RUN returns *psf*, modulus square of *wavefront*. That is PROPER convention.

This is how the main prescription looks like:

```
*************************************************************************************
PRO SPHERE_Common_Path, wavefront, wavelength, gridsize, sampling, PASSVALUE=PARS1

D_entrance_pupil = 8.0
beam_ratio = 0.25

prop_begin, wavefront, D_entrance_pupil, wavelength, gridsize, beam_ratio
prop_circular_aperture, wavefront, D_entrance_pupil/2
prop_define_entrance, wavefront

if (PARS1.PATH EQ 'IFS IFU') then begin
            SPHERE_PATH_IFS, wavefront, wavelength, gridsize, sampling, PARS1

if (PARS1.PATH EQ 'IRDIS CHANNEL 1') then …
…
prop_end, wavefront, sampling
return
END
*************************************************************************************
```

There are several paths implemented. Each path returns a wavefront in foci. Besides the sub-instruments foci, there are also important internal foci, like coronagraphic focus or adaptive optics focus. There are 10 foci in SPHERE and there are 10 corresponding paths.

(1) PASSVALUE.PATH = 'IFS IFU', IFS path
output: PSF at IFS IFU focus

(2) PASSVALUE.PATH = 'IRDIS CHANNEL 1', IRDIS CHANNEL 1 path
output: PSF at IRDIS CHANNEL 1 focus

(3) PASSVALUE.PATH = 'IRDIS CHANNEL 2', IRDIS CHANNEL 2 path
output: PSF at IRDIS CHANNEL 2 focus

(4) PASSVALUE.PATH = 'CORONAGRAPH', IR CORONAGRAPH path
output: PSF at IR CORONAGRAPH focus (mask)

(5) PASSVALUE.PATH = 'ADAPTIVE OPTICS', ADAPTIVE OPTICS path
output: PSF at AO focus

(6) PASSVALUE.PATH = 'ENTRANCE WINDOW IMAGE', ENTRANCE WINDOW IMAGE path
output: PSF at entrance window focus

(7) PASSVALUE.PATH = 'VLT IMAGE', VLT IMAGE path
output: PSF at VLT focus

(8) PASSVALUE.PATH = 'VIS WFS', VIS WFS path
output: PSF at VIS WFS focus

(9) PASSVALUE.PATH = 'ZIMPOL', ZIMPOL path
output: PSF at ZIMPOL focus

(10) PASSVALUE.PATH = 'VIS CORONAGRAPH' , 'VIS CORONAGRAPH path
output: PSF at visible coronagraph focus (mask)

Notice that propagation in **'SPHERE_Common_Path'** is monochromatic process (due to specifics of PROPER itself). To trace wavelength dependence one has to run **'SPHERE_Common_Path'** in a circle over wavelength.

3.2. Data flow

Full data flow diagram is shown in Figure 3. The optical elements are combined in groups. Each group is implemented as IDL procedure, separated in a file with a corresponding name. For example, first group implemented in **SPHERE_VLT_Nasmyth** propagates *wavefront* through the 3 mirrors of the VLT. The input of this module is *wavefront* at entrance pupil. The output by default is *wavefront* at M3 of the VLT. If this module is used as a part of another path different from **VLT IMAGE,** the output by default is used. If this module is used separately to see the image in the VLT focus the key word TO_VLT_IMAGE must be used in a call for this procedure. Then the output is the wavefront at the VLT image. In other words, in the module **SPHERE_PATH_VLTIMAGE** the procedure SPHERE_VLT_Nasmyth is called in this way:

SPHERE_VLT_Nasmyth, wavefront, wavelength, gridsize, sampling, PATH1, /TO_VLT_IMAGE

In other paths, for example in **SPHERE_PATH_ADAPTIVEOPTICS**, the procedure SPHERE_VLT_Nasmyth is called without a keyword:

SPHERE_VLT_Nasmyth, wavefront, wavelength, gridsize, sampling

In the first case the propagation stops in VLT focus, in the second case *wavefront* propagates through VLT system and goes further to adaptive optics focus.

