NIRSPEC

UCLA Astrophysics Program **U.C. Berkeley** **W.M. Keck Observatory**

Don Figer

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NIRSPEC Optics Design Note 9.00
Opto-mechanical Tolerance Analysis (OMTA)

1. Introduction

This document describes the optical alignment requirements for NIRSPEC. Note that this document does not describe how these requirements will be met; that topic requires intimate knowledge of mounting schemes, and thus it will be left to another document.

The alignment requirements are driven primarily by the desire to obtain 80% ensquared energy within one spectrometer pixel. Misalignments can produce several unwanted effects: 1). an increase in the wavefront aberrations across the beam, and thus an increase in the spot size, 2). a static vignetting of the beam, and 3). a dynamic vignetting of the beam due to the motion of the image rotator.

In general, component misalignments can be resolved as translations and rotations with respect to three orthogonal axes. When considering these six parameters, it is important to specify the reference coordinate system. There is usually one reference frame which will minimize the number of non-zero parameters, and this is not necessarily the same reference frame which is most appropriate from a designer's or a manufacturer's perspective. I will try to give the tolerances with respect to the most practical reference frame.

2. OMTA Performance Categories

The front-end tolerances were generated by assuming that we can accept a total weighted wavefront error (WFE) of 0.12$8_{2.2\ :m}$ RMS evaluated at the slit plane. I arrived at this figure empirically by inducing wavefront aberrations and measuring their effects on image performance. The condition ensures that the design gives 90% ensquared energy (ESE) within a 97 :m square field at the final (slit) focal plane for field points within the slit; the slit is rectangular and spans ±150 X ±0.20 on the sky. This WFE condition also ensures that the system gives 80% ESE within a 97 :m square field over the full square field of view of the slit viewing camera (SCAM); the SCAM covers ±230 on the sky. These performance criteria have been measured when the image rotator K-mirror is in the ideal configuration, i.e. 2_{IROT} = 0°. The weight ratios are 3:2:1 for the central field point:slit edge field points: SCAM FOV corner field points. Effects due to surface irregularity are discussed in more detail in the design note on the wavefront error budget, although the irregularity tolerances are generally given in the tables in this design note.

In some cases, requirements other than those due to image performance provided tighter constraints. These other requirements are listed below.

- **Image wander (iw)**. Requires a maximum image wander radius of ½ of a slit width, or 97 **:**, at the slit focal plane. The image wander constraint does not apply to the f/converter K-mirror because it is stationary.
- **Beam displacement (b)**. Requires a maximum lateral offset of 1.0 mm on any part from the beam's point of view. For instance, the beam could be displaced by 1.5 mm on the folding flats, but that would only result in a displacement of 1.0 mm from the beam's point of view. For downstream elements, this requirement amounts to a maximum allowable field for upstream elements. For instance, a tilt in the last flat mirror of the f/converter K-mirror assembly will mean that the imaged field will be offset at the instrument window. This offset is considered to be the same as "beam displacement."
- **Mechanical (m)**. Requires that parts remain within a reasonable profile for housings.
- **Pupil wander (pw)**. Requires a maximum of 1% in lateral offset of the pupil image; this amounts to 0.267 mm.
- **Scattering (s)**. Requires negligible scattering between 1 and 5 **:**m.

3. OMTA Model

I designed an opto-mechanical tolerance model in Zemax by making extensive use of coordinte break surfaces. These surfaces can be used to tilt or decenter individual optical surfaces or complete modules as can be seen in Figure 1. I have highlighted six of the coordinate breaks used in this model byu giving them square apertures: two per K-mirror module, and 2 for the mini-bench which will hold the 2 modules together. In addition, there are coordinate breaks before and after each optical surface; these are not shown in the figure for clarity. The model for the front end is saved as FEMECTOL.ZMX. A similar procedure was used to simulate misalignments in the back-end; although a special comprehensive model was not built up. Most of the coordinate breaks in the back end were left in the end-to-end model.

The following sections give opto-mechanical alignment tolerances for the various optical surfaces and modules. In general, compensators were not used to improve image performance. The "module" columns in the alignment tables refer to maximum deviations introduced by inserting the complete module into the path of an on-axis laser beam; in other words, they do not correspond to measured misalignments of the module itself. Those tolerances are given in a later section which discusses module alignment.

