Design of a Shack Hartmann Sensor, Vrns 2

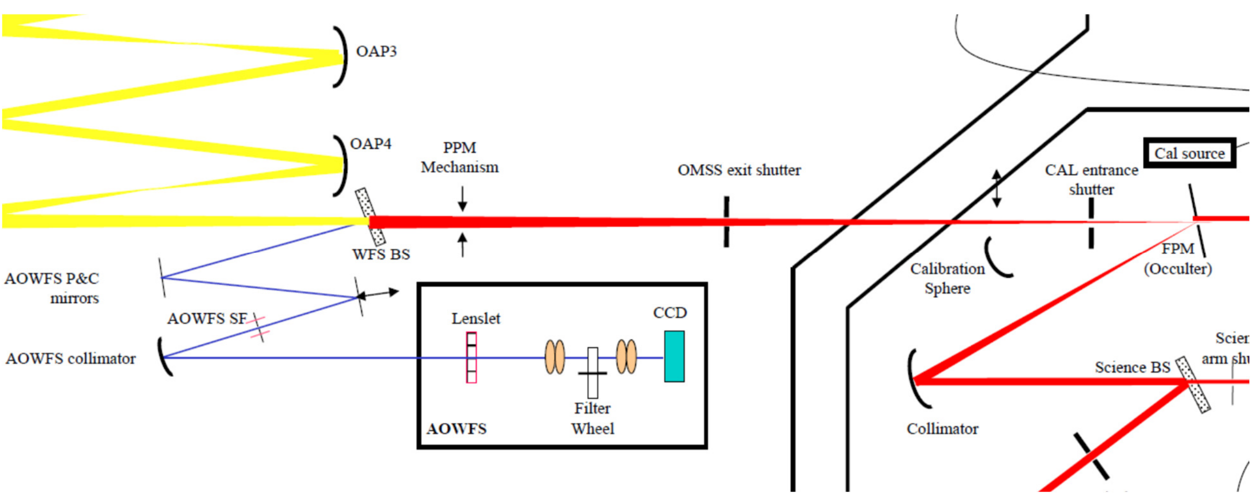
Introduction:

In Astronomy Notebook Section XVIII, pg 191, dated January 17, 2014 with conclusion on pg 217 we found surprisingly that the usual centroid or C-tilt was the least effective of several algorithms for reducing tip/tilt jitter, with peak detection being the best. Then we designed a Shack Hartman sensor, built a Reconstruction matrix, and took videos of the Hartmann spots from which wavefront OPD was reconstructed. Then in Astronomy Notebook Section VII, pg 93, dated March 23, 2015 with conclusion on pg 115 we simulated the tip/tilt servo using the reconstructed wavefront from the movies and found that servoing off of Z-tilt gave the best jitter mitigating result.

Relevant Literature

Relevant to this study is the dissertation by John Paul Siegenthaler, GUIDELINES FOR ADAPTIVE-OPTIC CORRECTION BASED ON APERTURE FILTRATION , December 2008 which describes the differences between G-tilt and Z-tilt, as well as the quad cell and PSD (Position Sensing Device) detectors and their abilities for providing an on-target beam. Excerpts form Siegenthaler's thesis will be another entry in this Astronomy Notebook.

The paper by Thomas, et., al., "Wavefront Sensing and Correcting With the Gemini Planet Imager", SPIE Proc, Vol 847, 2012 is also very relevant. In this paper he describes the purpose of relay lenses and a spatial filter within the S-H sensor of the Gemini South observatory. Its optical layout is,



Section 3.2 that describes the S-H sensor is particularly interesting.

In order to reach high adaptive optics performance, i.e. high Strehl ratio, we are using a spatial filter at the focus before the WFS unit, in the path non common with the science path. The spatial filter prevents cross talk and aliasing. The wavefront sensor itself is composed of a lenslet array of pitch 63 microns, a set of two doublets that relays the dots to the detector with a magnification equal to one. The detector is a CCID66 detector, with a readout noise around 3 to 4 electrons at 1KHz. Details on the internal alignment of the WFS can be found in a previous paper.[7]

Then the paper describes how the spatial filter is really an iris that is wide open upon servo start-up, then stops down to 1.87 mm or 2.2 mm, depending upon the sensor's wavelength band. The paper also dscribes the difficulty of aligning the spatial filter to the lenlet array and to the focal plane. The Gemini subaperture size is 18 cm (N=44 subapertures across 8 meter dia primary mirror), McIntosh, "The Gemini Planet Imager", SPIE Proc 6272, 27 June 2006.

