Specifications, Procurement and Testing of the TMT-NFIRAOS Double-Pyramid Prisms

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ABSTRACT

NFIRAOS, the adaptive optics system of TMT, uses a pyramid wavefront sensor in addition to the 6 LGS WFSs. This pyramid WFS, referred to as Visible NGS WFS (VNW) reach its final design and is now ready for fabrication. One of the high-risk items is the custom achromatic double-pyramid prisms that are very challenging to manufacture. Fortunately, for NFIRAOS we were able to relax the angular tolerance of the pyramid to 2 arcmin. First, this paper lists the main optical specifications and tolerances of the double-pyramid. Then, we present the fabrication process developed by BMV Optical Technologies, our supplier, who successfully produced four double-pyramids. Finally, we describe the sequence of tests we performed at NRC during the incoming inspections; including a new optical test we developed to quickly verify the angular tolerance of the delivered double-pyramid prisms. This is a simple, accurate and robust test that doesn't require any special lab equipment other than a pinhole source and a stock lens in front of the pyramid, and it is insensitive to lens imperfections and misalignment errors. We call this test the "Metafocus Test" as it makes use of a so-far unknown interesting optical property of the double-pyramid, for which the four exiting beams intercept into a single point. Any angular error on the faces of the pyramid will split the metafocus up to four spots. The as-built apex and azimuth angles, as well as assembly errors (wedge and clocking of front pyramid w.r.t. rear pyramid) can be derived from the measurement of the relative position of each spot.

Keywords: Pyramid wavefront sensor, optical design, optical testing.

1. NFIRAOS DOUBLE-PYRAMID SPECIFICATIONS

The Narrow-Field Infra-Red Adaptive Optics System (NFIRAOS) [1] will be the first light adaptive optics system of the Thirty Meter Telescope (TMT) [2]. NFIRAOS uses a pyramid wavefront sensor (WFS) working with a Natural Guide Star (NGS) in addition to the 6 laser-guide-star WFSs. The pyramid WFS, also known as Visible NGS WFS (VNW), reach its final design [3] and is now ready for fabrication.

One of the high-risk items is the custom achromatic double-pyramid prism that is very challenging to manufacture. The main requirements of VNW driving the design of the pyramid are the waveband (610-785nm), the field-of-view (2 arcsec.), the operating temperature range (-30 to +20C) and, above all, the positional tolerance of each pupil image formed on the detector (Figure 1). Fortunately, for NFIRAOS we were able to relax the latter tolerances thanks to an oversampling of the pupil (96 pixels across the pupil diameter, compared to 60 actuators). Simulations showed that the angular tolerance of the pyramid could be as loose as 2 arcmin. [4]. The final optical specifications of the NFIRAOS double-pyramid are listed in Table 1.

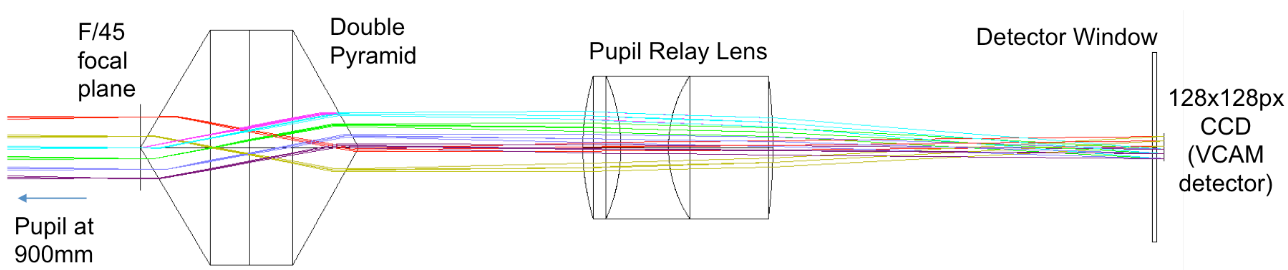

Figure 1: Optical layout of NFIRAOS pyramid WFS (VNW) from the pyramid focal plane to the detector where the four images of the pupil are formed.

