Geometrical optics numerical simulation of 2 subsystems from the James Webb Space Telescope

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Abstract: James Webb Space Telescope's documentation is publicly accessible and quite dense with several pointers to subsystem conception papers. It is a great opportunity to work on a cutting-edge optical system with direct applications of physical concepts seen in class. In this paper, numerical model using geometrical optics will be proposed for 2 optical subsystems embedded in the JWST.

Index Terms: James Webb Space Telescope, geometrical optics.

1. Introduction

James Webb Space Telescope was scheduled for launch and deployment in 2012 but was finally launched in December 2021 and successfully delivered its first image in June 2022. As the largest optical telescope in space, its high resolution and sensitivity allow it to view objects too old, distant, or faint for the Hubble Space Telescope. This will enable investigations across many fields of astronomy and cosmology, such as observation of the first stars, the formation of the first galaxies, and detailed atmospheric characterization of potentially habitable exoplanets. [2]
Documentation on JWST conception is publicly accessible and quite dense with several pointers to subsystem detailed description. A great opportunity to work on a cutting-edge optical system with direct applications of physical concepts seen in class. I aim at modeling 2 particular subsystems on the telescope: the first is The Optical Telescope Element (OTE), which consists of the primary, secondary, tertiary, and fine steering mirrors; the second is the Near Infrared Camera (NIRCAM) located in the scientific module. [1]

2. Methods

2.1. Numerical tool

First step is the choice of optical modelling software. Industry standards such as Lambda® OSLO, Ansys® Zemax OpticStudio or Synopsis® Code V are well suited but neither Université de Lorraine or CentraleSupelec supply licenses for complete versions. Free or educational version have a limit of around 10 surfaces which is too limited for our intent. Python libraries presented in class were either outdated or poorly documented. Since geometrical optics handling was the only

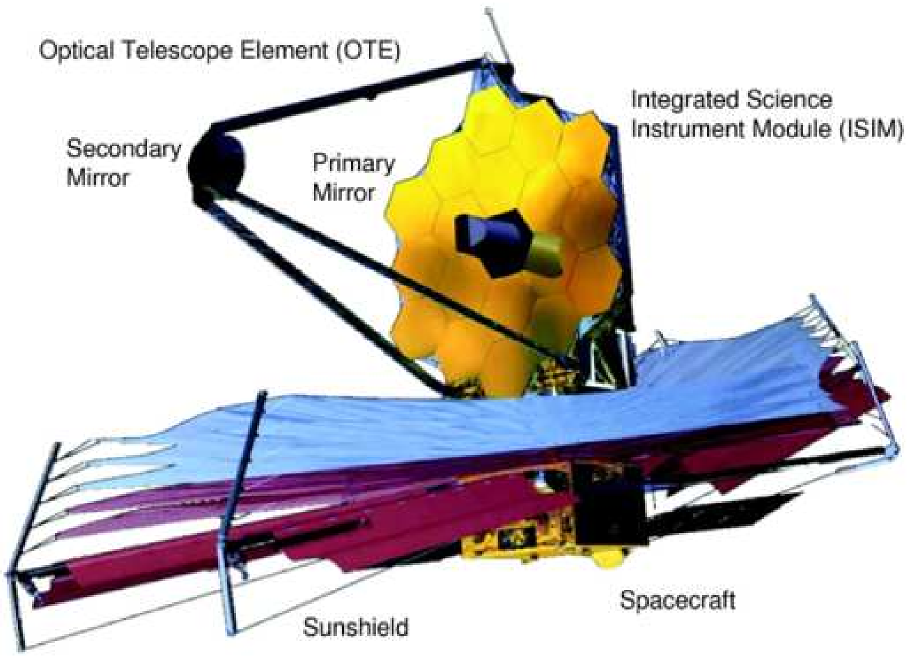

Fig. 1. The JWST Observatory. The optical telescope element contains the primary and secondary mirrors, the integrated science instrument module (ISIM) element contains the instrumentation, and the spacecraft element consists of the spacecraft and the sunshield.

requirement, a user-friendly software running on Java called *Optical Ray Tracer* [4] was chosen instead. The modelling equations used by the software are well explicated in the documentation. Beams are characterized by their starting and end point. The classical Snell laws for refraction are implemented and redirect beams crossing a defined surface which can be either spherical, parabolical or hyperbolical. The major flaw of *Optical Ray Tracer* is its poor versatility for instance the impossibility to choose the wavelength of source beams.