On page 58 of the **Conceptual Design Review Documents MCAO for Gemini South**, Gemini Obxervatory May 30-31, 2000 we find the conceptual optical diagram for the five laser guide stars. Note that the LGS return is to a lenslet array for wavefront sensing.

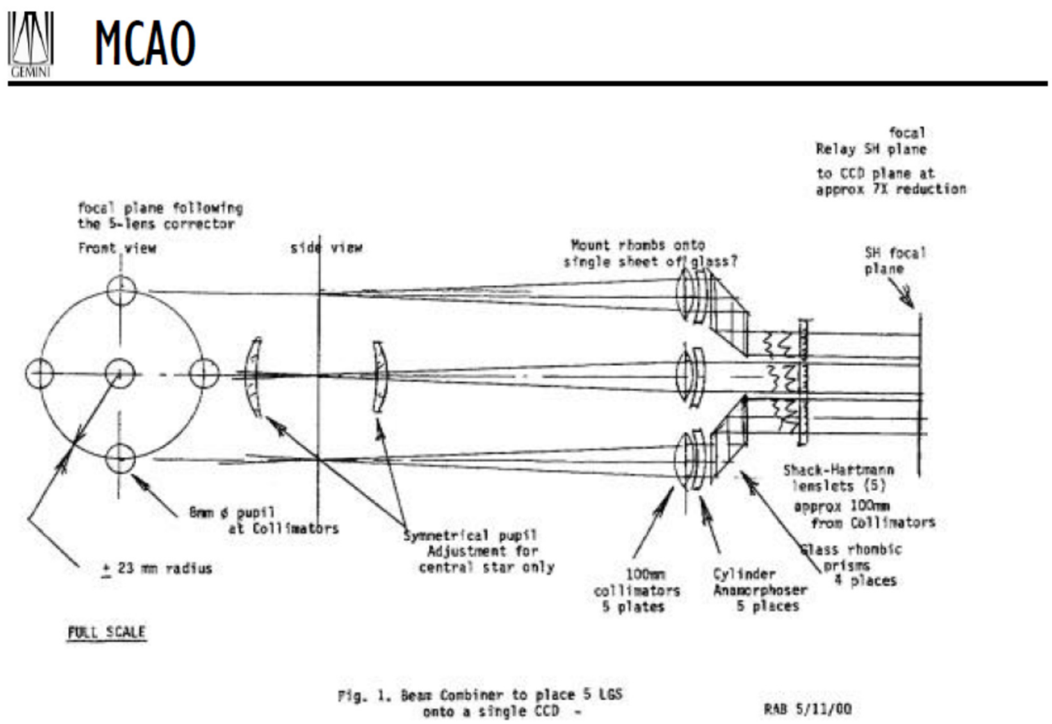


Figure 22: *Concept for combining all 5 LGS beams on a single lenslet array*

"The actual wave front sensors for the five LGS will be implemented using either 1 or 5 lenslet arrays and associated CCD arrays. The packaging with 5 lenslet arrays should be straightforward with an optical path of about 90 mm between the intermediate focal surface and the collimators. Figure 22 illustrates how the pupils from all five guide stars could be combined on a single sensor. Four rhomboidal prisms are used to reposition the separate collimator axes very close together. The rhombs could in principal have semicircular output apertures that

actually allow the five beams to touch, but we have assumed a separation of one millimeter between all 8mm beams. This additional spacing is consistent with placing all 5 sets of Hartmann spots on a single CCD array of 128^2 pixels. Transmission by the rhombs is 100% except for two air-glass reflections, and internal absorption is insignificant in Schott BK7 glass. Because the central beam has a shorter path to the SH lenslets, it may be necessary to add a field lens to ensure that the exit pupil of the telescope falls at the same longitudinal distance as the other four paths. This can be done with a singlet if the focal length of the collimator is appropriately adjusted."