Table 1: NFIRAOS double-pyramid optical prescription

Glass material (front, rear)	Ohara PBL6Y & S-BAL2
Glass CTE mismatch	$0.8\times10^{-6}/^{o}C$
Pyramid shape and size	Square base, 35.0±0.1mm and ±0.02^{o}
Pyramid center thickness	23.0 ± 0.1 mm each
Clear aperture (entrance, middle, exit)	14x14mm, 15x15mm, 18x18mm
Apex angle (front, rear)	40.00 & 38.35 ± 0.03 degrees
Apex angle variation	±0.03 degrees (2 arcmin)
Face azimuth angle variation	±0.02 degrees (1.2 arcmin)
Surface flatness	<30 nm RMS
Pyramid maximum roof & edge chips	<20um (front), <50um (rear)
Front pyramid surface quality	5/10x0,01;L1x0,006 within 1.5mm from tip
Middle plane surface quality	5/10x0,025;L5x0,006
Rear pyramid surface quality	5/10x0,04;L5x0,01
Pyramid bonding	<10um-thick NOA61 adhesive
Maximum relative decenter	<0.2mm
Maximum wedge angle	±0.03 degrees (2 arcmin)
Maximum clocking angle	±0.05 degrees (3 arcmin)
AR-coating (each pyramid)	R<0.5% average at 38-40° AoI in 610-785nm
Operating environment conditions	-35 / +25 °C, 600-1015 hPa, 5%-95% RH
Survival environment conditions	-45 / +55°C, 190-1025 hPa, 0%-100% RH

2. FABRICATION OF THE DOUBLE-PYRAMID

Our supplier was BMV Optical Technologies (*www.bmvoptical.com*), based in Ottawa, Canada. We purchased two pyramids for NFIRAOS (parts #1 & 2), and two extras for testing and R&D activities in the NRC AO lab (parts #3 & 4). The cost was ~5k C$ each with a 3-month lead-time.

Four identical pyramids had to be polished simultaneously in the same tool, so that sacrificial material can used to fill the gaps between the pyramids and then improve the surface flatness around the ridges and tips of each pyramid. The custom tool designed and built by BMV to polish the four front pyramids (40^{o} apex angle) is visible in Figure 2. A similar tool has been made for polishing the rear pyramids (38^{o} apex angle). BMV did also the assembly (bonding with NOA61 adhesive) and the anti-reflection coatings of the double pyramids (Figure 3).

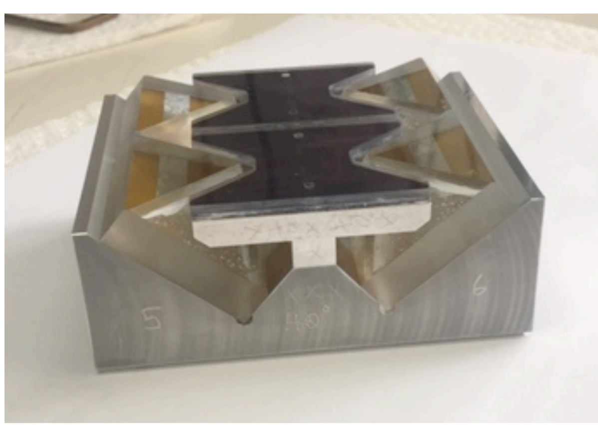

Figure 2: Polishing tool designed by BMV to polish the NFIRAOS pyramids (Courtesy of BMV Optical Technologies).