2.2. Gather data

Second step is to gather more detailed data on the systems to be modelled. As previously mentioned, the literature is dense but not so precise. For example, on a collimator triplet lens, I was able to access material, thickness, radius and curvature of surfaces but not the relative position between the collimator and other optical elements or even the distances between lenses [6]. The general conduct adopted was then to replicate at best on the same scale the physical principle used. Precise industrial values from JWST were implemented only when accessible.

3. Modelling

Before modelling light path into the JWST, let's have a general overview of it (Fig. 1)[2]. The sunshield enables passive cooling and provides a stable cryogenic environment by minimizing the amount of solar energy incident onto the telescope and ISIM. This constrains the JSWT to observe only a limited field of the sky depending on its orbital position. The most recognizable element of the telescope is its primary mirror of 6.5-meter diameter. A yet unmatched diameter for a telescope, too large to be fitted into a rocket. The concave parabolic structure was broken down into 18 hexagonal shaped that unfolded after launch. (Fig. 2) The parallel light beams concentrated by the primary mirror are reflected onto the convex secondary mirror (0,74m diameter) then onto the fixed tertiary mirror located in the middle of the primary mirror. The light is finally directed

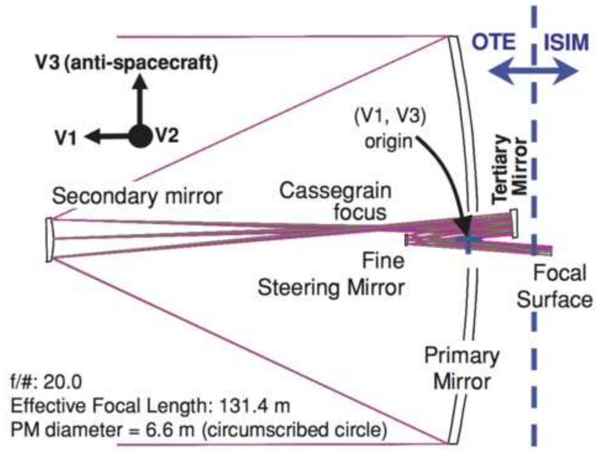

Fig. 2. The telescope optical layout. The JWST optical telescope has an effective f/number of 20 and an effective focal length of 131.4 m.

by a fine steering mirror towards the ISIM (Integrated Science Instrument Module). This module contains 4 different metrology devices, but we will only focus on the Near Infrared Camera for this project.

3.1. Cassegrain reflector

The Optical Telescope Element is modelled as a Cassegrain reflector with its primary and secondary mirror. The documentation doesn't provide data on the tertiary mirror and fine steering mirror. We only have access to f-number of 20 and the focal length of the glocal system which is 131,4 m. Following Cassegrain equations [7] : the radii or curvature of the primary and secondary mirrors respectively, in the classic configuration are

$$R_1 = -\frac{2F}{M} \tag{1}$$

and

$$R_2 = -\frac{2B}{M-1} \tag{2}$$

where F is the effective focal length of the system, B is the back focal length (distance from the secondary mirror to the cassegrain focus), D is the distance between mirrors and M = (F - B)/D is the secondary magnification. The primary mirror is parabolic and the secondary mirror is hyperbolic. The equation for the conical constants are given by :

$$K_1 = -1 \tag{3}$$

and

$$K_2 = -(\frac{M+1}{M-1})^2 \tag{4}$$

I estimated considering the photos and schematics given that the distance between mirrors must be around D = 10m and the ISIM must be 50 cm behind the primary mirror which lead to B = 10,5m. We can then estimate the set of values to implement in *Optical Ray Tracer*:

R1 = 21.737 m K1 = -1
R2 = 1.8936 m K2 = 1.3932

Some remarks on the modelling (Fig. 3):

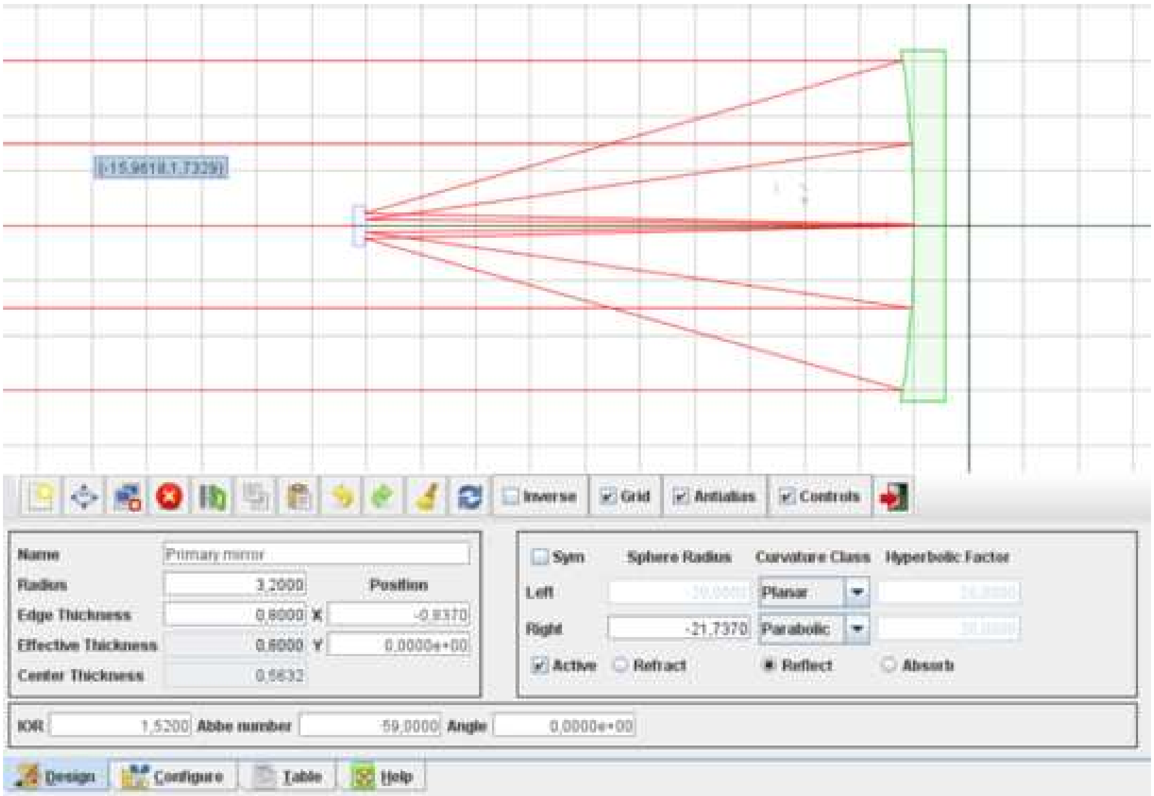

Fig. 3. Modelling of a JWST-like Cassegrain reflector on Optical Ray Tracer

- The software does not enable holes into optical surfaces so the model have a final reflection on the quasi planar center of the primary mirror. This changes the position of the focal plane from behind to before the primary mirror. For that same reason, I will be compelled me to model all the NIR Cam optical elements before the primary mirror.
- Calculated parameters were good starting values but the software did not seem to compute the hyperbolic value as conical constant. I had to tweek it manually to achieve a satisfactory anastigmatism.
- As reflection based optical device, the modelled telescope is not sensible to dispersion.