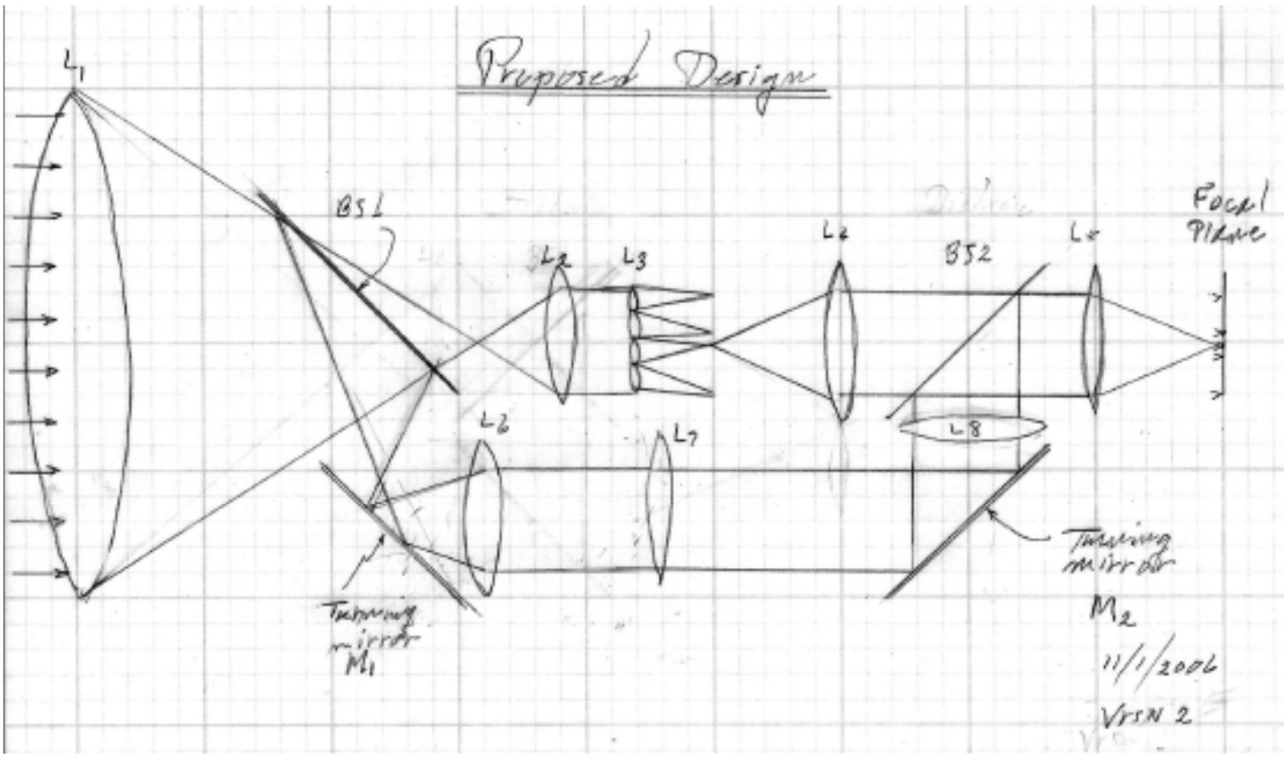
Motivation

The motivation for a new S-H sensor verson 2 is to study different sensing methods, as per Siegenthaler's above thesis, and to see how well the telescope blur spot is corrected before investing time and money to build a tip/tilt servo system.

Inevitably such a tip/tilt servo will be imperfect and it is valuable to understand these errors before building the servo. In the \ShackHartmann\papers folder see Rigaut_AnalyticalModelForShackHartmannBasedAdaptiveOpticsSystem_1038_1.pdf for a discussion of errors. As seen from Siegenthaler's Ph.D. dissertation there are subtleties in sensing methods that need to be explored and exploited. In debugging different sensing methods it will be valuable to know the wavefront that produces the blur spot.

To that end, this S-H sensor version 2 provides not only the S-H spots for wavefront analysis, but also the telescope's blur spot. The intent is to correlate the two, since the blur spot is the Fourier transform of the wavefront reconstructed from the Hartmann spots.

The original version 1 of the S-H sensor design that is detailed in Astronomy Notebook pg 1, April 26, 2014, with diffraction effects given on pg 10, April 27, 2014, is modified by adding two beam splitters that bypass the S-H lenslet array and send its light directly to the focal plane. In this way only one focal plane senses both the Hartmann spots and the telescope blur spot and avoids the synchronization and data rate problems of what otherwise would be two focal planes. The proposed design is diagramed below. Note that the drawing date should be November 1, 2016, and not 2006.