OMTA Model for Front-end

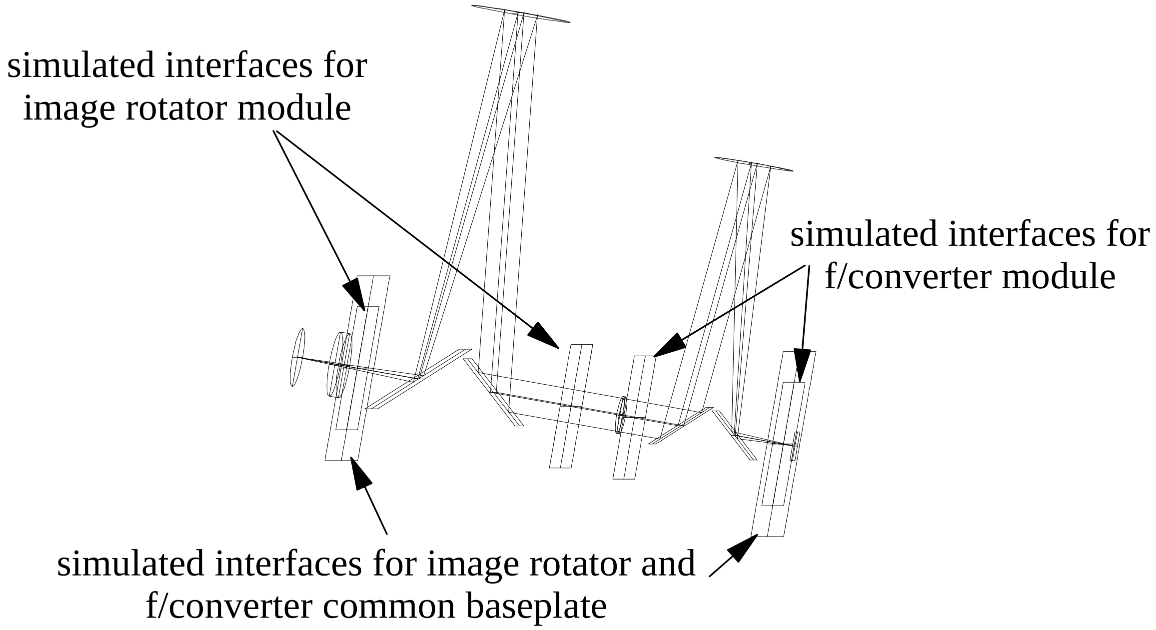


Figure 1. Layout of front-end OMTA model used in Zemax.

4. Window Tolerances

The window tolerances are discussed in greater detail in another design note. The final tolerances are reproduced below in Table 1. D is the clamped window diameter; we allow for 5 mm in total oversizing over the diameter. t is the required thickness; we allow for a factor of 3 over the breakage thickness. $\mathbf{2}_t$ and $\mathbf{2}_{np}$ give the maximum tilt of the window with respect to the input beam and the maximum degree of non-parallelism between the window faces. These are constrained by image and pupil wander.

Table **1: Opto-mechanical Tolerances for Window**

Tolerance Category	Tolerance Requirement	Parameter	Value
clearance	100% + 5 mm	D	52 mm
breakage		t	7.5 mm
image/pupil wander	$r_{\text{image wander}} < 1.0$ pixels $r_{\text{pupil wander}} < 267$ **:**m	$\mathbf{2}_t$	2°.8
		$\mathbf{2}_{np}$	5N

5. Image Rotator Tolerances

The image rotator alignment is shown in Table 2. Notice that many of the constraints come from image or pupil wander. Evidently, if the image rotator is aligned properly to control wander, then the image performance should be adequate. The tightest angular alignment requirement is 210, and the tightest translational alignment requirement is 100 :m. Both of these requirements are due to wander, so they probably cannot be increased by compensating with other elements.