3.2. Near Infrared Camera (NIRCam)

The NIRCam instrument for JWST is one of the four science instruments installed into the ISIM directly behind the JWST primary mirror. NIRCam's requirements include operation at 37 kelvins to produce high resolution images in two wave bands encompassing the range from 0.6 microns to 5 microns. There are two redundant module back to back on the same plate like the one visible on photo (Fig. 4) and 3D model (Fig. 5). There are made to visualize two adjacent patches of sky at the same time [3] [1].

3.2.1. Architecture

In one module (Fig. 6), the light is first picked up from the OTE. A coronagraph is located in the focal plane after the mirror. A collimator made of a triplet lens create a plane wavefront. Light is then divided between short-wavelength (0.5um to 2.3um) and long wavelength (2.3um to 5um) by a dichroic beam splitter. Each channel has a wheel of pupil and filters that can be applied to further select wavelength or further shape the beam. Each channel is focused by another triplet onto a camera sensors, the short wavelength SW sensor being a assembly of 4 like long wavelength LW

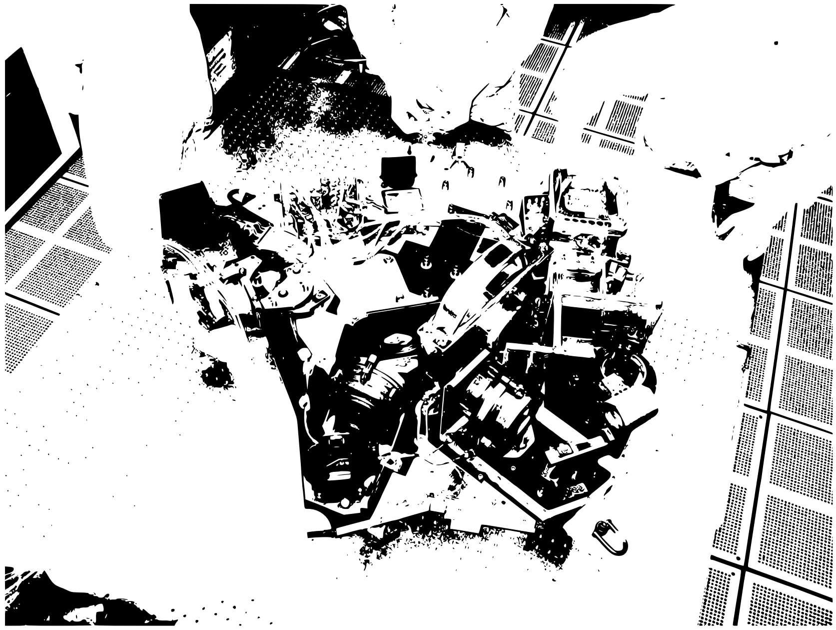

Fig. 4. Photo of one side of the NIRCam module

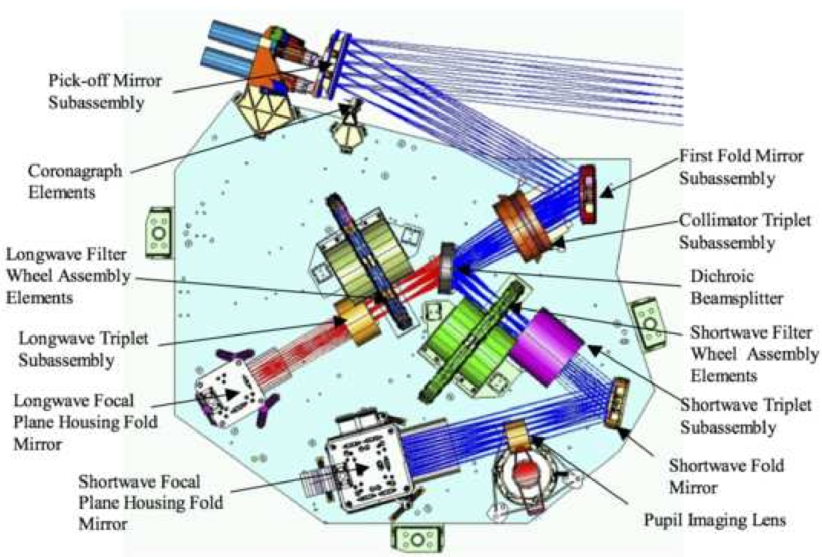

Fig. 5. 3D model of one side of the NIRCam module

sensor offering then twice the resolution [2][1].