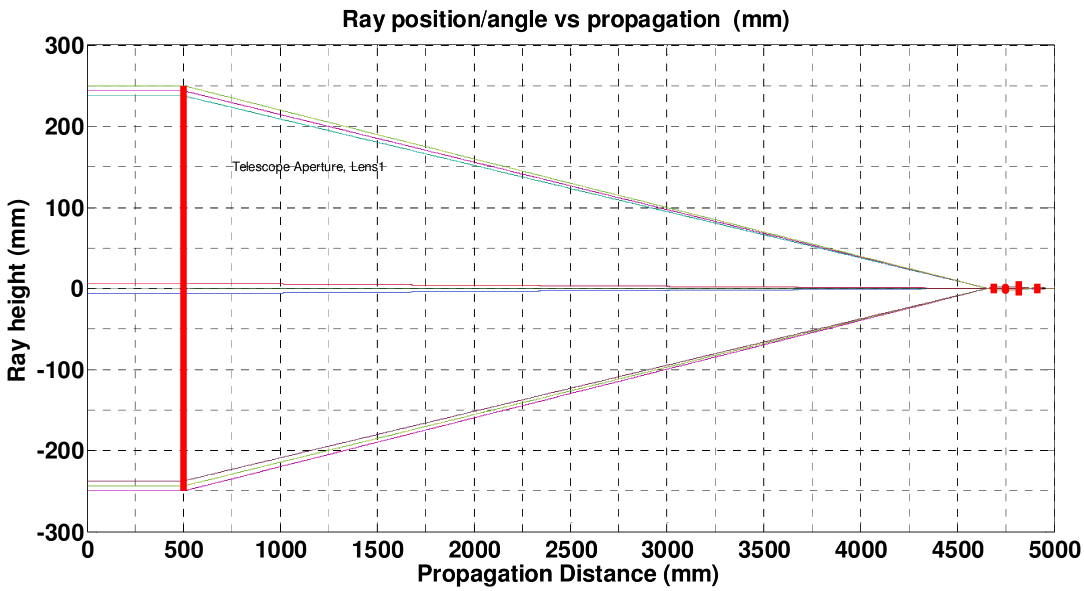


In this design the beam splitter is before lens Lens2, with Lens6 duplicating Lens2's exit pupil wavefront that relays to L3. The problem with this configuration, however, is that rays incident to beam splitter BS1 are converging and therefore are not perfectly orthogonal to the beam splitter, whose dielectric film design assumes orthogonality. A test of subassembly BS1 and L6 with an eyepiece in the telescope showed star images to be somewhat distorted. So BS1 is moved and instead inserted in the collimated path between lens Lens2 and Lens3, removing the need for lens L6 and renaming Lens7 and Lens8 as Lens6 and Lens7, respectively.

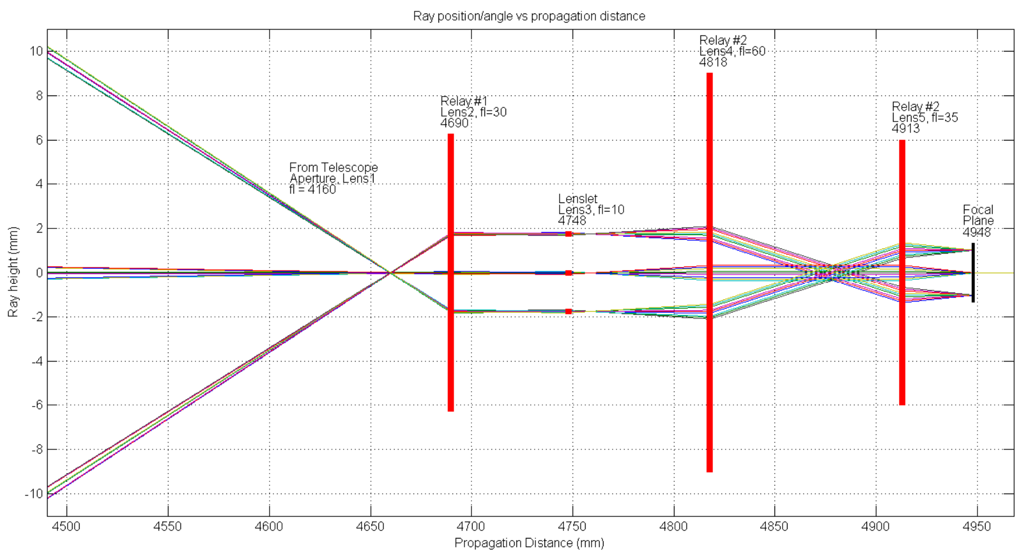
2. Shack Hartmann Sensor Vrsn 2

In this study a Shack Hartmann Vrsn2 superimposes the telescope's blur spot in the middle of the array of Hartmann spots. Matrix ray trace diagrams of the two optical paths are shown below. Common optics of the two paths are the telescope's primary/secondary mirrors, reimaging Lens2, and projection Lens 5.