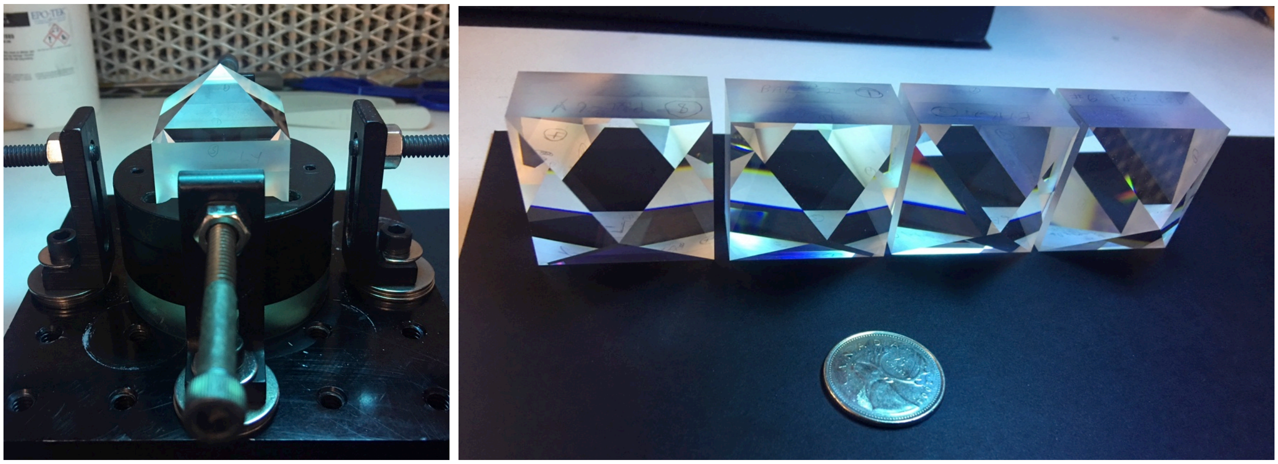

Figure 3: Left: Bonding and assembly of the double pyramid (left). Right: Canadian pyramids ready for coating (Courtesy of BMV Optical Technologies).

3. ACCEPTANCE TEST PLAN

Upon delivery of the four double-pyramids, parts #1 and 2 (the best two according to our supplier in terms of tip size) were kept in their package and set aside for NFIRAOS, while parts #3 and 4 have been unpacked and installed in a custom cage mount to provide extra protection and ease the handling during the acceptance tests (Figure 4). The overall acceptance test plan conducted at NRC is as follows:

1. Inspections for gross errors
    a. Compare expected vs. measured weight (this test is used as a checksum)
    b. Measure pyramid base side with caliper
2. Tip size and edge chip
    a. Pictures taken under microscope (Sec. 4)
3. Assembly errors
    a. Measure gap, decenter and clocking between front and rear pyramid under microscope (Sec. 4)
    b. Metafocus test (Sec.5)
4. Face angles:
    a. Coordinate Measuring Machine (CMM) metrology test (not detailed in this paper)
    b. Metafocus test (Sec.5)
5. Throughput:
    a. Use white source, bandpass filters and fluxmeter with and without pyramid (test not detailed in this paper).
6. Survival to cold:
    a. Perform four cooldown cycles to -30^{o}C

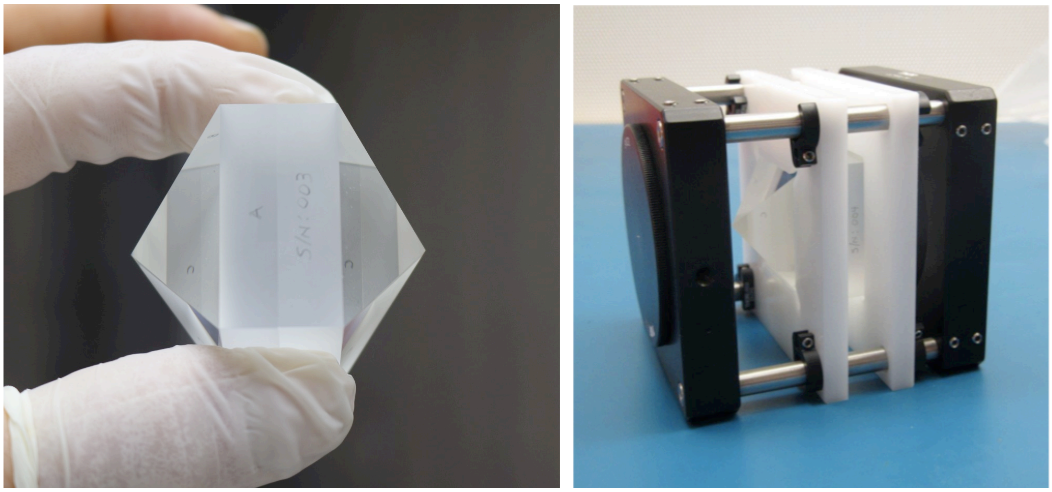

Figure 4: Left: Double pyramid prism after delivery at NRC. Right: Double pyramid installed in its mount ensuring safe handling during the tests.

4. TEST UNDER MICROSCOPE

A long working distance microscope (Leica MZ8 stereo zoom “macroscope”) equipped with a camera has been used to inspect the double-pyramids of NFIRAOS and measure the size of the tips and the width of the ridges. At maximum magnification, the pixel scale is 1.4um. Figure 5 shows the images of the front and rear pyramid tips and edges (front only) for the part #3. The photography of the edges requires the pyramid to be tilted at ~40^{o} with respect to the microscope optical axis. Based on the plate scale, tips are smaller than 10um, and edges are narrower than 6um (requirement is 20um).

