# TECHREP
# Telecentric lenses and CODE V calculations for the HiLo microscope

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## Telecentric lens system

### Definition

A lens (or a system of lenses) is telecentric when the entrance or exit pupil is at infinite distance.

- Object space telecentric: entrance pupil is at infinity
- Image space telecentric: exit pupil is at infinity.
- Double telecentric: both entrance and exit pupils are at infinity.

Reminder: the pupil

- Entrance pupil: image of the aperture stop, as seen through the front (object side) of the lens system.
- Exit pupil: same thing than entrance pupil, but from the image side.

Reminder: the field-of-view (FOV)

The FOV for a sensor system is the span over which a given object is imaged. The FOV can be expressed as an angle, or as a horizontal or vertical distance (since the sensors are typically rectangular).

Key features of telecentric systems:

- The chief ray is parallel to the optical axis in the object and/or image space.
- The magnification does not change in respect to depth.
- The stop is usually placed at a lens' focal point.
- Other advantages not covered in this document: less distortion in the image, and larger depth-of-field that is symmetric around the best focus spot. These features may be investigated eventually.

### Object-space telecentric system

In a system composed of a single lens, the aperture stop is at the rear focal point (Fig. 1). When the object is moved, the height of the image does not change.

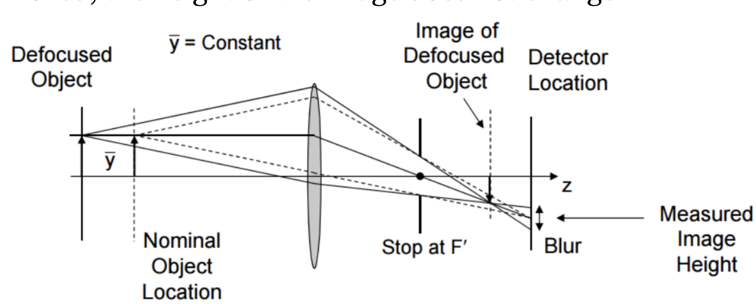


*Figure 1 - Object-space telecentric system.*

**Image-space telecentric system**
In a system composed of a single lens, the stop is placed at the front focal plane of the lens (Fig. 2).
Defocus of the image plane or the detector will not change the image height or magnification.

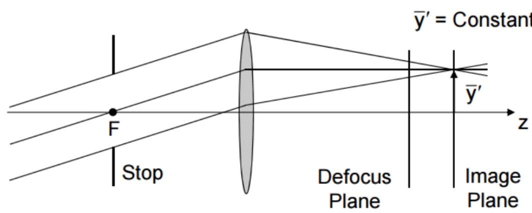



*Figure 2 - Image-space telecentric system.*

**Double telecentric system**
In a 4f system, the stop is placed at the common focal point of the two lenses (Fig. 3).
All double telecentric systems are afocal (they have an infinite effective focal length).

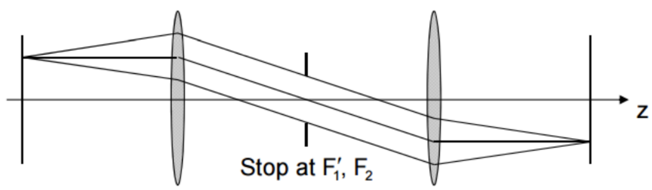



*Figure 3 - Double telecentric system.*

## The HiLo microscope

The acquisition part of the HiLo microscope can be represented by the system shown in Fig. 4 . The specifications of the lenses in the system are listed in Table 1. The tube lens and the objective form a 4f system, and the ETL (electrically tunable lens) is placed at the exact middle focal spot of the system. The sensor and image planes are conjugates. In that case, the system is double telecentric, and the aperture stop is the ETL.

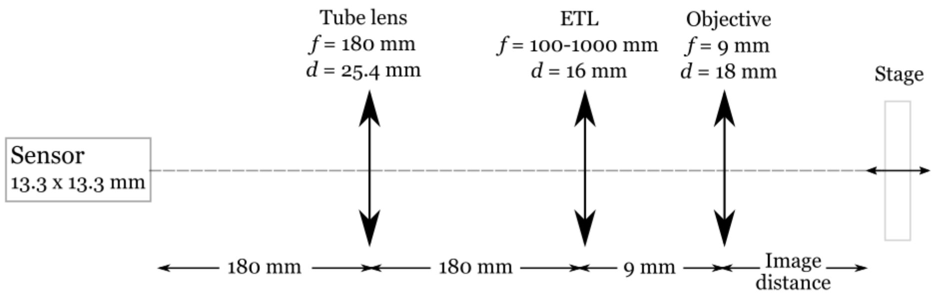



*Figure 4 - HiLo acquisition setup. The illumination part of the setup is not represented. The sensor and image plane are conjugates.*

In the lab, the placement of the ETL at the exact focal spot is impossible due to the housing dimensions of both the objective and the ETL. We are forced to move the ETL of approximately 10 mm in front of the focal spot. In that case, the system is not telecentric anymore.

| **Component** | **Name** | **Specification** |
|---|---|---|
| Sensor | ORCA-Flash4.0 V3 [1] | Effective area (horizontal x vertical): 13.312 mm x 13.312 mm. |
| Tube lens | Olympus UTL-U [2] | Focal length of 180 mm.<br>Diameter of 25.4 mm (1 in.). |
| ETL | EL-16-40-TC [3] | Focal lengths ranging approximately from 100 mm to 1000 mm for currents from 0 to 250 mA.<br>Diameter of 16 mm. |
| Objective | XLUMPlanFLN20X [4] | We can approximate this objective being a perfect lens with focal length of 9 mm.<br>Diameter of 18 mm. |

*Table 1 - Specifications of each component of the acquisition system of the HiLo microscope.*

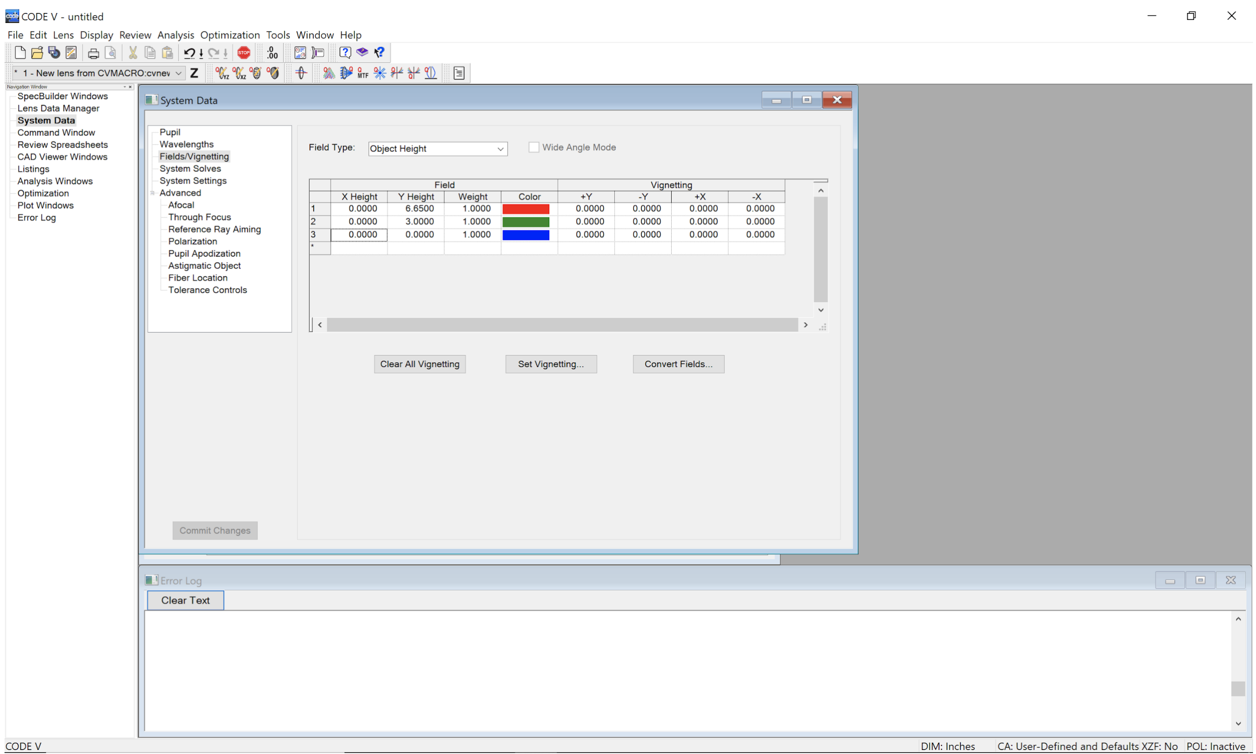
In this document, we will design the acquisition system using CODE V and look at the consequences of a non-telecentric system.