Table 2: Opto-mechanical Tolerances for Image Rotator

Tolerance	**units**	**F1**	**OAP1**	**F2**	**Module**
Surface					
Radius	mm	-	-3.5p +1.0p	-	-
Irregularity	$8_{632.8nm}$ (P-V)	1/5p	1/5p	1/10p	-
RMS surface roughness	Å (RMS)	< 55s	< 55s	< 55s	-
Orientation					
x-tilt	mrad	0.3pw	0.2iw	0.1iw	0.3pw
	asec	62	41	21	62
y-tilt	mrad	0.5pw	0.2iw	0.2iw	0.3pw
	asec	103	41	41	62
z-tilt (clocking)	mrad	30m	3.5pw	30m	30m
	asec	6188	722	6188	6188
Center Position					
x-decenter	mm	1.0b	0.3pw	1.0b	0.3pw
y-decenter	mm	1.5b	0.4pw	1.5b	0.3pw
z-decenter	mm	0.1iw	1.0p	0.2pw	1.0m

Tolerances are measured with respect to local coordinate axes fixed on the optical surfaces. The z-axis is normal to the clear aperture tangent plane. The y-axis runs along the long arm of the f/converter as shown in Figure 1. The x-axis is orthogonal to the y- and z-axes in a left-handed coordinate system.

Tolerance codes:

p - image performance gives 90% ESE within a 97 :m per side square for slit field points, and 80% ESE for SCAM FOV corner field points
iw - image wander radius = 97 :m at slit plane
b - 1.0 mm offset of beam footprint on any element
m - mechanical clearance
pw - pupil wander radius = 267 :m (1% of pupil diameter)
s - negligible scattering between 8 = 1 and 5 :m

6. F/converter Tolerances

The f/converter and image rotator optics are similar, and their tolerances are were generated in much the same way. Almost all of the tolerances are due to beam offset, mostly on upstream elements such as the dewar window. Notice that the tolerances are somewhat relaxed compared to those for the image rotator.

Table 3: Opto-mechanical Tolerances for f/converter

Tolerance	**units**	**F3**	**OAP2**	**F4**	**Module**
Surface					
Radius	mm	-	-0.5p +1.5p	-	-
Irregularity	$8_{632.8nm}$ (P-V)	1/10p	1/5p	1/5p	-
RMS surface roughness	Å (RMS)	< 55s	< 55s	< 55s	-
Orientation					
x-tilt	mrad	1.3b	1.3b	6.8b	2.6b
	asec	268	268	1403	536
y-tilt	mrad	1.8b	1.3b	10b	1.9b
	asec	371	268	2063	392
z-tilt (clocking)	mrad	30m	13b	30m	30m
	asec	6188	2681	6188	6188
Center Position					
x-decenter	mm	1.0b	0.6b	1.0b	0.7b
y-decenter	mm	1.5b	0.6b	1.5b	0.7b
z-decenter	mm	1.5b	1.0p	0.7b	1.0m

Tolerances are measured with respect to local coordinate axes fixed on the optical surfaces. The z-axis is normal to the clear aperture tangent plane. The y-axis runs along the long arm of the f/converter as shown in Figure 1. The x-axis is orthogonal to the y- and z-axes in a left-handed coordinate system.

p - image performance gives 90% ESE within a 97 :m per side square for slit field points, and 80% ESE for SCAM FOV corner field points
iw - image wander radius = 97 :m at slit plane
b - 1.0 mm offset of beam footprint on any element
m - mechanical clearance
pw - pupil wander radius = 267 :m (1% of pupil diameter)
s - negligible scattering between 8 = 1 and 5 :m

7. Collimator Tolerances

The collimator tolerances are shown in Table 4. The tolerances were generated by assuming that we can accept a total system wavefront error (WFE) of - 0.66 $8_{0.6328\ :m}$ RMS. After considering others sources of wavefront error in the system, we believe that we can accept - 0.15 $8_{0.6328\ :m}$ RMS WFE due to the OAPC design alone.

This condition ensures that the system gives 80% ensquared energy (ESE) within a 27 :m square field at the final array focal plane for field points within the slit; the slit is rectangular and spans ±150 X ±0.20 on the sky. These performance criteria have been measured when the image rotator K-mirror is in the ideal configuration, i.e. 2_{IROT} = 0°. Different image rotator angles will introduce very large wavefront errors from the front-end optics, so the final tolerances on the OAPC will only be important for the case where the front-end is essentially diffraction limited, i.e. 2_{IROT} = 0°. The weight ratios are 2:1:1 for the central:side slit edges:top and bottom slit edges field points.

In some cases, requirements other than those due to image performance provided tighter constraints. These other requirements are listed below. The tolerance table contains symbols following each tolerance value. These symbols are described below and at the bottom of each table. They indicate which requirement was used to calculate the tolerance value.

- **Beam displacement (b)**. Requires a maximum lateral offset of 1.0 mm on any part from the beam's point of view.
- **Scattering (s)**. Requires negligible scattering between 1 and 5 :m.