Another example of the same principle is **SPHERE_Corrective_Optics** module, which has its own focus. The input of this module is wavefront at Derotator M3, means that before entering **SPHERE_Corrective_Optics** module the wavefront must pass through **SPHERE_VLT_Nasmyth**, **SPHERE_Entrance_Window** and **SPHERE_Foreoptics** modules. Output by default is wavefront of the front surface (S1) of Vis/IR Dichroic. In this way the module is used in a chain to propagate further. If the keyword /TO_AO_IMAGE is on, the output is wavefront at AO focus. In this case propagation stops here, at the AO focus:
In **SPHERE_PATH_ADAPTIVEOPTICS** the call is

SPHERE_Corrective_Optics,wavefront, wavelength, gridsize, sampling, PATH1, /TO_AO_IMAGE

In **SPHERE_PATH_IFS** path (for example) the cal is

SPHERE_Corrective_Optics,wavefront, wavelength, gridsize, sampling, PATH1

All paths which correspond to intermediate foci (**'VLT IMAGE'**, **'ENTRANCE WINDOW IMAGE', 'CORONAGRAPH', 'ADAPTIVE OPTICS'** and **'VIS WFS'**) are made in the same way – with a keyword.

For internal groups the logical place, where one module stops and another begins is a beamsplitter. This allows to construct the different paths out of blocks. The first separation is Vis/IR dichroic. The default output of **SPHERE_Corrective_Optics** is *wavefront* on the front surface (S1) of the Vis/IR dichroic. This output is an input for two other modules: **SPHERE_WFS_ZIMPOL_CommonPath** to follow the visible path and **SPHERE_CORONAGRAPH** to follow the IR path. Again, default output for **SPHERE_WFS_ZIMPOL_CommonPath** is *wavefront* on the front surface (S1) of WFS/ZIMPOL beamsplitter. For **SPHERE_CORONAGRAPH** the default output is *wavefront* on the front surface (S1) of IR DTTS Beamsplitter.

Three first modules common for the most of paths, **SPHERE_VLT_Nasmyth**, **SPHERE_Entrance_Window** and **SPHERE_Foreoptics**, are combined in the common module called **SPHERE_UPSTREAM**.