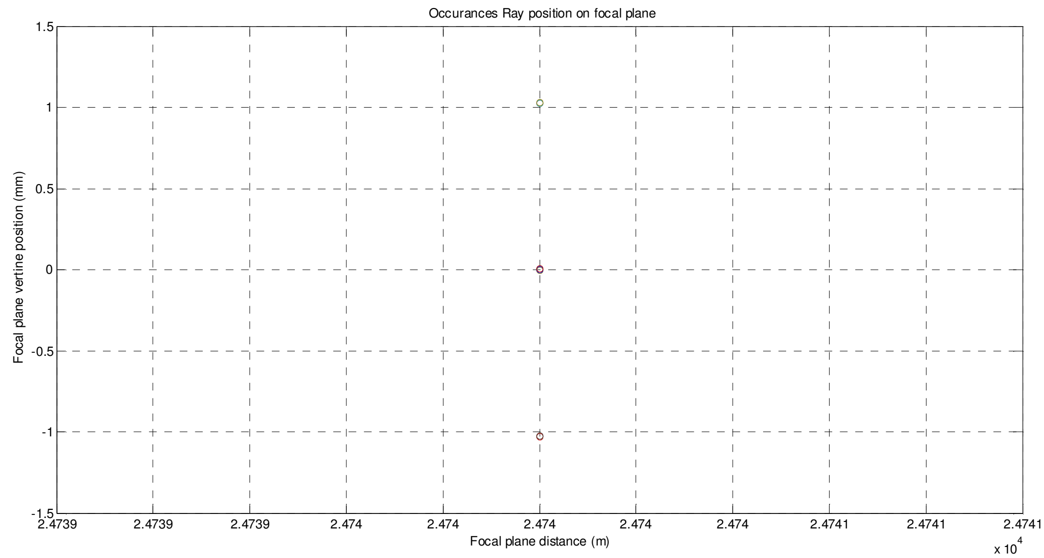
The first relay pair uses the telescope's primary/secondary mirrors along with Lens2 to relay the telescope's entrance pupil to the lenslet array. A second relay pair consisting of lens L4, and L5 relays and rescales the lenslet array's blur spots to fit on the smaller focal plane. These two relay systems form the first optical path. The complete first path ray trace is shown by Figure4



The detail close to the focal plane is given by Figure 5.



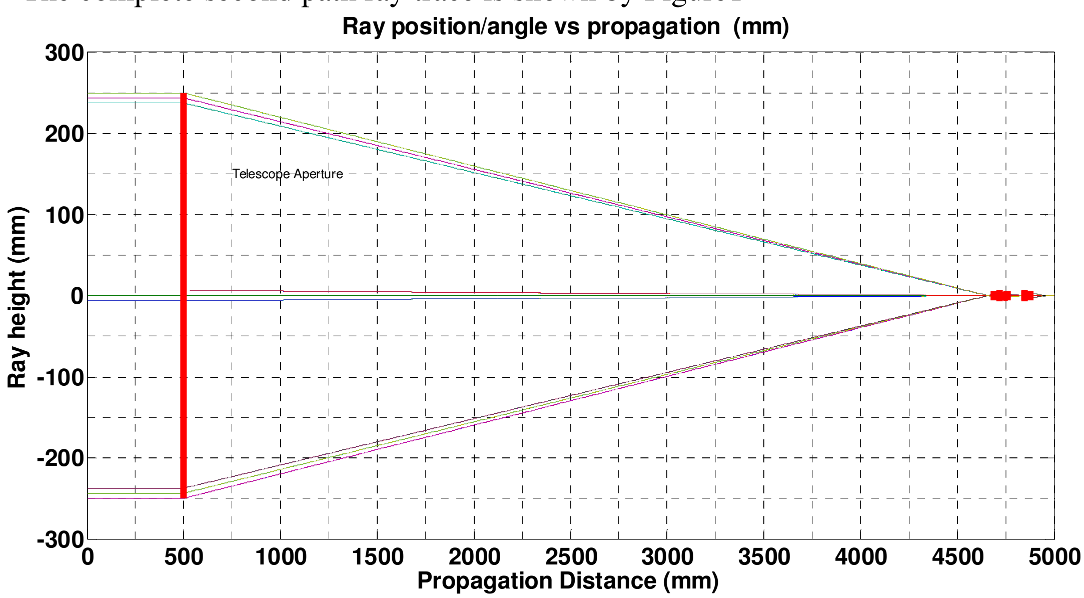
The focal plane spots are given below by Figure 6. Figure 6 shows all of the rays to be at one of three locations corresponding to input slopes of -5, 0, and +5 micro radians at the entrance pupil as inputted by the for k=[-1:1:1] loop beginning at line 571 and ending at line 640.