# HiLo microscope design with CODE V

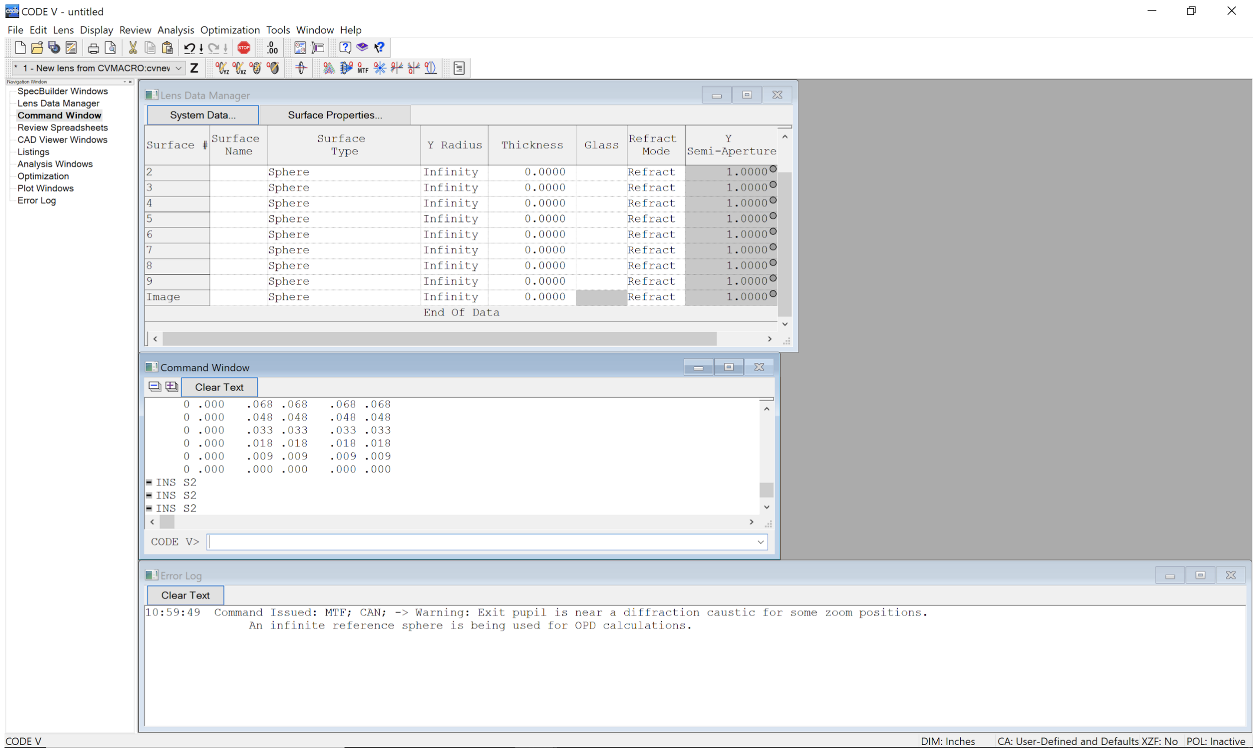
## Importing the system in CODE V (with GUI)

1. Open a new blank lens.

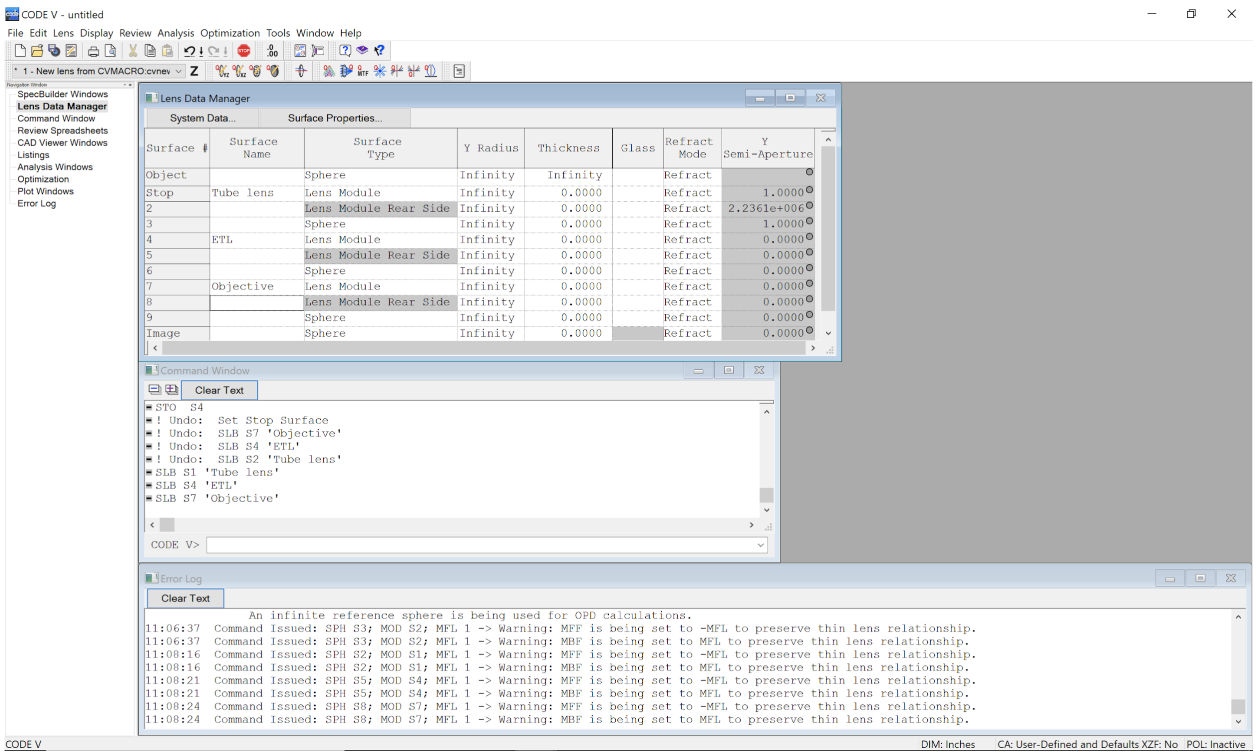
2. In System data... -> Fields/Vignetting, add 3 entries under the Field Type “Object height”. We will set three different chief rays in the system. The first one corresponds to the maximal sensor height with respect to the optical axis (in other words, half its width, which is 6,65 mm). The second ray is set arbitrarily to a middle distance (here we chose 3 mm), and the third ray lies on the optical axis.