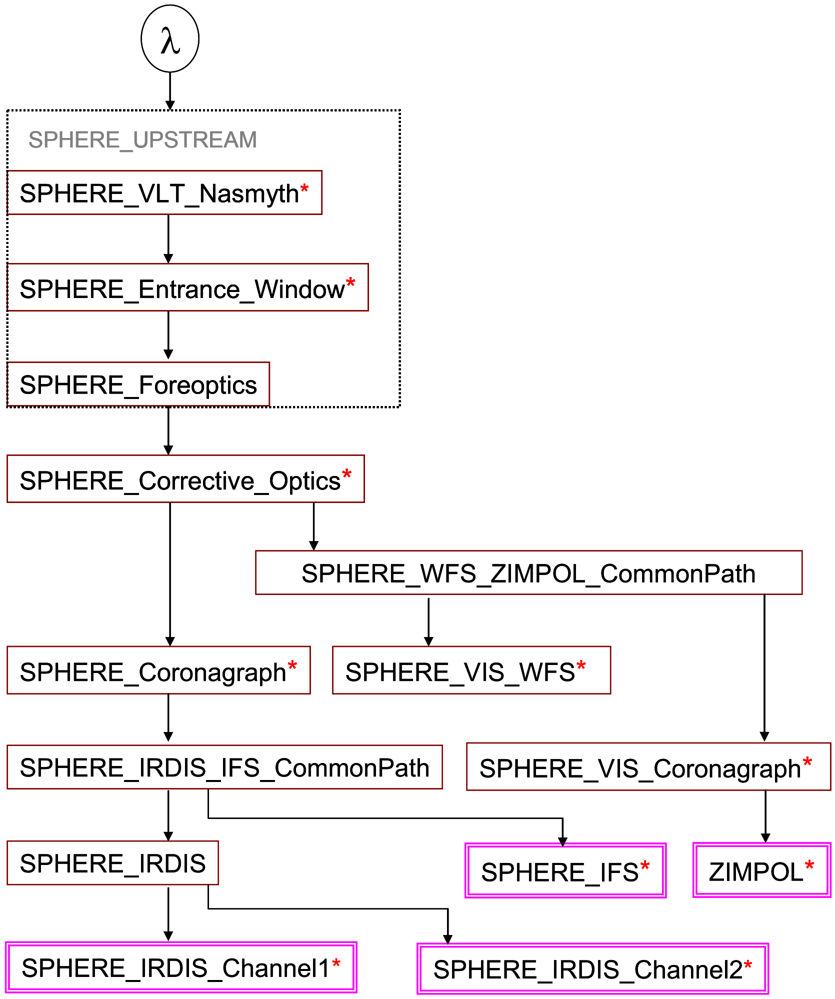

Figure 3. FOROS data flow diagram. Asterix indicates the modules containing foci, i.e. terminal modules in a chosen path. Modules in double pink lines are scientific sub-instruments.

3.3. Phase screens

Phase screen are not entirely implemented yet, but the mechanism is present. Each surface can have aberrations defined by a phase screen. The phase screen is generated from theoretical power spectra or created base on the measurements and stalled in a FITS file. Corresponding procedure reads the FITS file and adds the phase in the proper place of the code. Phase errors (screens) can be switched on or off by the keywords. For example **SPHERE_Corrective_Optics** has 6 surfaces: wavefront propagates to Toric Mirror 1 –> to Image Tip-Tilt corrector mirror (ITT) –> to Toric Mirror 2 –> to Deformable Mirror –> to Toric Mirror 3 –> to Folding Mirror. There are 6 keywords:
TORMIR1_ERRORMAP, ITT_ERRORMAP, TORMIR2_ERRORMAP, DEFMIR_ERRORMAP, TORMIR3_ERRORMAP, FOLDMIR_ERRORMAP

If /TORMIR1_ERRORMAP keyword is "on" when calling **SPHERE_Corrective_Optics**, the procedure reads FITS file TORMIR1_ERRORMAP.fits and adds an error to the wavefront at the position of Toric mirror 1. If this keyword is absent, the wavefront propagates through Toric mirror 1 without errors. The same is with all other surfaces. All keywords are independent, so any combination of screens can be implemented. As we don't have data of decent quality now, this option is not currently used.

4. DIFFRACTION LIMIT RESULTS

To verify the entire code, we compare the beam diameter at each surface during propagation with the beam footprints, reported in the CP Optical Design Description[6]. The beam diameter in FOROS equal to $2w(z)$, where $w(z)$ is Gaussian beam radius given by Eq.(2) and calculated by PROPER. The foot prints reported in Ref.6 are calculated from ZEMAX (printed in red). At the foci we print the distance between the design focus and the position of the beam waist. Also at foci we compare the diameter of the beam with the diameter of the Gaussian beam in waist (D_theor). Below we present the results for 0.95μm for near IR channels (IRDIS and IFS) and for 0.5μm for visible channels.

4.1. IRDIS CHANNEL 1 path

λ=0.95μm

VLT NASMYTH
Beam diameter at M1 8000.0000 mm (8000)
Beam diameter at M2 1113.0952 mm (1113)
Beam diameter at M3 453.33296 mm (453.6)

ENTRANCE WINDOW
Beam diameter at Entrance Window S1 13.332846 mm (13.34)
Beam diameter at Entrance Window S2 12.633217 mm (12.64)

Distance to focus at Entrance Window Image= 0.018719502mm
Beam diameter at Entrance Window Image = 0.018186528 mm D_theor = 0.018154476 mm
F ratio at Entrance Window Image = 14.999982 (15)