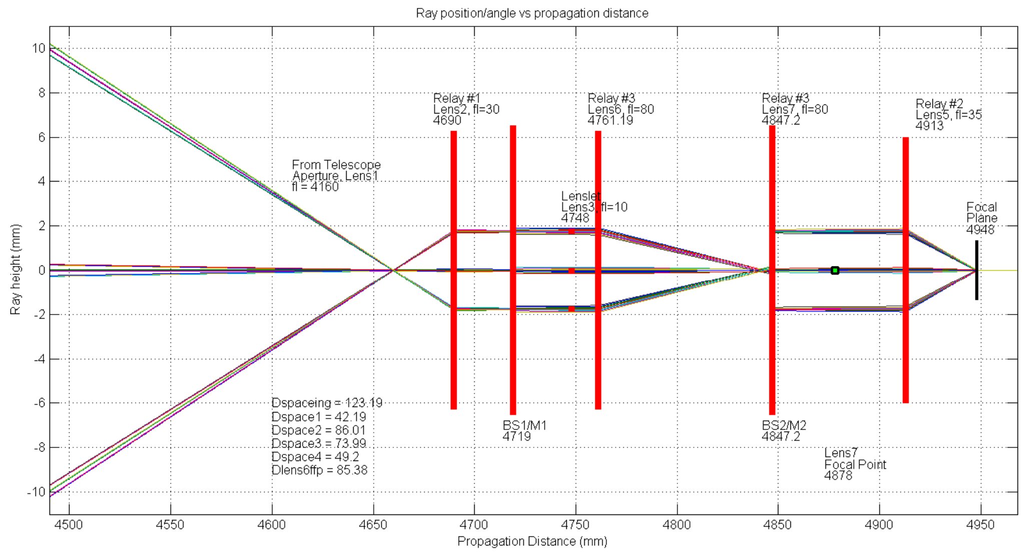
This completes the ray trace for the first optical path. Note that the tip/tilt gain from Figure 6 is $\frac{1.02\ mm}{5\ mico\ radians} = 0.2040\ \frac{mm}{micro\ radian} = 204\frac{microns}{micro\ radian}$.

The second optical path bypasses the lenslet array of the first optical path with a beamsplitter at 4719 mm distance along the optical path. After bypassing the lenslet array the two optical paths are merged with a second beamsplitter inserted at 4847 mm distance along the optical path. This second path uses a third relay pair consisting of L6,and L7 to relay the optical wavefront seen at lenslet array L3's front focal point to the front focal point of L5, thereby rejoining the first optical beam path's Hartman spots.

The complete second path ray trace is shown by Figure1



The detail close to the focal plane is given by Figure 2.



Note the apparent ray trace discontinuity at BS2 position 4847.2 mm. The discontinuity occurs because the ray trace from M2 to BS2 cannot be shown, since its propagation is perpendicular to the main optical beam path that propagates from left to right. Similarly, there would be a discontinuity from BS1 to M1, except that this is collimated space. Relay #3 relays the collimated space seen by Len3 to the front focal point of Lens5.

The focal plane spots are given by Figure 3.