3.2.2. Lens implementation

We will only model the light trajectory through a simplified architecture. Collimator made of 3 lenses set the wavefront linear after the OTE focal surface. Beam splitter are non computable on this software, so we will replace it by a switch between a plate being either totally reflective or totally refractive. For each channel, a secondary triplet lens converges the beam into a final surface modelling the sensor. Most specifications on lenses are given by [6] (Fig. 7). Data on the spaces between lenses and general architecture is lacking, I will adjust myself these spatial parameters. See the interface of the software for implementing lenses (Fig. 8).

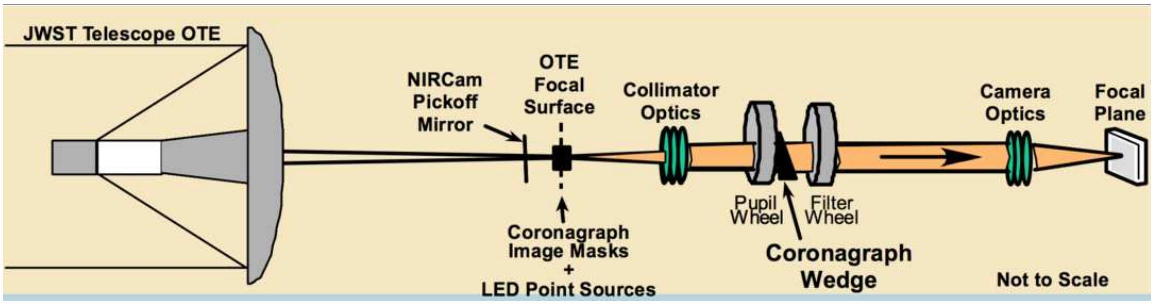

Fig. 6. Schematic of NIRCam optical design.

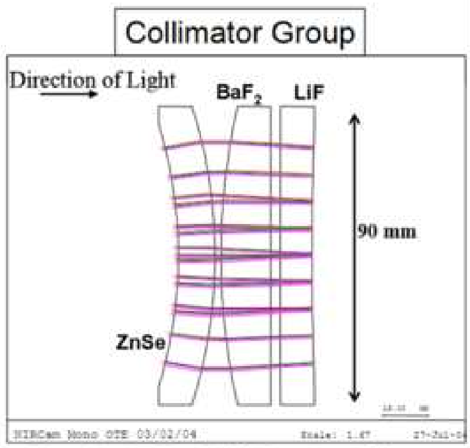

Figure 2. NIRCam Triplet Lens Assemblies

Element	Material	R1	R2	Thickness
COL1	ZnSe	122.9	136.6	12.8
COL2	BaF2	184.2	∞	17.5
COL3	LiF	∞	1096.2	11.1

Element	Material	R1	R2	Thickness
SW1	LiF	64.98	93.47	8.0
SW2	BaF2	311.3	80.79	19.9
SW3	ZnSe	69.22	107.85	12.0

Element	Material	R1	R2	Thickness
LW1	LiF	42.33	57.07	7.5
LW2	BaF2	453.3	60.0	17.65
LW3	ZnSe	56.68	65.76	9.8

All dimensions in mm

Fig. 7. Typical specifications found on the lenses in the documentation.