Additional microscopic images (not shown here) have been taken to visually assess the assembly errors (wedge, decenter, clocking) between the front and rear pyramids, as a sanity check before doing the more accurate metafocus test (Sec. 5). The wedge can be quickly assessed from the apparent thickness of the adhesive gap at each corner of the pyramid base, while clocking and decenter errors can be assessed based on how the ridges of the pyramid bases lined up with respect to each other, at each corner.

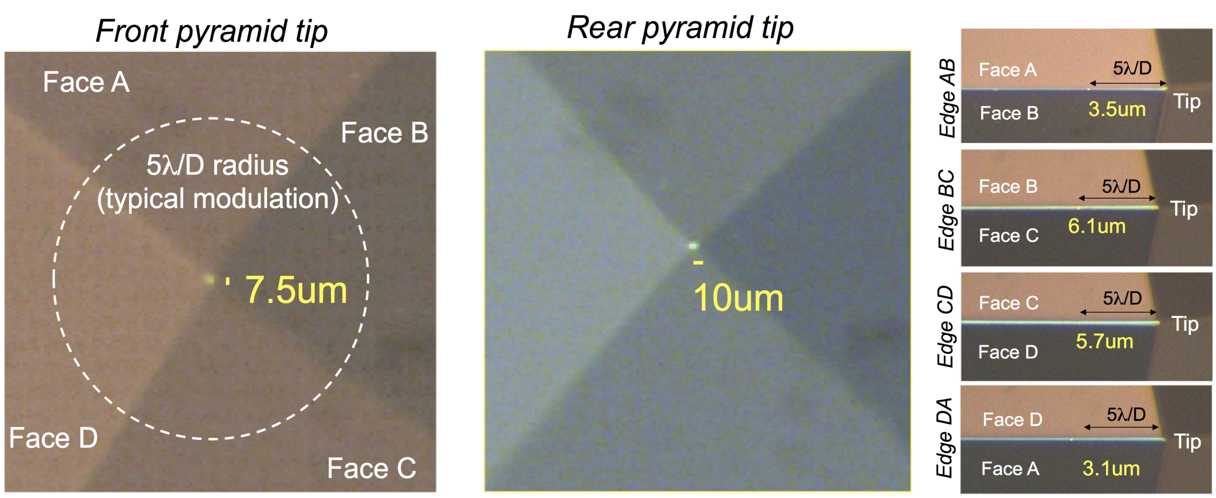

Figure 5: Images of pyramid (part #3) tips and edges under microscope.

5. METAFOCUS TEST

At NRC we developed a new optical test to quickly verify the angular tolerance of the delivered double-pyramid prisms. This is a simple, accurate and robust test that doesn't require any special lab equipment other than a pinhole source and a stock lens in front of the pyramid. This test is insensitive to lens imperfections and misalignment errors.

5.1 Metafocus Test Concept

We call this test the "Metafocus Test" as it makes use of a so-far unknown interesting optical property of the double-pyramid, for which the four exiting beams intercept into a single point. Indeed, if one has one's eye located behind a double-pyramid without any relay lens in between, one can see four virtual images of any object placed in front of the pyramid, like a kaleidoscope (for a WFS, the object is the telescope pupil). Interestingly enough, the lines of sight of the four virtual images intersect in a single point ("metafocus") as shown in Figure 6. If one's eye is not at metafocus distance, only one image over four can be seen at a time. However, if one's eye is exactly at metafocus the four images are visible simultaneously (Figure 7).

Any angular error on the faces of the pyramid will shift the four pupil images and split the metafocus up to four spots (Figure 6). In NFIRAOS pyramid case, a spot shift of 250µm in the metafocal plane corresponds to a pupil shift of 1 pixel on the detector. These shifts can then be translated to apex and azimuth angle errors, as well as assembly errors (wedge and clocking of front pyramid with respect to rear pyramid) and compared with the specifications sent to the supplier.