FOREOPTICS
Beam diameter at PTTM 7.9987740 mm (8)
Beam diameter at Derot M1 15.998765 mm (16.01)
Beam diameter at Derot M2 22.665430 mm (22.68)
Beam diameter at Derot M3 29.332097 mm (29.35)

CORRECTIVE OPTICS
Beam diameter at Toric Mirror 1 115.92881 mm (115.9)
Beam diameter at ITT 50.002204 mm (50.04)
Beam diameter at Toric Mirror 2 6.8797169 mm (6.882)
Beam diameter at Deformable Mirror 180.00111 mm (180.2)
Beam diameter at Toric Mirror 3 352.55292 mm (352.5)
Beam diameter at Folding Mirror 140.55353 mm (140.7)

Distance to focus at AO Image 0.031857794mm
Beam diameter at AO Image 0.012508307 mm D_theor = 0.012103033 mm
F ratio at CAO Image = 10.000028 (10)

Beam diameter at Vis/IR DichroS1 9.9967933 mm (10.01)

CORONAGRAPH
Beam diameter at Dichro IR/Vis S2 10.619583 mm (10.64)
Beam diameter at IRLens1_S1 17.376252 mm (17.42)
Beam diameter at IRLens1_S2 17.498471 mm (17.55)
Beam diameter at IRLens1_S3 17.992732 mm (18.0)
Beam diameter at ADC1_S1 18.004275 mm (18.0)
Beam diameter at ADC1_S4 18.004761 mm (18.0)
Beam diameter at APODIZER 18.005178 mm (18.0)
Beam diameter at ADC2_S1 18.005595 mm (18.0)
Beam diameter at ADC2_S4 18.006082 mm (18.0)
Beam diameter at IRLens2_S1 18.007541 mm (18.0)
Beam diameter at IRLens2_S2 17.972958 mm (17.76)
Beam diameter at IRDTTS BS 4.6712135 mm (4.655)

IRDIS_IFS
Distance to focus at Corono mask 0.56799582mm
Beam diameter at Corono mask 0.050433260 mm D_theor = 0.048422594 mm
F ratio at CORONO mask 40.008757 (40)
Distance to focus at Corono mask 0.56799582mm
Beam diameter at IRLens3_S1 9.3259455 mm (9.346)
Beam diameter at IRLens3_S2 = 9.3692083 mm (9.391)
Beam diameter at IRLens4_S1 = 9.7762564 mm (9.796)
Beam diameter at IRLens4_S2 = 9.9877562 mm (10.0)
Beam diameter at IRDIS/IFS BS S1 = 9.9909707 mm (10.0)

IRDIS
Beam diameter at IFS/IRDIS BS S1 = 9.9909707 mm (10.0)
Beam diameter at CRYO S1 = 9.9972050 mm (10.0)
Beam diameter at CRYO S2 = 9.9976863 mm (10.0)
Beam diameter at BBFilter S1 = 10.006341 mm (10.0)
Beam diameter at BBFilter S2 = 10.006463 mm (10.0)
Beam diameter at Lyot Stop = 10.008911 mm (10.0)
Beam diameter at BB Splitter S1 = 10.010328 mm (10.0)

IRDIS CHANNEL 1
Beam diameter at SphericalMirror = 10.015701 mm (10.0)
Beam diameter at DualFilter_S1 = 5.2503244 mm (??)
Beam diameter at DualFilter_S2 = 5.1590771 mm (??)

Distance to focus at IRDIS Channel 1 = -0.41429655mm
Beam diameter at IRDIS Channel 1 = 0.046974419 mm D_theor = 0.045700677 mm
F ratio at IRDIS Channel 1 = 37.759796 (37.77)

4.2. IRDIS CHANNEL 2 path

λ=0.95μm

Up to and including block IRDIS the propagation is the same after the broad band beam splitter (BB Splitter S1) the results are

IRDIS CHANNEL 2
Beam diameter at Broad Band Beam Splitter S2 = 10.010541 mm (10.0)
Beam diameter at FoldingMirror = 10.011180 mm (10.0)
Beam diameter at Compensator S1 = 10.011731 mm (10.0)
Beam diameter at Compensator S2 = 10.011945 mm (10.0)
Beam diameter at SphericalMirror = 10.016558 mm (10.0)
Beam diameter at DualFilter_S1 = 5.0389124 mm (??)
Beam diameter at DualFilter_S2 = 4.9476331 mm (??)