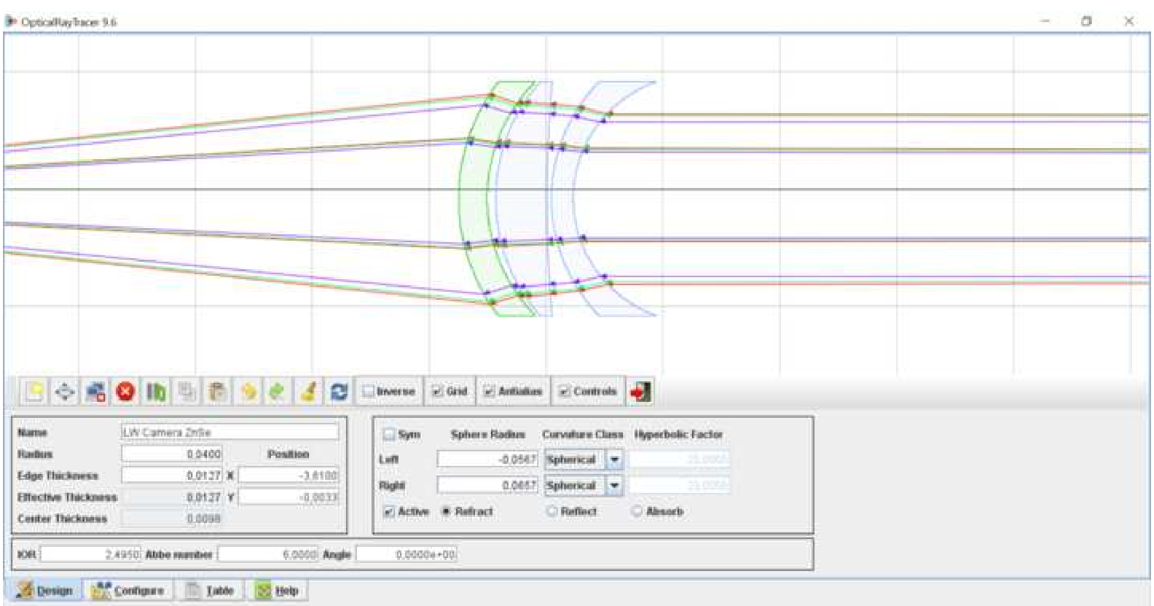

Fig. 8. Optical Ray Tracer interface : modelling of the collimator triplet lens.

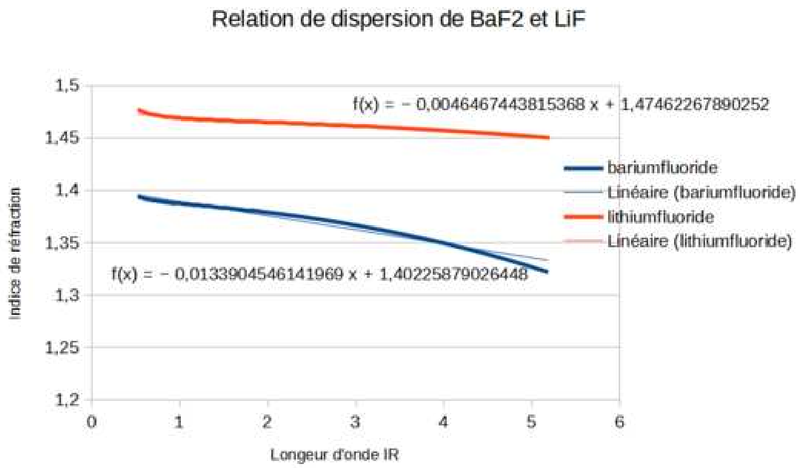

Fig. 9. Dispersion : refractive index dependency to wavelength for BaF2 and LiF.

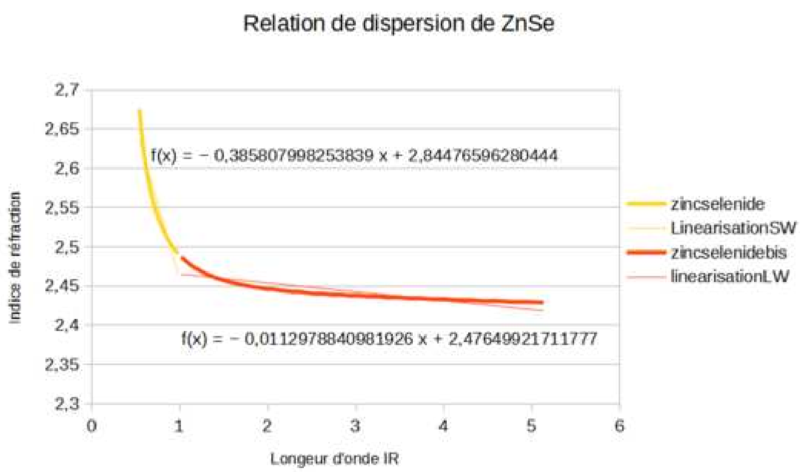

Fig. 10. Dispersion : refractive index dependency to wavelength for ZnSe.