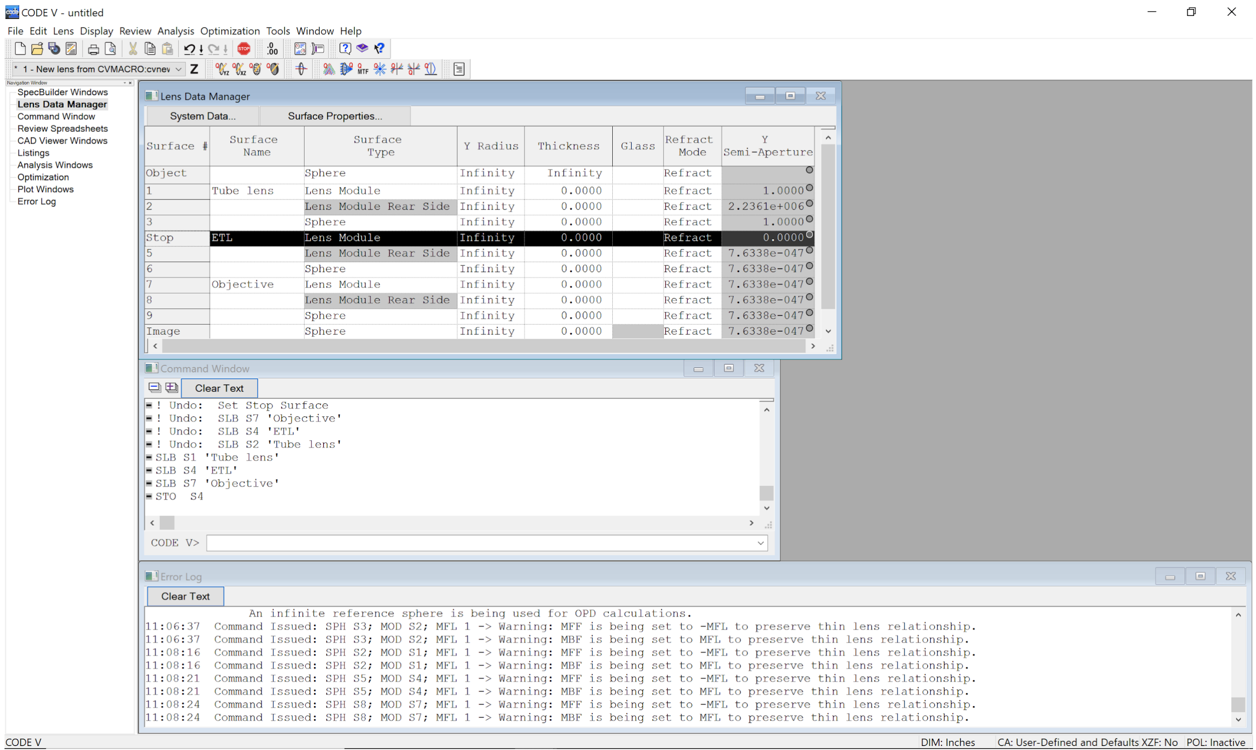
3. In the Lens Data Manager (LDM), right-click on “Image”. Choose “Insert”. Repeat this step until there are 9 surfaces inserted.



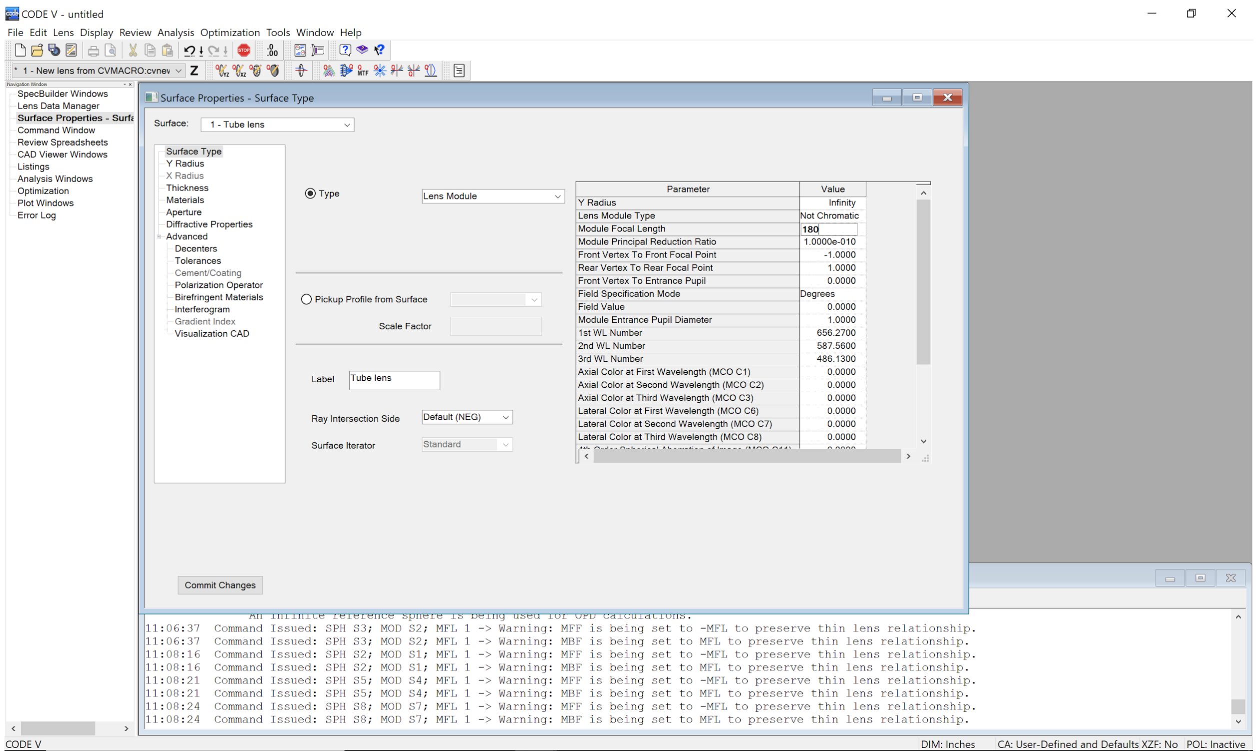
4. For surfaces 1, 4 and 7, click on “Sphere” under “Surface Type” and choose “Lens Module” in the list. The surfaces right after (surfaces 2, 5 and 8) should also change automatically for “Lens Module Rear Side”. For convenience, we will identify the lenses under “Surface Name” with “Tube lens”, “ETL” and “Objective”. In CODE V, the “Lens Module” is a perfect thin lense that is free of aberrations.



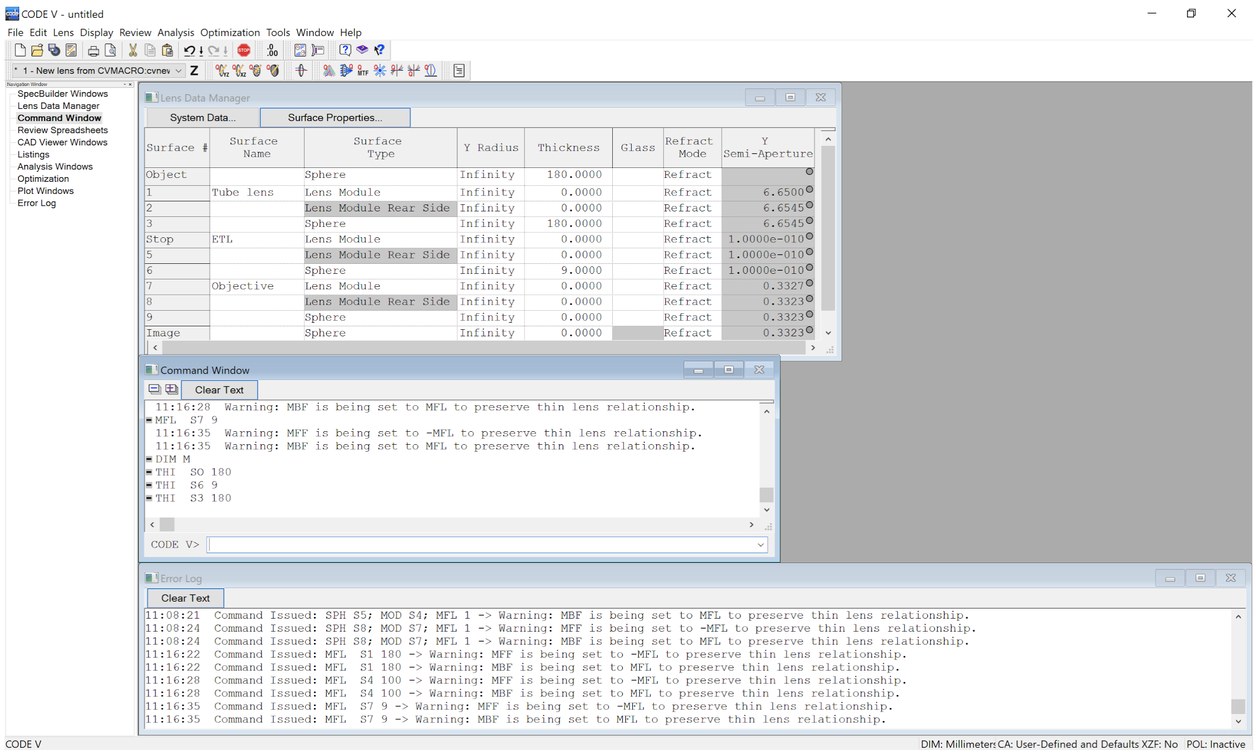
5. Set the stop surface on surface 4, which is the ETL. To do so, right-click on “4” under “Surface #”, and select “Set Stop Surface”.