Distance to focus at IRDIS Channel 2 = -0.41475851 mm
Beam diameter at IRDIS Channel 2 = 0.046973756 mm D_theor = 0.045696674 mm
F ratio at IRDIS Channel 2 = 37.756488 (37.77)

4.3. IFS IFU path

λ=0.95μm

Up to and including IRDIS_IFS the propagation is the same as for IRDIS. After IRDIS/IFS beamsplitter (IRDIS/IFS BS S1) the results are

IFS
Beam diameter at IRDIS/IFS beamsplitter S2 = 9.9913343 mm (10.0)
Beam diameter at Folding Mirror M1 = 10.007126 mm (10.0)
Beam diameter at Lyot Stop = 10.009249 mm (10.0)

Beam diameter at Lens1 S1 = 10.010312 mm (10.0)
Beam diameter at Lens1 S2 = 10.006253 mm (10.0)
Beam diameter at Lens1 S3 = 10.005320 mm (10.0)
Beam diameter at FoldingMirror M2 = 6.3668967 mm (6.309)
Beam diameter at FoldingMirror M3 = 3.7273782 mm (3.625)
Beam diameter at Lens2 S1 = 2.0684974 mm (1.922)
Beam diameter at Lens2 S2 = 2.0546477 mm (1.907)
Beam diameter at Lens2 S3 = 2.0441438 mm (1.896)

Distance to focus at IFS IFU = 34.288906mm
Beam diameter at IFS IFU = 0.39718234 mm D_theor = 0.37555079 mm
F ratio at IFS IFU = 310.29565 (316)

4.4. Near IR paths design amendments

To arrive to these results we had to change the following parameters in the design:

(1) Radius of curvature of Lens 2 S2 of coronagraph increased by 0.0036725m:
Lens2_S2_RADIUS = -0.56388387-0.0036725
Without this amendment the F ratio at the coronagraph mask position was 39.85 (instead of 40) and the focus was missing by -2.2mm for all wavelengths. The value was optimized to have the minimal distance to focus shift for all wavelength in 0.95-2.32μm range (see Figure 4).

(2) In IRDIS IFS Common path Radius of curvature of Lens 4 S2 increased by 0.00047024m:
Lens4_S2_RADIUS = -0.21266239-0.00047024
Without this amendment the beam diameter at Lyot stop (collimated beam) was 9.985mm for all wavelengths instead of 10mm.

These amendments are probably due to some bugs in FOROS code. The problem is currently under investigation.

4.5. VIS WFS path

λ=0.5μm

VLT NASMYTH
Beam diameter at M1 8000.0000 mm (8000)
Beam diameter at M2 1113.0952 mm (1113)
Beam diameter at M3 453.33296 mm (453.6)

ENTRANCE WINDOW
Beam diameter at Entrance Window S1 13.332838 mm (13.34)
Beam diameter at Entrance Window S2 12.636731 mm (12.64)

Distance to focus at Entrance Window Image= 0.071554159mm
Beam diameter at Entrance Window Image = 0.010674482 mm D_theor = 0.0095549949 mm
F ratio at Entrance Window Image = 14.999992 (15)

FOREOPTICS
Beam diameter at PTTM 7.9952375 mm (8.004)
Beam diameter at Derot M1 15.995237 mm (16.01)
Beam diameter at Derot M2 22.661904 mm (22.68)
Beam diameter at Derot M3 29.328573 mm (29.35)

CORRECTIVE OPTICS
Beam diameter at Toric Mirror 1 115.92529 mm (115.9)
Beam diameter at ITT 50.002366 mm (50.04)
Beam diameter at Toric Mirror 2 6.8822739 mm (6.882)
Beam diameter at Deformable Mirror 180.00170 mm (180.2)