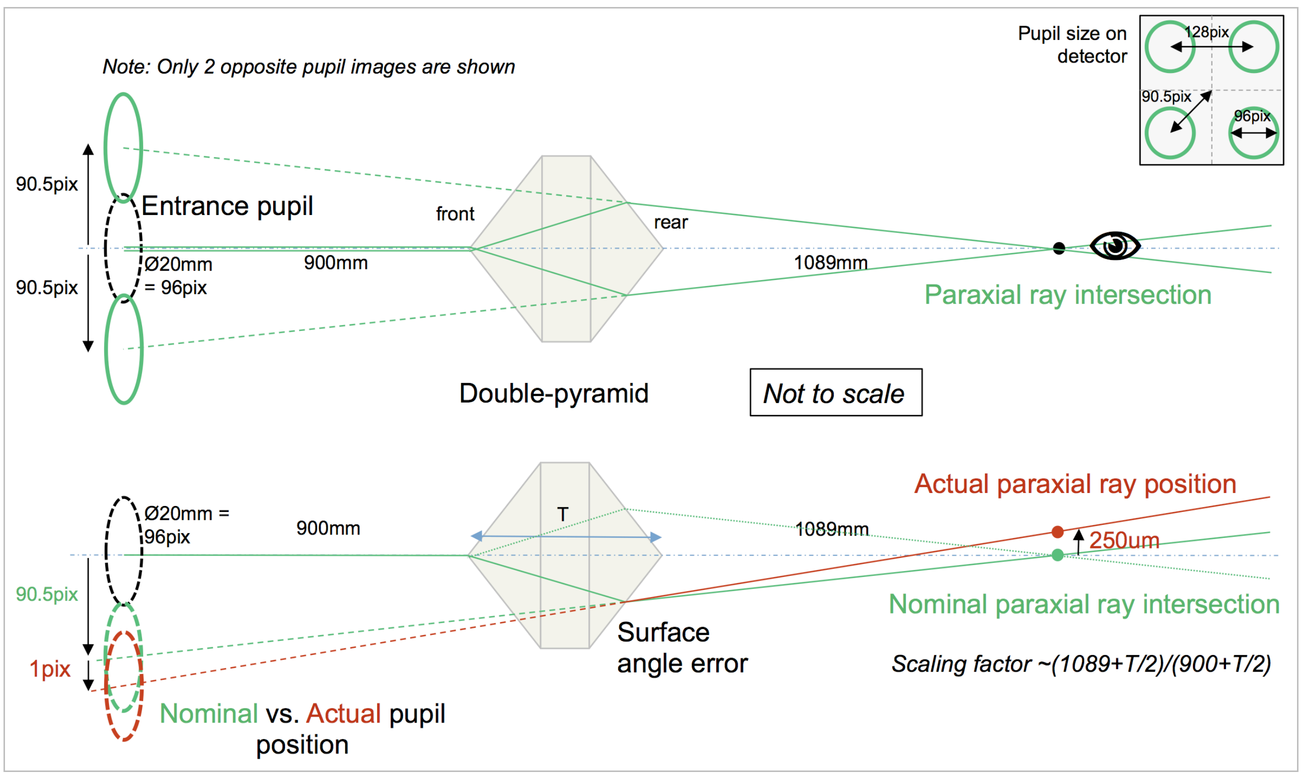

Figure 6: Concept of the Metafocus test.

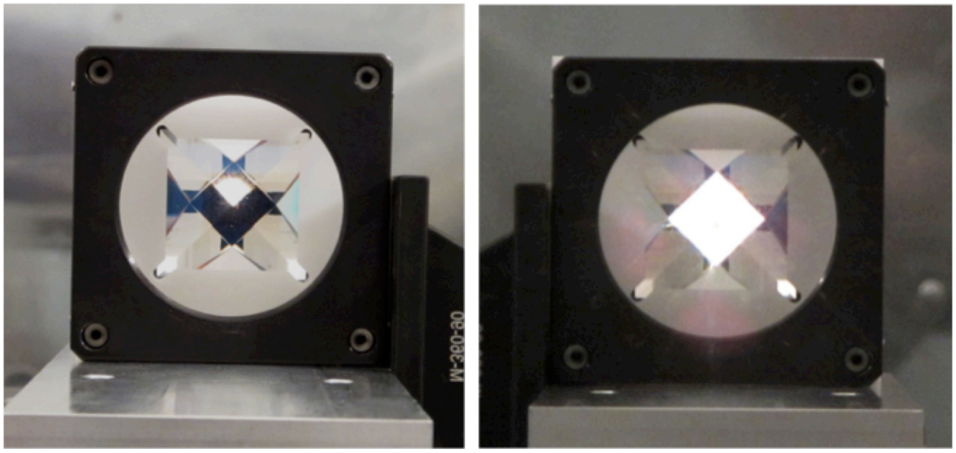

Figure 7: Looking directly behind a double-pyramid: if one's eye is not at metafocus distance, only one face can be seen illuminated at a time (left), but if instead, one's eye is at metafocus, the 4 faces appear simultaneously illuminated (right).