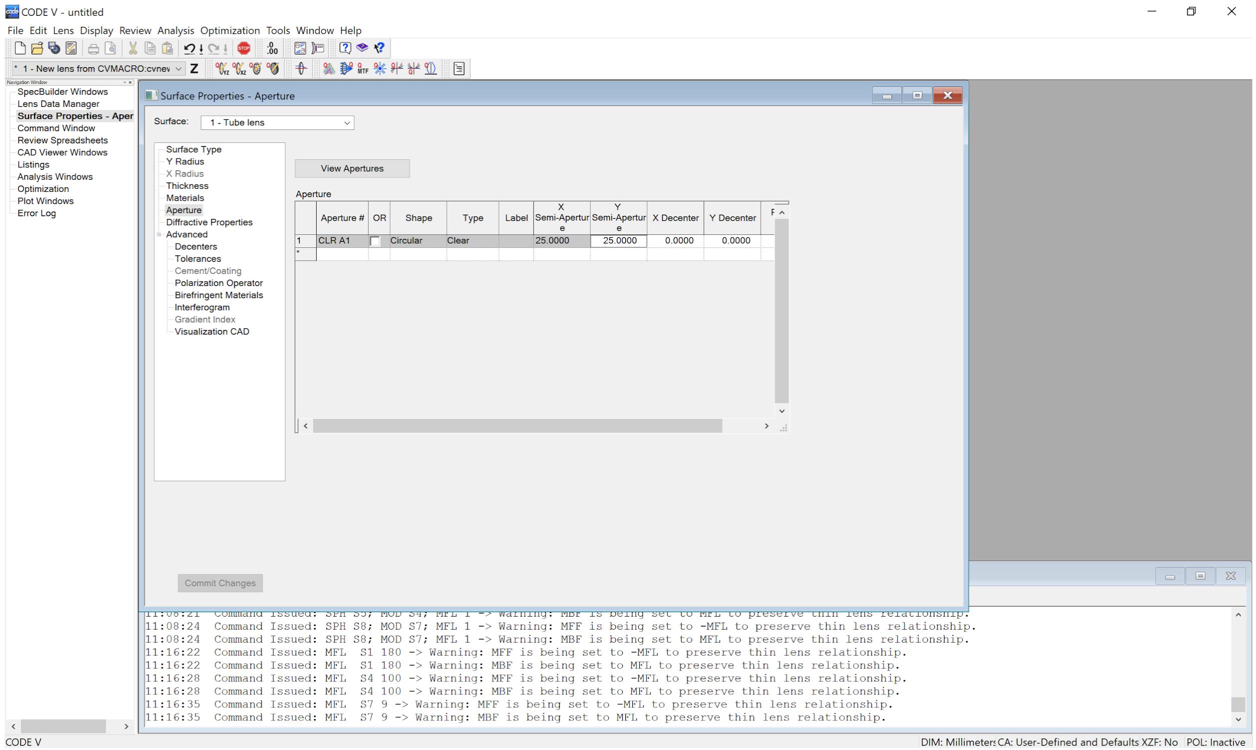
6. Add the focal lengths of the three lenses by clicking on the surface number, and then on “Surface Properties…”. On the right panel, change the “Module Focal Length” for the focal length of the lens. Set focal lengths of 180 mm for the tube lens, 100 mm for the ETL and 9 mm for the objective.
   Pro tips
   - After writing the value for the “Module Focal Length”, press enter. It will commit changes automatically. Otherwise, you will have to click on “Commit Changes” on the bottom left, which is longer.
   - You don’t have to click on the X when you are done, to go to the next lens and repeat the same steps. On the top left, you can select another surface and it will bring you directly to the next surface’s menu.



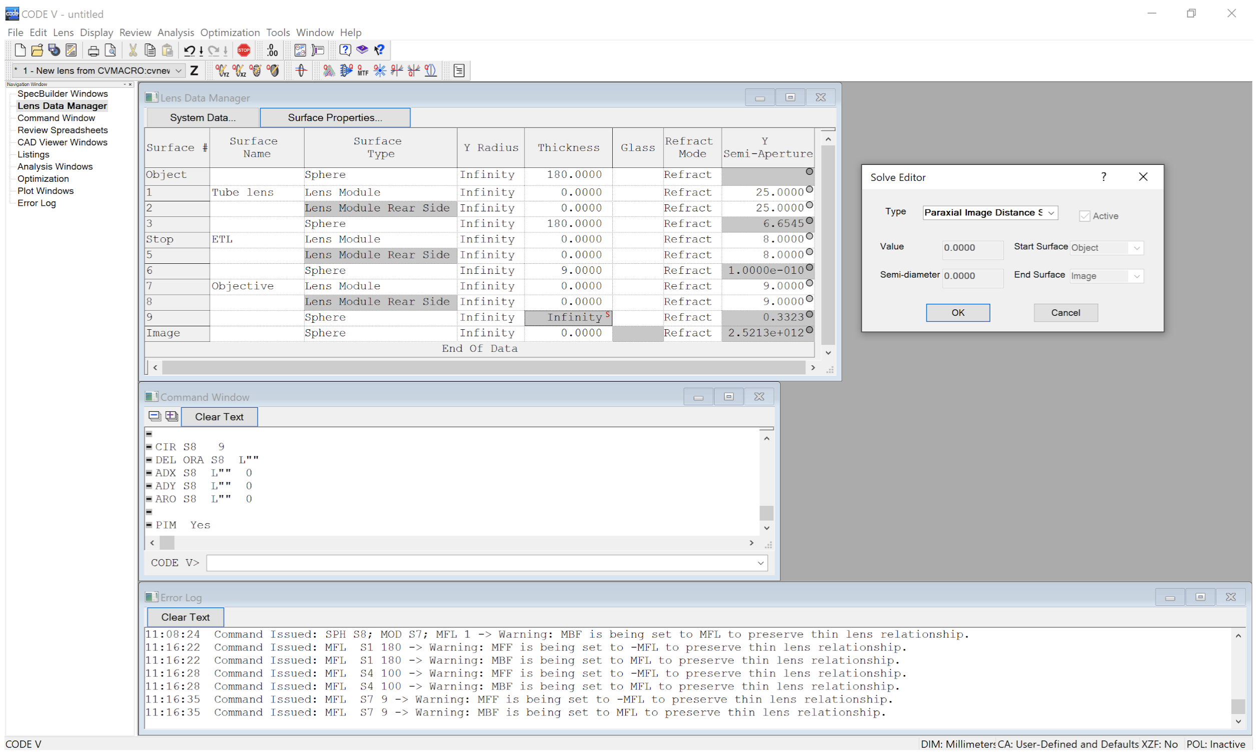
7. Set the right distances between the surfaces. Set the object thickness at 180 mm (corresponds to the sensor-tube lens distance). Set the thickness of Surface 3 with 180 mm and Surface 6 with 9 mm. In that way, the ETL is set to be at the exact focal planes of both the tube lens and the objective.
   Be careful with the units of CODE V. Notice on the previous image captures that on the bottom grey bar, we can read DIM: Inches. To change the dimensions from inches to millimeters, write in the command line "DIM M".