3.2.3. Practical implementation

3.2.3.a. Refractive index

A painful point concerns the refractive index of lenses because the software is limited. It only calculate beams going from 400 to 650 nm wavelength and dispersion is only implemented through Abbe number. This will not work on material such as ZnSe with high dispersion and on near IR range of wavelength.
Data about the dispersion of each of the 3 materials used in the triplet lenses (ZnSe, LiF, BaF2) can be found online [5]. I plotted it on the range of interest for wavelength 0.5um – 5um (Fig. 9 and Fig. 10). LiF and BaF2 can almost be linearized on this range of wavelength. The problematic material is ZnSe with its strong dispersion on 0.5–1um. Since these compound lenses are mostly made to suppress chromatic aberration, I want to test this. The most extreme case of dispersion (0.5 – 1um) should suffice to qualify triplet lens.

There is a tip to bypass these restrictions. Since the creator of the software detailed the way he implemented dispersion, we can map the 400nm beam to 0.5um and 650nm to 1um and

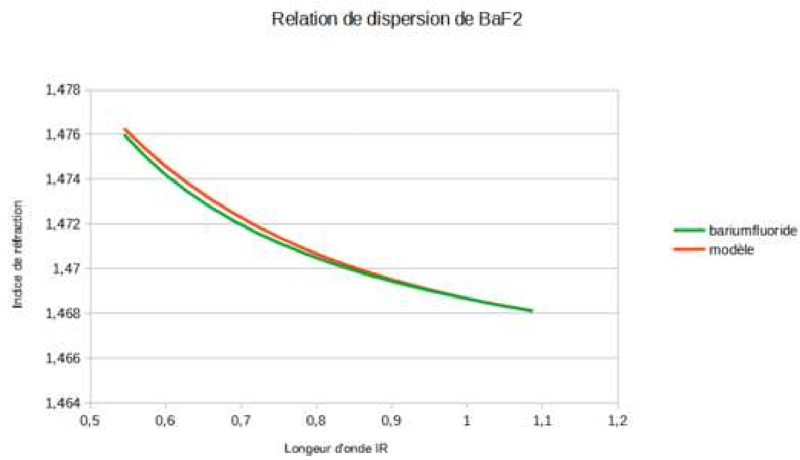

Fig. 11. Fitting the software dispersion model to BaF2 dispersion relationship.

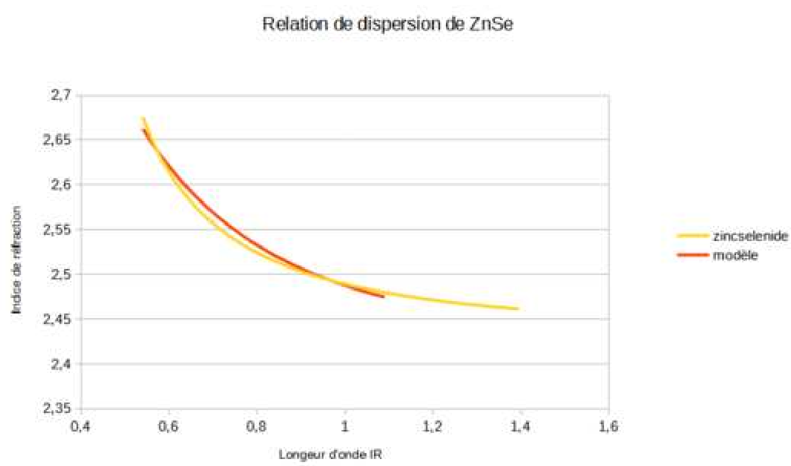

Fig. 12. Fitting the software dispersion model to ZnSe dispersion relationship.