All values are with respect to the center of the OAPC clear aperture, not the parent vertex. Some of these tolerances refer to the positioning of the reference flat.

Table 4: Opto-mechanical Tolerances for OAPC

Tolerance	units	OAPC
Surface		
Radius	mm	-1.4p +0.4p
Irregularity	$8_{632.8nm}$ (P-V)	1/4p
RMS surface roughness	Å (RMS)	<75s
Orientation		
x-tilt	mrad asec	0.4b 83
y-tilt	mrad asec	0.4b 83
z-tilt (clocking)	mrad asec	0.4b 83
Vertex Position		
x-decenter	mm	0.4b
y-decenter	mm	0.4b
z-decenter	mm	-

Tolerances are measured with respect to local OAPC coordinate axes. The z-axis is normal to the clear aperture tangent plane. The y-axis runs along the long arm of the f/converter as shown in Figure 1. The x-axis is orthogonal to the y- and z-axes in a left-handed coordinate system.

p - image performance gives 80% ESE for the 27 :m pixels on the array
b - 1.0 mm offset of beam footprint
s - negligible scattering

8. Gratings Tolerances

The grating alignment tolerances are controlled by the constraint to have less than 1.0 mm in lateral offset at each suface. Misalignments will not induce any change in image performance because gratings act like flat mirrors, i.e. they don't change the wavefront map across the beam. Of course, misfiguring of the surface will induce wavefront aberrations, although that topic is more fully discussed in the note on the wavefront error budget.

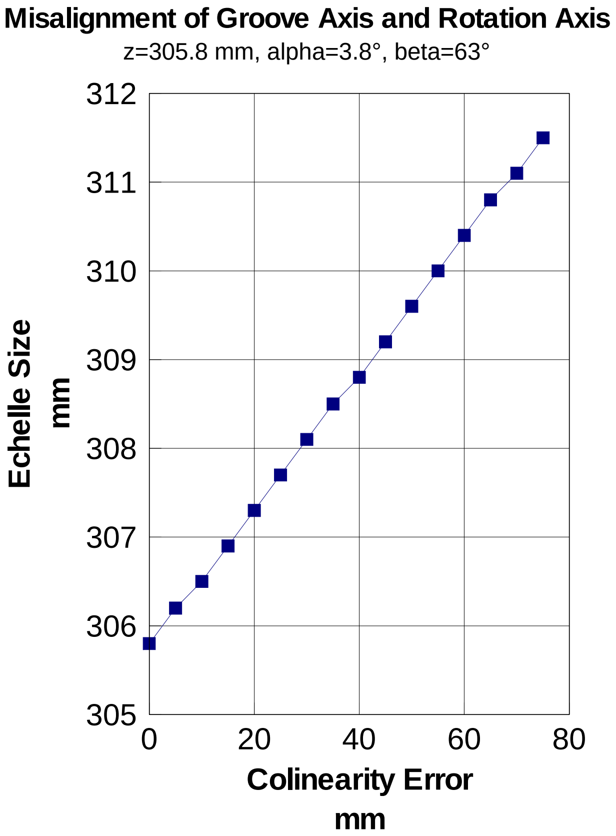
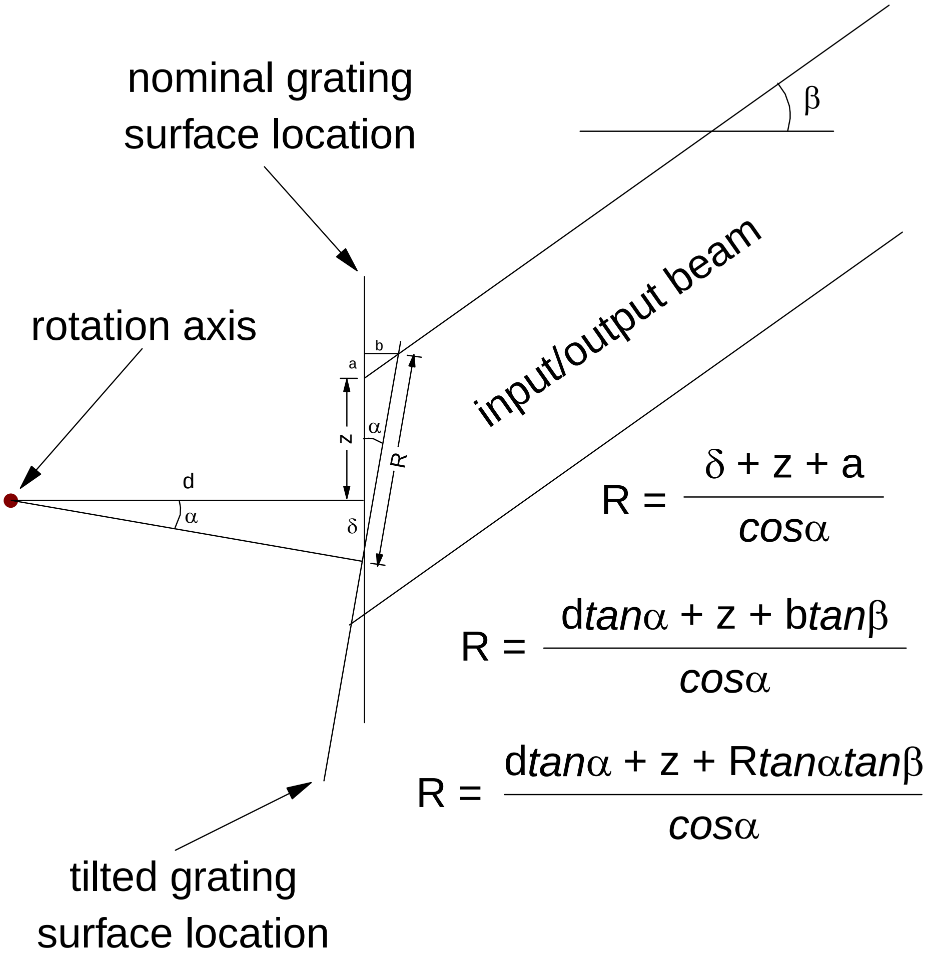