5.2 Test Setup

The metafocus test is relatively easy to implement, as it only requires a pinhole source and a collimating lens in front of the pyramid. If the pyramid is illuminated with a perfectly collimated beam, the exit beam is sliced in four square beams. The exit beams are still collimated but they are each tilted and they intercept at the metafocal plane right on their very corner, where the pyramid tip was (paraxial ray) as shown in Figure 8 (top). If instead one adjusts the axial position of the lens to make the incoming beam converging, one can get four focused images of the pinhole at the metafocus as shown in Figure 8 (bottom). As there is no optics behind the pyramid, the relative positions of four spots are insensitive to the lens imperfections and misalignment. With a perfect double-pyramid, the four spots should be exactly superimposed.

In our set-up, we used a white source, a 10μm diameter pinhole, a commercial stock lens (F=100mm, Dia.=25mm) and a bare DSLR camera located at metafocus (Figure 9).

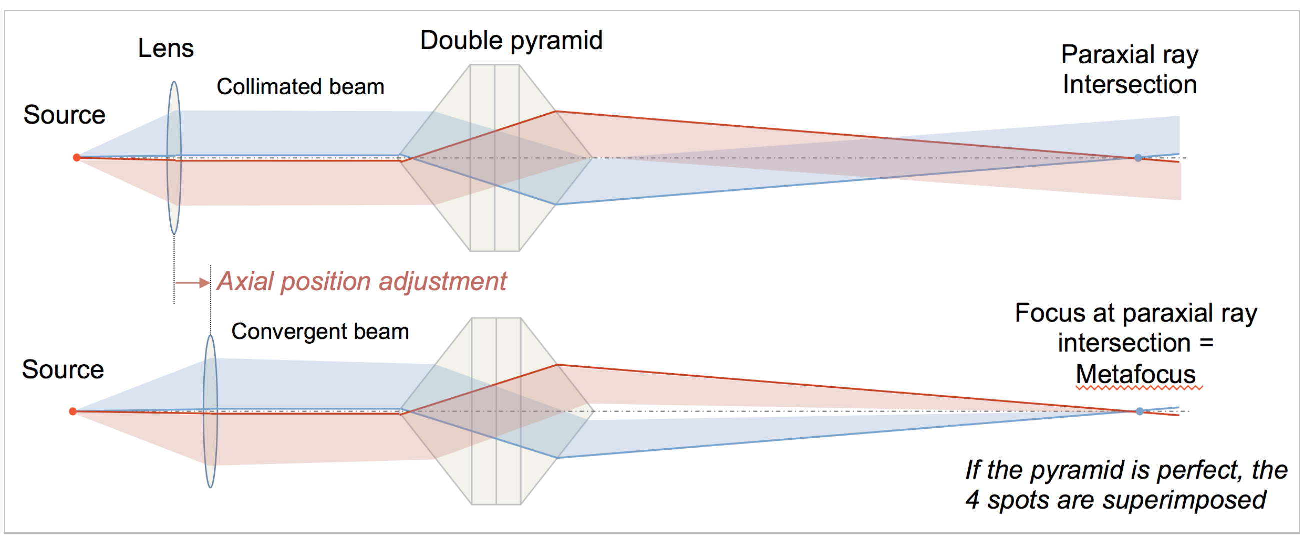

Figure 8: Metafocus test setup.

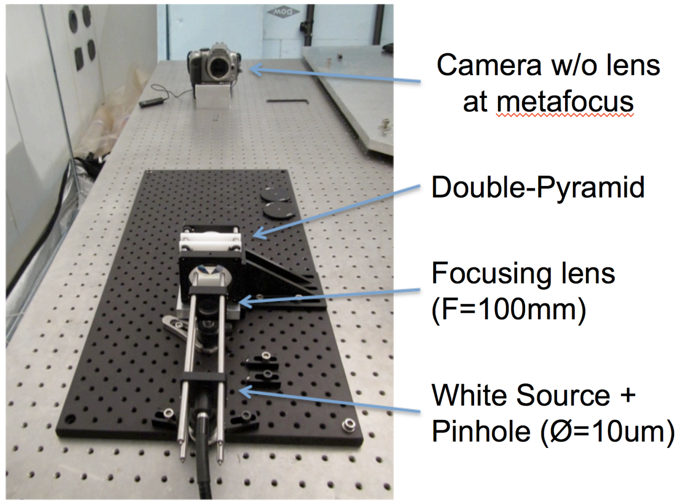

Figure 9: Implementation of the metafocus test.