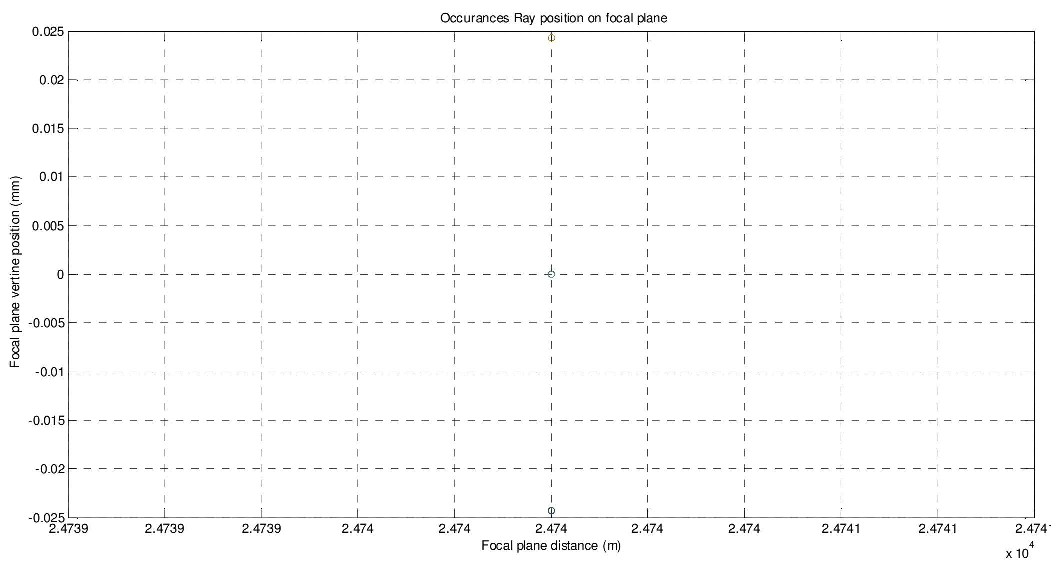
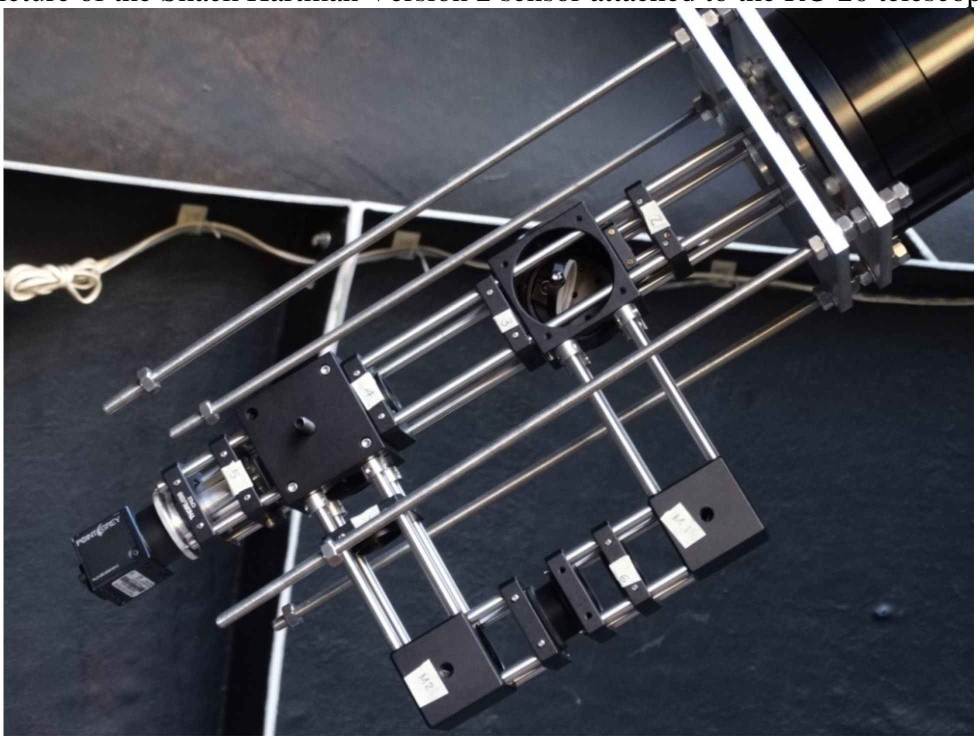


Figure 3 (as does Figure 6 for the first path) shows all of the rays to be at one of three locations corresponding to input slopes of -5, 0, and +5 micro radians at the entrance pupil as inputted by the for k=[-1:1:1] loop beginning at line 263 and ending at line 339. Tip/tilt gain is