Beam diameter at Toric Mirror 3   352.55641 mm (352.5)
Beam diameter at Folding Mirror   140.55634 mm (140.7)

Distance to focus at AO Image=   0.055338506mm
Beam diameter at AO Image =   0.0084351625 mm   D_theor =   0.0063699976 mm
F ratio at CAO Image =   9.9999960 (10)

Beam diameter at VisIR DichroS1   9.9944724 mm (10.01)

VIS WFS ZIMPOL Common Path
Beam diameter at Vis Lens S1   21.300616 mm (21.35)
Beam diameter at Vis Lens S2   21.507117 mm (21.58)
Beam diameter at Vis Lens S3   22.000665 mm (21.99)
Beam diameter at ADC1 S1   21.990944 mm (21.99)
Beam diameter at ADC1 S4   21.990430 mm (21.99)
Beam diameter at PUPIL   21.990337 mm (21.99)
Beam diameter at ADC2 S1   21.990244 mm (21.99)
Beam diameter at ADC2 S4   21.989730 mm (21.99)
Beam diameter at WFS/ZIMPOL BS   21.977270 mm (21.99)

VIS WFS
Beam diameter at WFS Lens 1 S1   21.969831 mm (21.99)
Beam diameter at WFS Lens 1 S2   21.854559 mm (21.87)
Beam diameter at WFS Lens 1 S3   21.765582 mm (21.79)
Beam diameter at DTTPlate_S1   11.935443 mm (11.95)
Beam diameter at DTTPlate_S2   11.480080 mm (11.50)

Distance to focus at Diaph Image =   -0.042716327mm
Beam diameter at Diaph Image =   0.012905846 mm   D_theor =   0.012735352 mm
F ratio at Diaph Image =   19.992703 (20)

5. THICK OPTICAL ELEMENTS

SPHERE has a number of thick pieces of optics: windows, beamsplitters, lenses and doublets. They are made of different materials. Unfortunately, in PROPER the propagation through such elements is not implemented. The only available routine is **prop_lens** which alters the wavefront curvature as would a thin lens do. The lens is introduced by changing the radius of curvature of the Gaussian beam:

$$R_{new} = \frac{1}{\frac{1}{R_{old}} - \frac{1}{f}} \tag{5}$$

Here f is the focal length of the lens, the input parameter of **prop_lens** algorithm.

We model a thick lens with index of refraction n, by setting two thin lenses. First lens is at the first surface of the thick lens, second lens is at the second surface. The focal length given as a parameter to PROPER is calculated from index of refraction of the first medium, n_1, index of refraction of the second medium, n_2, beam curvature R_{beam} and the curvature of the surface separating two media, R.

$$f = \frac{n_2}{n_1 - n_2} \frac{1}{\frac{1}{R_{beam}} - \frac{1}{R}} \tag{6}$$

If the separating surface is flat R=*infinity*, as for example for the entrance window, the change of beam curvature is defined by the initial beam curvature. The doublets are modeled by three thin lenses.
Therefore the shift of the focus position introduced by a thick lens depends not only on the dispersive properties of material, but also on the beam radius of curvature, which is wavelength dependent (Eq.3). The dispersion of material is modeled by Sellmeier equation:

$$n^2 - 1 = \lambda^2 \left[\frac{S_1}{\lambda^2 - l_1^2} + \frac{S_2}{\lambda^2 - l_2^2} + \frac{S_3}{\lambda^2 - l_3^2} \right] \tag{7}$$

Where the values for S_1, S_2, S_3, l_1, l_2 and l_3 where taken form web site.[7]