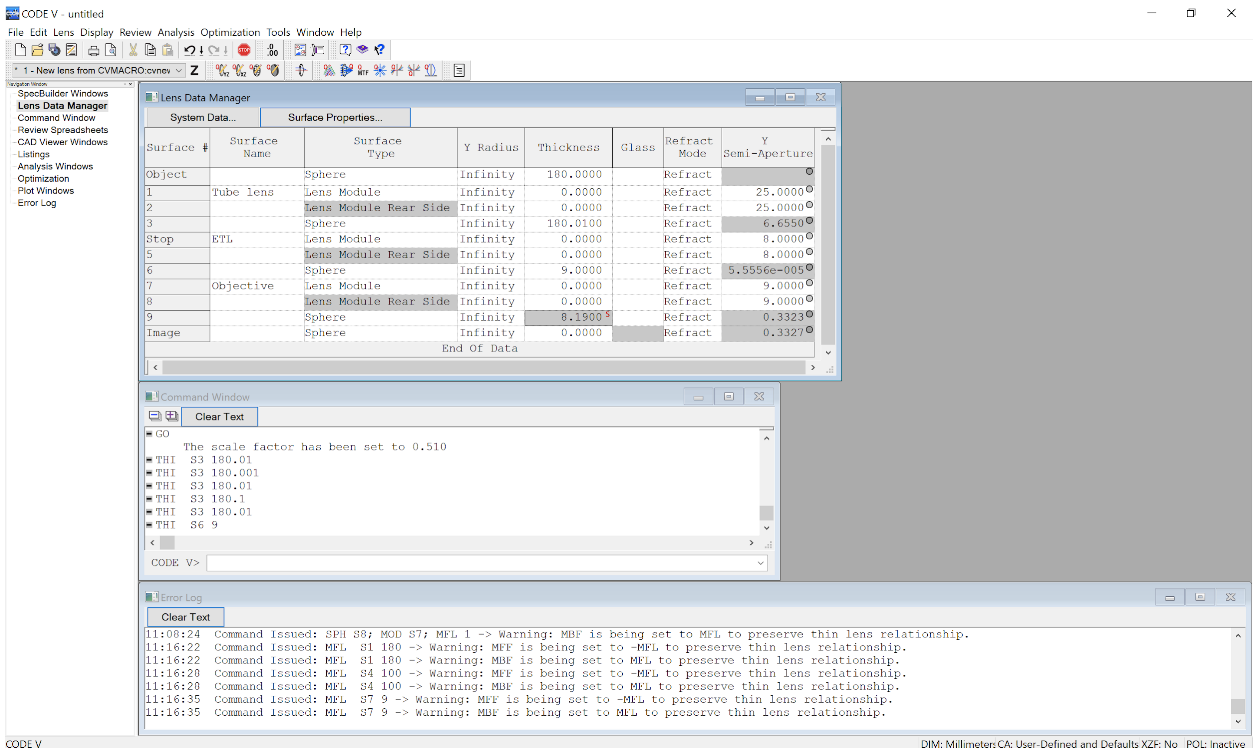
8. Set the right apertures of the surfaces. Click on the number under “Y Semi-Aperture” and then on “Surface Properties…”. On the table add a new line and change the “Y Semi-Aperture” for the right number. Set the semi aperture of the tube lens with 25 mm. For the ETL, choose 8 mm, and for the objective, 9 mm.



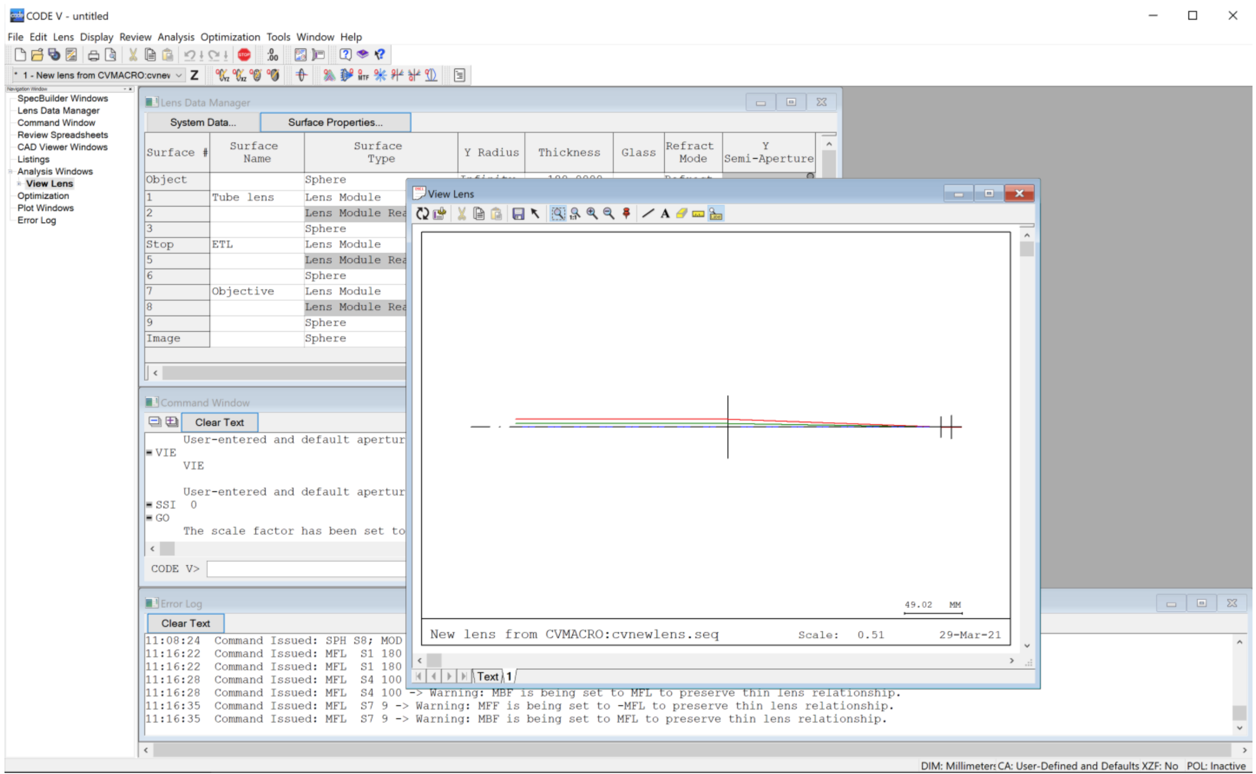
9. Solve for the paraxial image distance. Right click on the thickness of the surface 9, and choose “Solve…”. Set the type to “Paraxial Image Distance Solve”, and click OK. CODE V will automatically determine the distance from the last surface where the image is formed. Notice that the thickness has been calculated and is now “Infinity”. This behaviour is normal since we have a double telecentric system, which is afocal. However, this situation is not convenient for doing calculations.



10. In order to get an image distance value, we will change the thickness of Surface 3 with 180.01 mm. The image distance should change for 8.19 mm. Now that we have finite distances, we will be able to do the ray tracing and perform some calculations.