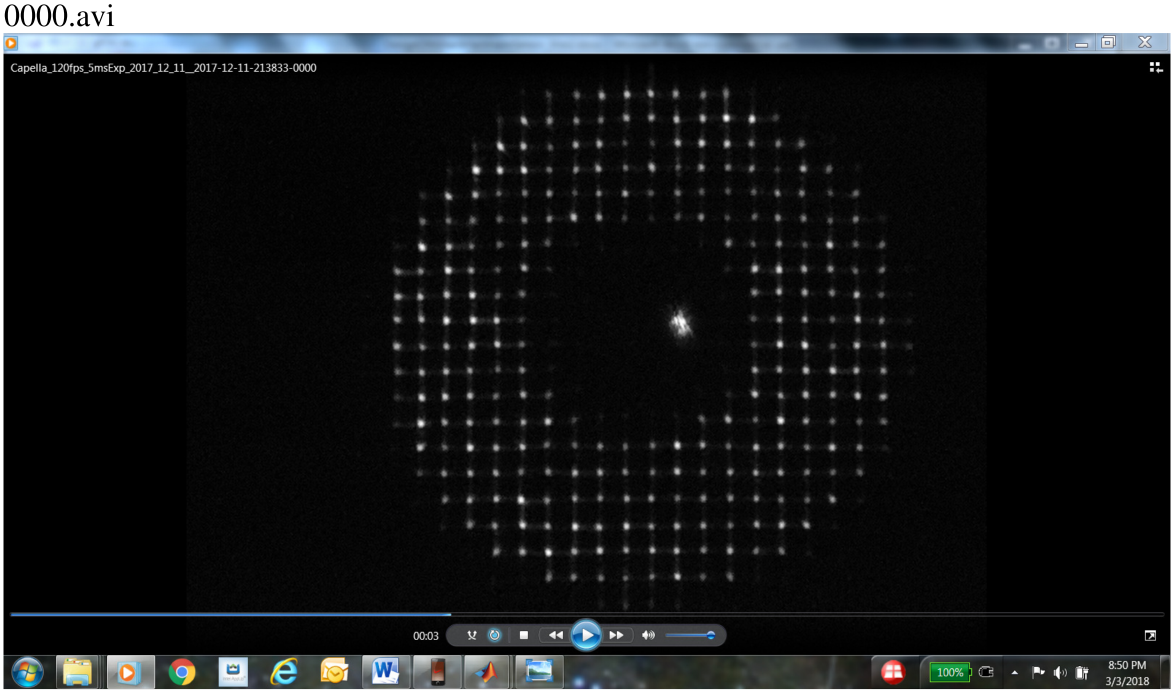
$$\frac{0.02427\ mm}{5\ micro\ radians} = 4.85 \times 10^{-3} \frac{mm}{micro\ radian} = 4.85\ \frac{microns}{micro\ radian}.$$

Results

This is a picture of the Shack Hartman Version 2 sensor attached to the RC-20 telescope.



This is a frame of the movie, Capella_120fps_5msExp_2017_12_11__2017-12-11-213833-0000.avi



It is seen that the central blur spot is located in the center of the S-H spot array as designed. Alignment was not too difficult, although in debug I had to order for BS2 the wider BSW26R 25mm x 36 mm 50:50 UVFS Plate Beamsplitter along with its FFM1 30 mm Cage

Cube rectangular filter mount to accommodate the incidence positioning of path 2's beam upon BS2. Note the presence of scintillation at 120 fps. The exposure time is 5 msec, which is chosen to avoid subaperture pixel saturation.

Conclusion

Shack Hartmann version 2 sensor has been designed and is operating. Bypass Path 2 has a more limited FOV than does Path1 because its optical path length is longer. A minor redesign would be to shorten the distance of Path 2 by reducing the distance between BS1 and M1 and between BS2 and M2, thereby pushing Lens6 closer to M1.

It was not quite possible to further shorten the distance between BS1 and M1 and between BS2 and M2 by pushing Lens6 past M1 because then the required optical distance between BS1 and M1 and between BS2 and M2 would be too small to be physically realized, considering the dimensions of the beam splitters and corner mirrors. To avoid this conflict one would also have to use achromats with slightly smaller focal lengths.

The tip/tilt gain of path 1 (through the lenslet array) is $204 \frac{microns}{micro\ radian}$. The tip/tilt of the second (bypass) path is $4.85 \frac{microns}{micro\ radian}$. Note that the second path gain is very close to that of the focal length of the telescope at 4.16 meters, or $4.16 \frac{microns}{micro\ radians}$ because of relay 3 optics.