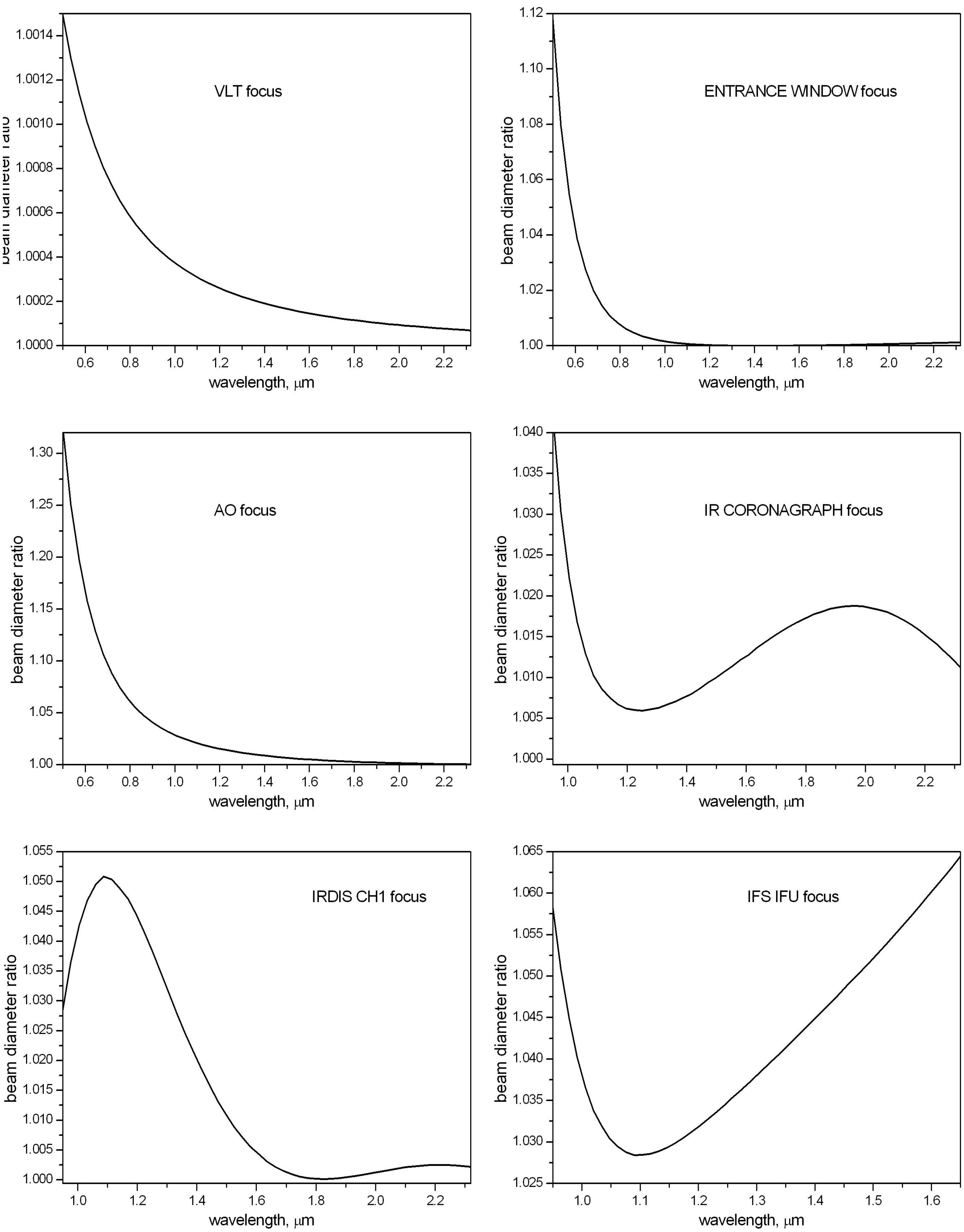

Figure 4. Ratio of the beam diameter in the focus position defined by the design to the beam diameter at the waist of the beam as a function of wavelength. The wavelength range changes according to the sub-instrument.