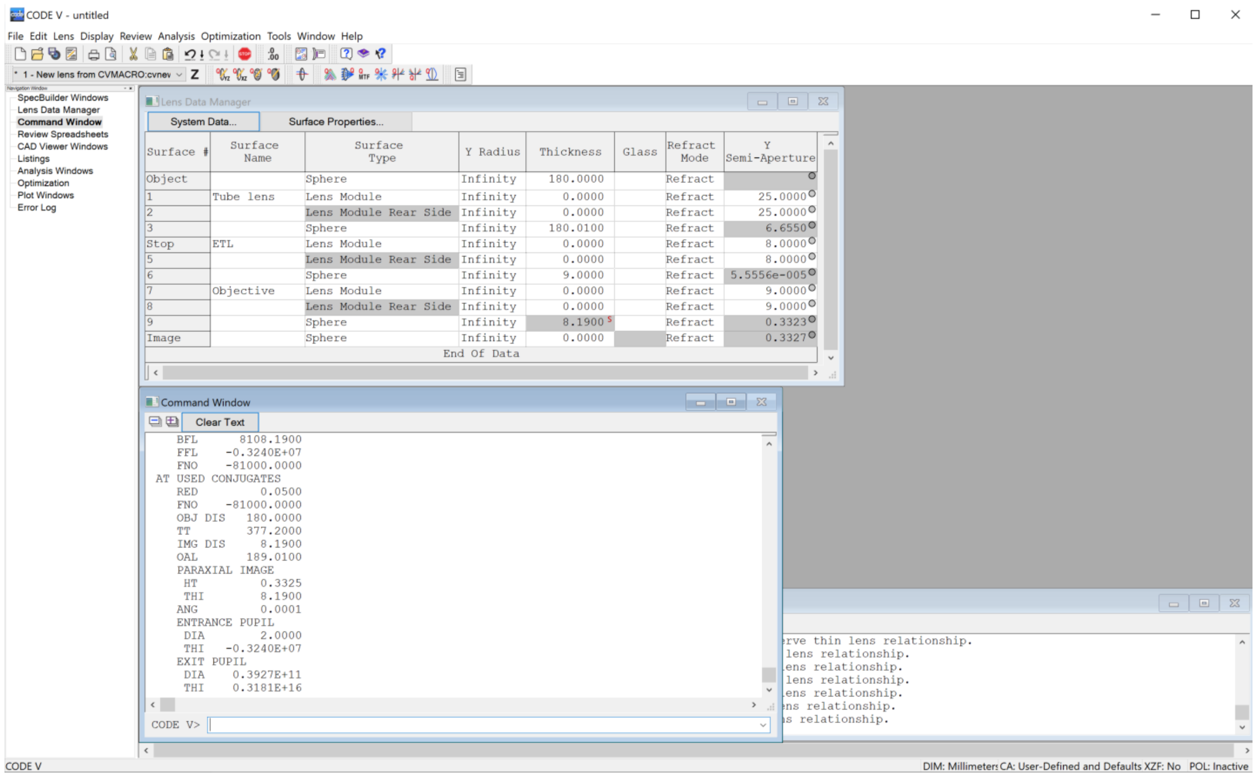
11. Now, let’s visualize the system with ray tracing. On the menu “Display”, select “View lens”, and click “OK”. The three chief rays with heights of 6.65 mm, 3 mm and 0 mm will appear with different colors. Notice that the three rays are perfectly parallel to the optical axis on the object space. In the object space, we found previously that the rays were parallel too (image at infinite distance). Since the chief rays are parallel in both object ans image spaces, we can confirm that the system is double telecentric.



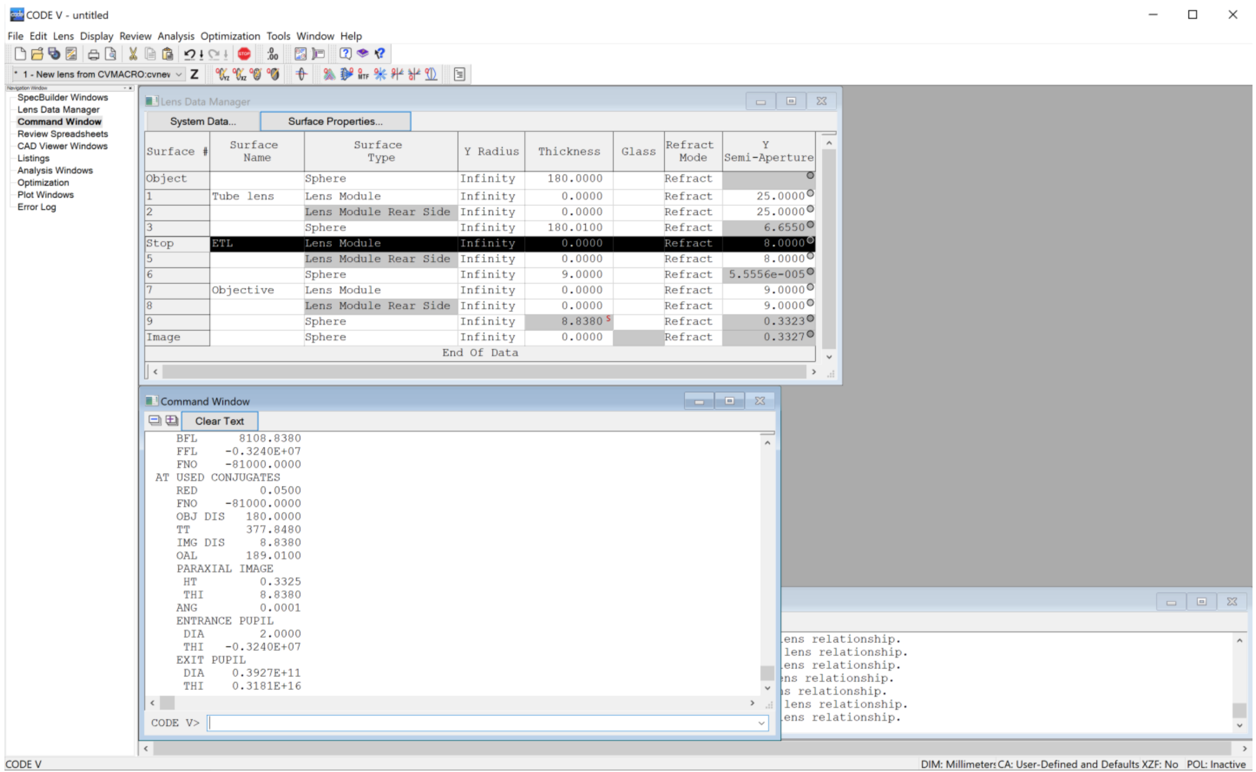
**Calculations with CODE V: double telecentric system**

1. In “System Data”, in the “Field/Vignetting” panel, remove the object heights of 3 mm and 0 mm. Keep the object height of 6.65 mm.

2. We will use the first order calculation (write “FIR” on the command line and press enter) to calculate the image distance and the FOV. For the telecentric system, the surface 3 must have a thickness of 180.01 in order to be able to make the calculations. For an ETL having a focal length of 100 mm, the FIR command indicates an image height (HT) of 0.3325 mm and an image distance (TH) of 8.19 mm. Note that the double of the image thickness gives us the vertical and horizontal FOV of the system. In the present case, the detector height is the same as its width.