5.3 Metafocal Images Interpretation and Sensitivity

If the source is white, one can see four little rainbows at metafocus (2 horizontal, 2 vertical) due to pyramid lateral color (NFIRAOS pyramid being only achromatic over 610-785nm and for an entrance pupil located at 900mm from the pyramid tip). With a perfect pyramid, the red ends of the rainbows ($\lambda \sim 700$nm) would be exactly superimposed.

The pitch and yaw of the pyramid assembly may require be adjusted in order in order to superimpose, as best as possible, the vertical pair of rainbows with the horizontal pair of rainbows (yaw moves the horizontal pair horizontally as a whole, while pitch moves the vertical pair vertically). This step makes sure the pyramid axis is parallel to the test setup optical axis.

The position of each spot is the combined result of three error terms:

- front surface angular errors (apex or azimuth)
- opposite rear surface angular error (apex or azimuth)
- assembly error (wedge or clocking).

The presence of rainbows actually helps identifying surfaces and angular errors:

- Apex or wedge error shifts the rainbow along the color dispersion direction (longitudinal shift).
- Azimuth or clocking error shifts the rainbow sideways (lateral shift) as shown in Figure 10.

The relative position of each spot measured in the metafocal plane can then be translated in angular errors using the sensitivities computed by Zemax and listed in Table 2.

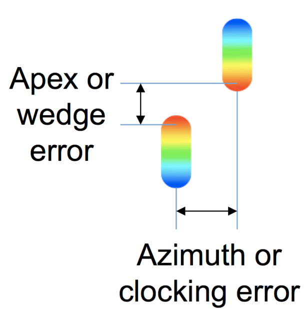

Figure 10: Pair of rainbow images formed at metafocus by 2 opposite faces of the pyramid (the perpendicular pair of rainbows formed by the 2 other faces is not drawn for clarity).

Table 2: Sensitivity of the metafocus test to angular errors in the case of the NFIRAOS double-pyramid (* Weak sensitivity. Absolute apex angle can be verified by weight or with a coordinate measuring machine instead)

Measurement	**Sensitivity**	**Cause** (i.e. variable in Zemax)
Metafocal length	53.7mm/2arcmin	Front-rear apex angle difference
Matafocal length	2mm/2arcmin	Absolute apex angle* (constant front-rear diff.)
Spot image longitudinal shift	473μm/2arcmin	Apex or wedge error
Spot image lateral shift	261μm/2arcmin	Azimuth or clocking error

5.4 Metafocus Test Results

Figure 11 shows the actual images obtained with a bare DSLR camera placed at the metafocus of the double pyramids parts #3 and 4. The measured metafocal length is 1090±2mm for both pyramids (nominal is 1089mm). All metafocus spots are within ±160μm, which translates to position errors of the pupils lower than ±0.64 pixel on VCAM (Figure 11), and to angular manufacture errors lower than ±0.5arcmin (req.= ±2arcmin) per surface or assembly error (Table 3).

In Table 3, apex and wedge errors are derived from the rainbows' longitudinal shifts, while azimuth and clocking errors are derived from the lateral shifts. Each angular error are computed as follows:

$$\textit{Error}\ (\text{arcmin}) = \textit{spot\_position}\ (\mu\text{m}) \,/\, \textit{sensitivity}\ (\mu\text{m/arcmin}) \,/\, \sqrt{3}\,, \qquad (1)$$

with *sensitivity* coming from the last two rows of Table 2. Each measurement (longitudinal or lateral shifts) is assumed to be the quadratic sum of three error terms (front apex, wedge and rear apex impact radial shift, while front azimuth, clocking and rear azimuth impact lateral shift), which explains the division by $\sqrt{3}$.