them try to fit his model (which use abbe number) on the material dispersion data. This way the 650nm beam on the software will see the same refractive index as a 1um beam would see on this particular material in a realistic simulation. The software model for dispersion :

$$n'(W) = n_{param} + \frac{W_{ref} - W}{W_{ref} W^2} * \frac{5e5}{Abbe} \tag{5}$$

The fitting of his model with the material curve is given by Fig. 11 and Fig. 12. The deduced parameters to input in the software are summarized hereafter :

Material	Refractive index	Abbe number
ZnSe	2.495	6
BaF2	1.469	135
LiF	1.387	170

Fig. 13. Simplified NIRCam short-wavelength light path.

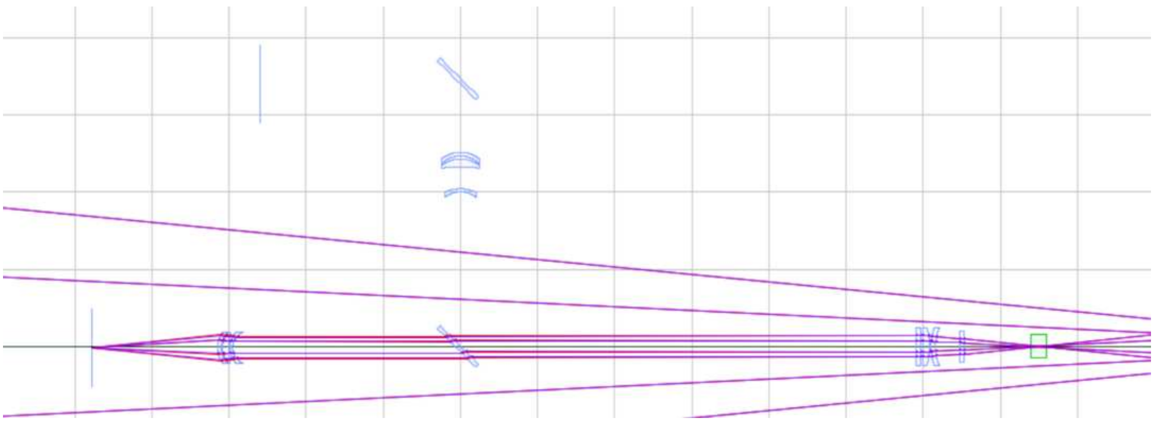

Fig. 14. Simplified NIRCam long-wavelength light path.

3.2.3.b. Spatial constraint

The effective focal length of the Cassegrain telescope modelling was changed so the beams reflected by the secondary mirror could avoid the NIRCam module modelled before the primary mirror. A correction lens was added into the path of beams to correct that focal length mismatch before the collimator triplet.

3.2.3.c. Resulting model

The light path are modelled for SW (Fig. 13) and LW (Fig. 14). On the two channels, the aberration are not completely suppressed. With the values from the specs and our custom spaces between length, the value was 100um for the dispersion on maximum aperture beams which is much larger than the resolution 5um. Parameters could be adjusted further to gain a bit more but the order of the magnitude for the error would stay the same. It is already satisfying for such a simplified model on a basic software.

4. Discussions

I have only just scratched the surface of what could interesting to model on JWST. Basically, the requirements for precision are so high that every physical phenomenon must considered during engineering process. Absurd close-to-perfection values are expected for lens surfaces. Actuators are controlling the position / angle of mirrors and lens on the nanometer level. Multiple reasons could explain why our model did not achieve achromatism. Among the simplifications made, refractive index values were taken at 300K while the lenses will be working at 37K. On a more complete software like Zemax with precise 3D model of the system, it could be interesting to see the system response to slight perturbation for example in the alignment of triplet lens. Try to figure out how that perturbation would distort the final image and why requirements for precision were so high.

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