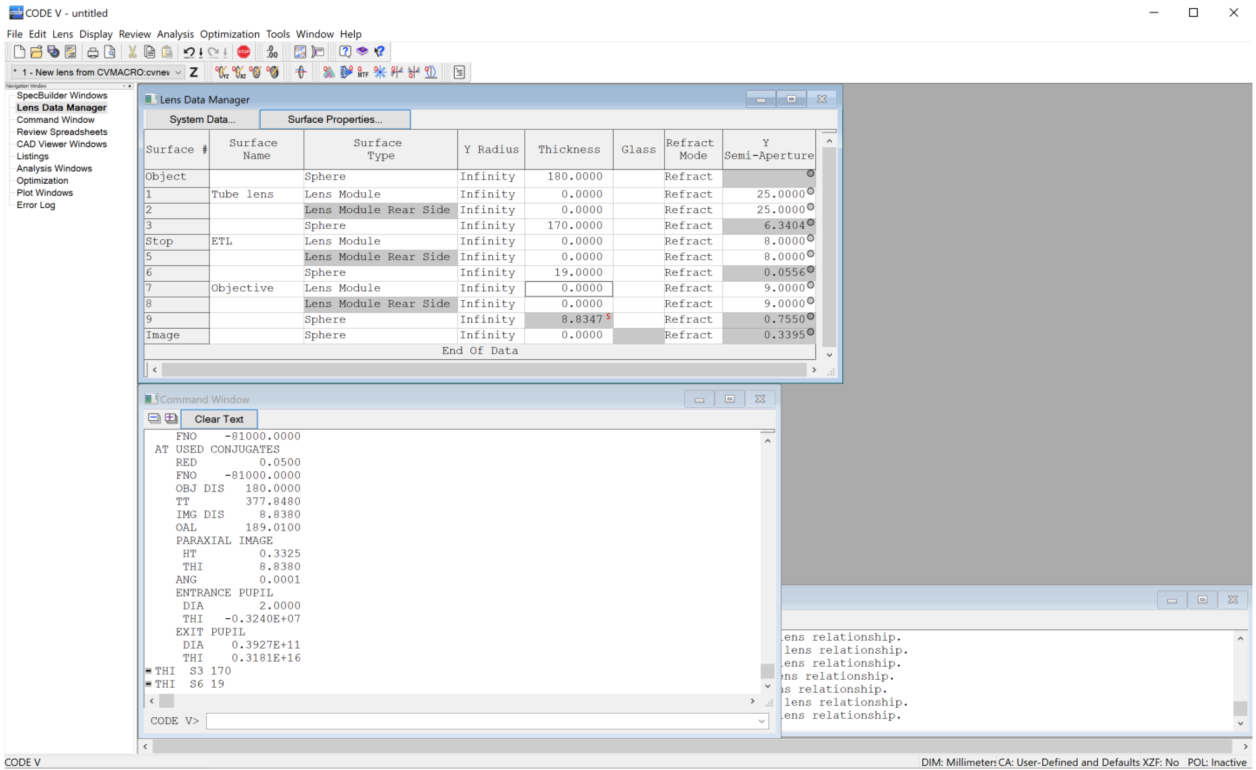


3. Change the ETL focal length to 500 mm. Calculate the first order parameters with FIR. The image height is still 0.3325, meaning that the FOV has not changed. This is normal since we have a telecentric system. However, the image distance has been raised to 8.838 mm. Notice that the image angle is 0.0001 rad, which is very small, almost zero. This means that the rays that are parallel to the optical axis on the image side (or almost parallel in this case, since we have set the thickness so Surface 3 to 180.01 mm).

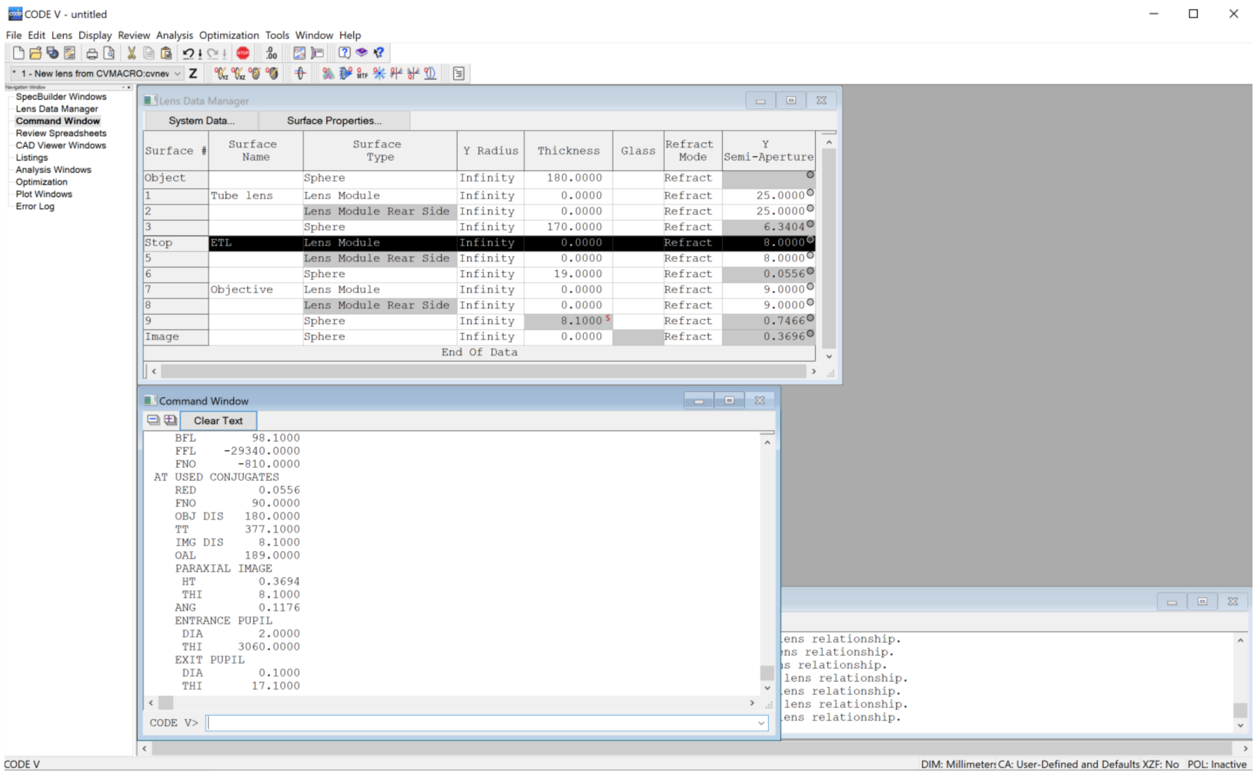


## Calculations with CODE V: non-telecentric system

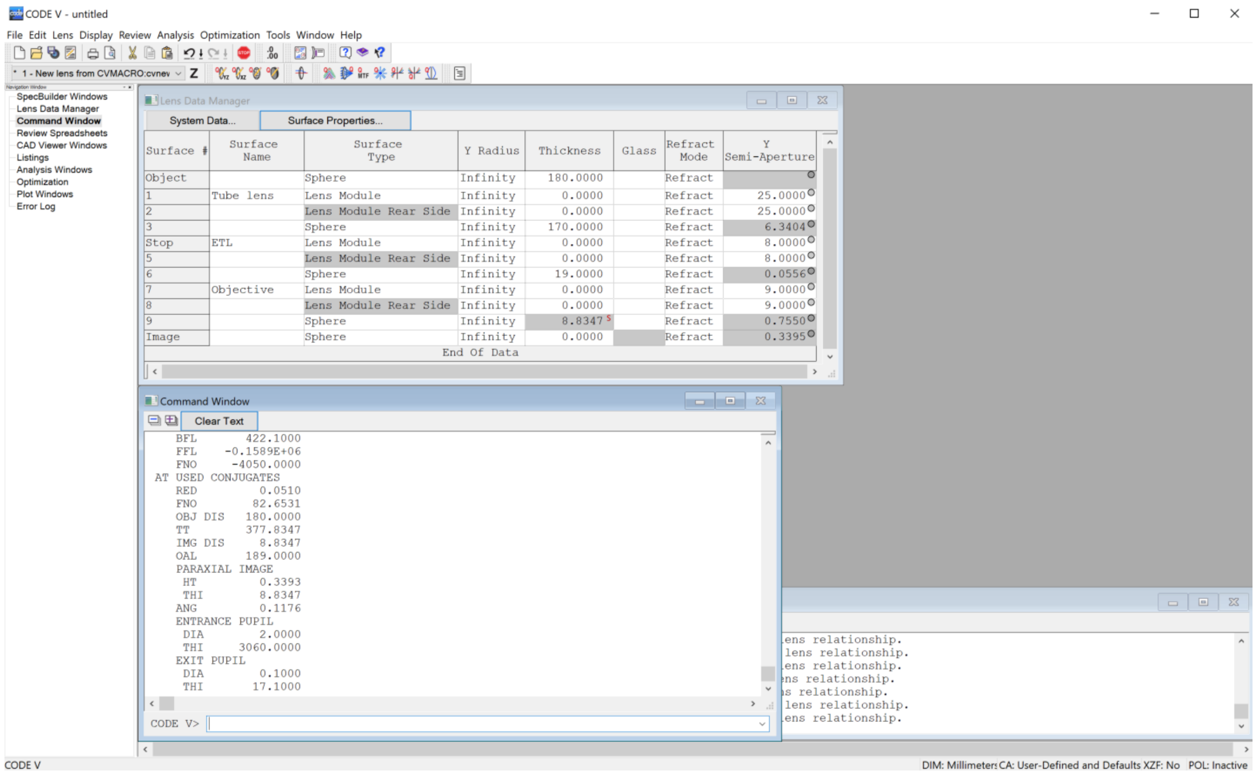
1. Change the thickness of Surface 3 to 170 mm, and the thickness of Surface 6 to 19 mm. In that way, there is still 189 mm between the tube lens and the objective, but the ETL is moved 10 mm in the direction of the tube lens.