While propagating through the whole system the chromatic effect increases, and at the sub-instruments foci it becomes quite essential. This lateral chromatism is more than expected by design and the reason for this effect is currently under investigation. To quantify this effect several parameters can be used. For example the distance between the design focus (for example AO focus at x=-393.1062mm and y=-865.2621mm in global system coordinate) and the position of the beam waist. This parameter tells how much is beam defocused at the position of design focus compare to Airy pattern. But this effect depends on the focal ratio of the beam, because for slow beams the same amount of de-focal distance is less critical on diffraction pattern than for the fast beam. In this respect the better criterion for the lateral chromatism is a ratio of the diameter of the beam at the design focus to that at the beam waist, calculated as $4\lambda F/\pi$.

$$r = \frac{w(z)}{w_0} = \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \tag{8}$$

If r is less than $\sqrt{2}$ the position of the design focus is within the beam's depth of focus ($z < z_R$) and the effect is small. For lager r the defocus effect starts show up on the diffraction pattern. We plot this ratio for several foci in Figure 4 and diffraction pattern for few parameters of r – in Figure 5. The dispersion at VLT focus is pure Gaussian beam effect. There are no dispersive elements before this focus, only 3 VLT mirrors. The effect is small. The Entrance Window focus and the Adaptive Optics Focus suffer from dispersion introduced only by one optical element – the entrance window plate. This effect can be verified with geometrical optics equations and we have proven that the lateral chromatism obtained in FOROS and calculated directly match. The situation becomes more complicated for coronagraphic focus, formed by one doublet (S-FTM16, CaF2) to form a collimated beam for the coronagraph pupil and a thick lens (BaF2) to focus the beam on the coronagraphic mask. As we mentioned earlier we had to change the radius of curvature of the second surface of the second lens. We have chosen an amendment value to minimize the chromatic effect for the whole wavelength range, in another word – to minimize a peak to valley of the fourth curve at the Figure 4. Chromatic effect at IRDIS and IFS foci is even more complicated and needed to be studied further.

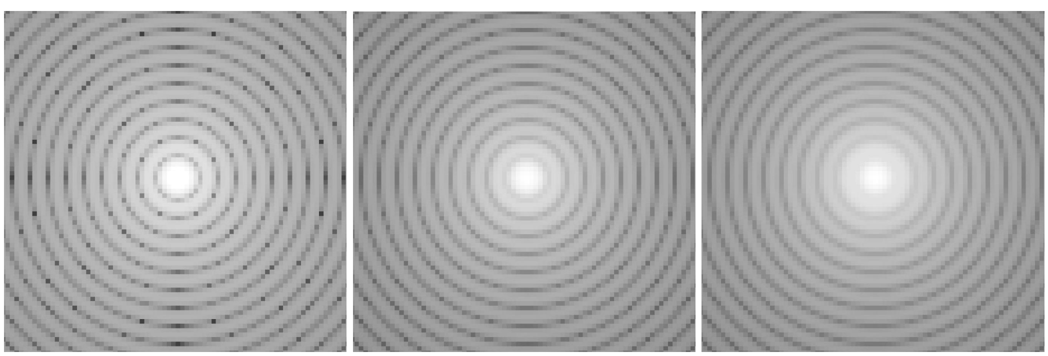

Figure 5. Diffraction pattern in AO focus for different wavelengths, characterized by a ratio between diameter of the beam to the diameter of the beam waist. Left: *r*=1 (perfect focus), central: *r*=1.3, right: *r*=2.2.

6. CONCLUSION

SPHERE is a far progressed project, currently in the phase of integration and test. Of course, FOROS is not unique software instrument to verify the performance of SPHERE. Multiple different studies have been done within the community to arrive to the current design. Nevertheless, FOROS is unique software in a sense that it delivers a full end-to-end model which includes all optical surfaces and propagates using near-field and far field optical methods. It allows to check optical quality of the beam at any chosen location (by default – in foci, but in principle any location can be extracted). It can be useful to complete instrument modeling and possible debugging the unexpected features.

For now FOROS is a linear code, i.e. it propagates through the entire system without a close loop, so no adaptive optics or tip-tilt correction is implemented. The next important update after including of phase screens is to combine it with CAOS[8] - the adaptive optics software for SPHERE.

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