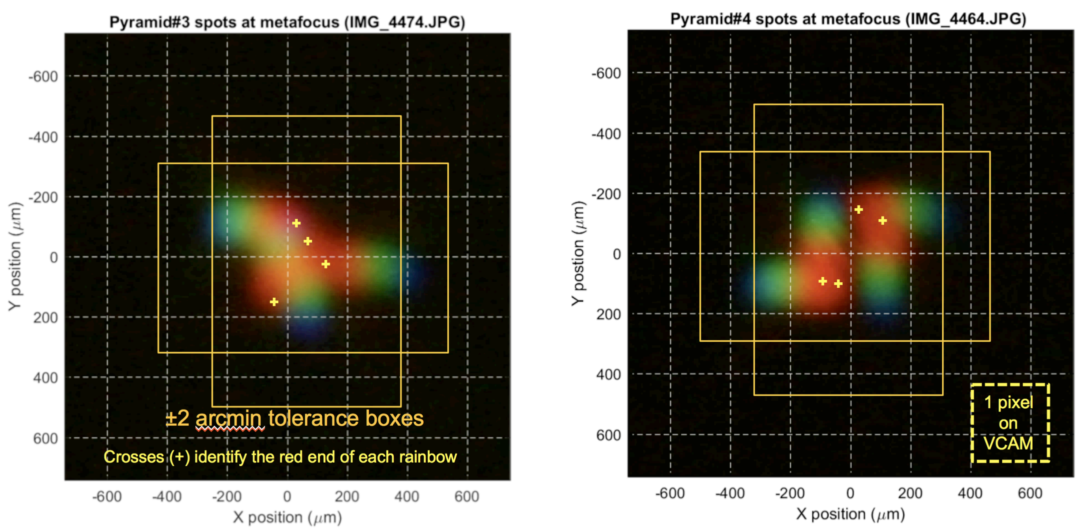

Figure 11: Matafocal images obtained with parts #3 and 4.

Table 3: Metafocus spot positions converted into angular errors per surface or per assembly error.

	Error (arcmin.)	**Spot #1** *(front A + rear C)*	**Spot #2** *(front B + rear D)*	**Spot #3** *(front C + rear A)*	**Spot #4** *(front D + rear B)*
Pyr#3	Apex or wedge	+0.06	-0.03	+0.42	+0.06
	Azimuth or clocking	-0.49	+0.15	-0.37	+0.19
Pyr#4	Apex or wedge	-0.06	+0.05	+0.21	-0.18
	Azimuth or clocking	+0.53	-0.53	-0.43	+0.43

6. CONCLUSION

Four double-pyramid prisms have been successfully procured for the NFIRAOS NGS WFS, which was initially perceived as a high-risk item. Even if the angular tolerance of the NFIRAOS pyramid has been relaxed, the fabrication of such prisms remains challenging. As costumers, it's important to be able to verify all the critical specs quickly after delivery. The size of tips and edges can be verified under microscope, while the angles can be verified optically with the metafocus test presented here, a simple and accurate test that does not require the availability of the other optical components of the WFS. Table 4 summarizes the overall results of the acceptance tests conducted at NRC. More recently, one of the double-pyramid has been validated in the NRC AO lab as a regular Pyramid WFS and as a Flattened PWFS [5].

Table 4: Acceptance test results of the NFIRAOS double-pyramid.

Requirement	**Value**	**BMV report**	**NRC test**
Pyramid side (mm)	35±0.1	35.100 x 35.099	35.11x35.10
Pyramid centre thickness (mm)	23±0.1	23.09	*Not tested*
Front apex angles (deg)	40.00^{o}±0.03	39.983	40.00^{o}±0.02
Rear apex angles (deg)	38.35^{o}±0.03	38.35	38.35^{o}±0.02
Azimuth angles (deg)	90.00^{o}±0.03		90.00^{o}±0.03
Apex angle variations (arcmin)	±2		<±0.5
Azimuth angle variation (arcmin)	±1.2		<±0.5
Surface flatness (nm rms)	<30	<9.3	*Not tested*
Front roof size (μm)	<20 (goal 10)		7.5
Front edge chip (μm)	<20 (goal 5)		3.1 to 5.5
AR coating	<0.5% avg <1% abs	0.32% avg (derived from normal incidence measurement)	~0.67% avg ~1.25% abs
Relative decenter (mm)	<0.2		<0.015
Relative wedge (arcmin)	±2		<±0.1
Relative clocking (arcmin)	±3		<±0.3

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