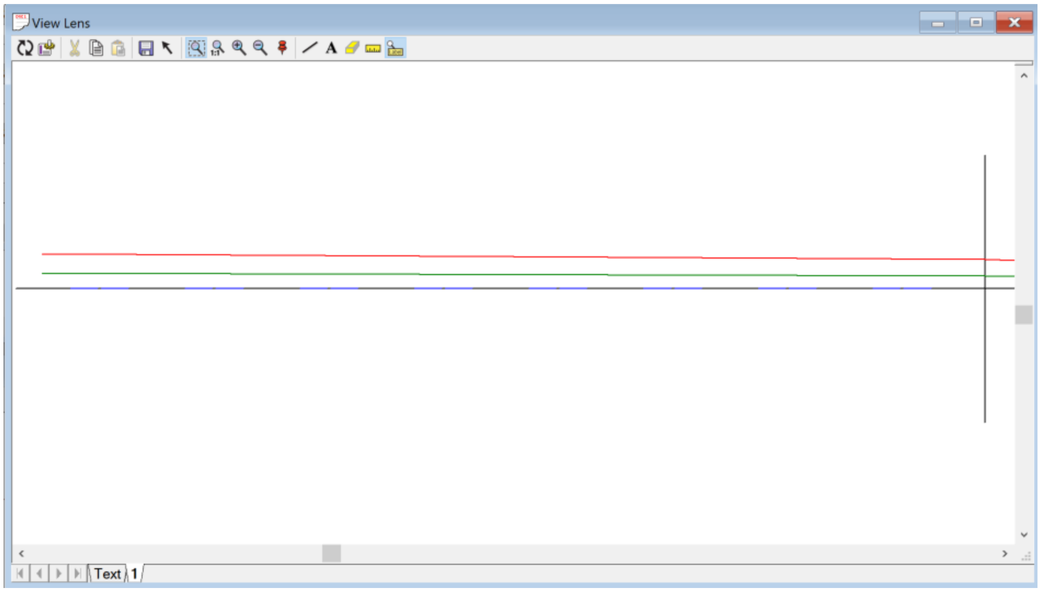
2. Set the focal length of the ETL back to 100 mm. Calculate the first-order parameters of the system with FIR. The image height is 0.3694 mm and the image distance is 8.1 mm. Notice that the ray angle (ANG) has raised to 0.1176 rad. This is a sign that the rays are not parallel to the optical axis anymore on the image side.



3. Change the focal length of the ETL to 500 mm. Calculate the first-order parameters of the system with FIR. We now have an image height of 0.3393 mm and an image distance of 8.8347 mm. The image height has changed from the previous ETL focal length. This is an indication of a non-telecentric setup.



4. Visualize the ray tracing with "Display" -> "View Lens". Notice that the chief rays in the object space are not parallel to the optical axis anymore. This is another indication that the system is not telecentric. The image below shows three rays in the object space, right before the tube lens.



5. Compute the FOV (two times the image height) for various focal lengths and displacements of the ETL. Calculations performed for the measured focal lengths of the ETL are shown in Figs. 5-6.

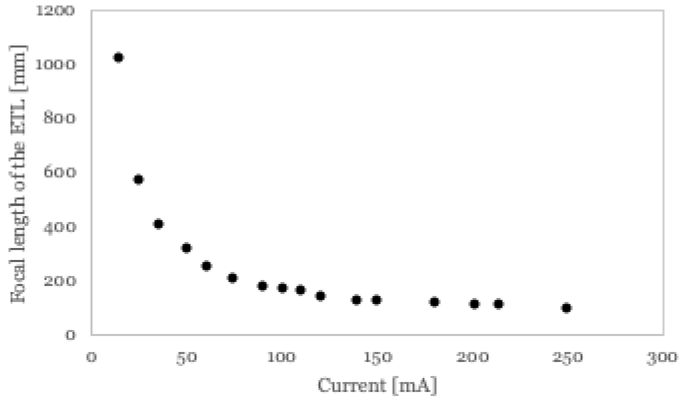



*Figure 5 - Focal length of the ETL for various currents.*

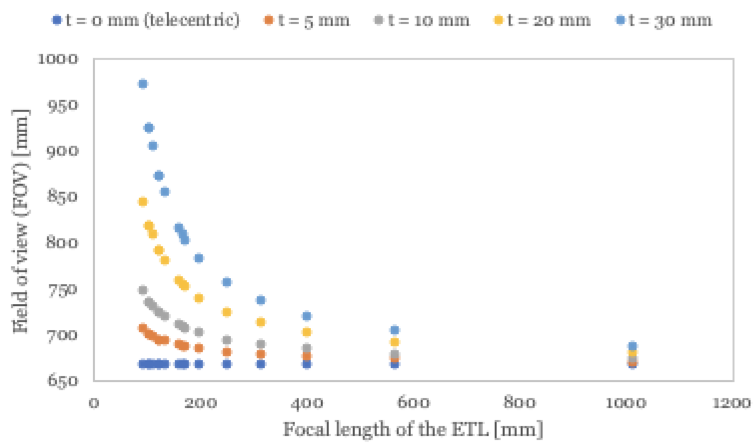



*Figure 6 - Field of view of the acquisition system of the HiLo designed on CODE V for various focal lengths of the ETL. The values of "t" correspond to the distances between the ETL and the central focal spot to the 4f system. The distance t=0 mm corresponds to the situation where the ETL lies perfectly on the central focal spot of the 4f system.*

## In a nutshell

When the ETL is placed at the central focal spot of the 4f system (composed of the tube lens and the objective):

- The system is double telecentric.
- There is no angular magnification and no change in the FOV when the focal length of the ETL changes.
- The NA of the system remains constant with ETL focal length change
- The chief ray is parallel to the optical axis in both object and image spaces.

When the ETL is misplaced (for example, before the central focal spot)

- The system is not telecentric anymore.
- The FOV of the system changes.
- Since the optical invariant must remain the same, the NA raises when the FOV diminishes.
- There is an angular magnification when the ETL focal length changes.
- The chief ray is not parallel to the optical axis in both object and image spaces.

## References


[1] Hamamatsu, *ORCA-Flash4.0 V3 Digital CMOS Camera C13440-20CU,* https://www.hamamatsu.com/resources/pdf/sys/SCAS0134E_C13440-20CU_tec.pdf.

[2] Edmund Optics, *Olympus Single Port Tube Lens, 180mm Focal Length,* https://www.edmundoptics.com/p/olympus-single-port-tube-lens-180mm-focal-length/29244/.

[3] Optotune, *Electrically tunable large aperture lens EL-16-40-TC (5D)*, https://static1.squarespace.com/static/5d9dde8d550f0a5f20b60b6a/t/5f7c853794b4351f0e4ddc5d/1601996095275/Optotune+EL-16-40-TC.pdf.

[4] Olympus, *Objective Finder*, https://www.olympus-lifescience.com/en/objective-finder/.