Figure 2. Effect of separating rotation axis from groove axis.

Figure 2 shows shows the relationship between axis misalignment and grating size. The mathematical formalism is derived in Figure 3. Notice that there is very little consequence for having relatively large errors in misalignment. Of course, this assumes that the only deleterious effect of misalignment is an increase in the grating size. This is probably true although the detailed shape of the beam footprints on the cross-disperser will change somewhat from the case of perfect alignment. This also means that the footprints in the TMA will change. Even in the ideal case, the beam footprints are quite complex and change versus grating position, so this effect is likely to be negligible.

Geometric Construction for Calculating Grating Size as a Function of the Misalignment Between the Rotation Axis and the Groove Axis



$$R = \frac{\delta + z + a}{\cos\alpha}$$

$$R = \frac{d\tan\alpha + z + b\tan\beta}{\cos\alpha}$$

$$R = \frac{d\tan\alpha + z + R\tan\alpha\tan\beta}{\cos\alpha}$$

$$R = \frac{d\tan\alpha + z}{\cos\alpha(1 - \tan\alpha\tan\beta)}$$

Figure 3

9. TMA Tolerances

The TMA is treated as an assembly in this document. Internal tolerances for the 3 mirror surfaces can be found in the bid package for the TMA. The TMA tolerances are dominated by beam offset, and thus, they are quite relaxed for lateral offset. The angular tolerances are actually somewhat challenging to achieve, but no more so than other angular tolerances elsewhere in the instrument.

10. Array Tolerances

The array tolerances are given in the section on module tolerances. Notice that the depth of focus requires longitudinal positioning to within 50 :m. Otherwise, the tolerances are very relaxed.

11. Module Tolerances

Table 5 gives the module tolerances for all the optical assemblies in the instrument. Some of the columns are just repeated from eariler tables. The “Super” column refers to tolerances for the combined IROT/FCON/Slit mini-bench assembly. The tolerance categories and criteria have been discussed in previous sections.

The “Super” tolerances assume that the slit assembly and individual slits have been placed in the beam to within the appropriate tolerances. These tolerances are not yet specified in any documentation. The tolerance on lateral motion will be given by the beam displacement requirement, 1 mm, and the tolerance on angular position will be given by requirements in the SCAM, probably due to beam displacement. Longitudinal placement will be given by image performance. The WFE changes from zero to $0.12\mathbf{8}_{2.2\ :\mathrm{m}}$ RMS when moving the slit plane by 0.5 mm, so that will be the focus tolerance on the slits.

The tolerances are deviations between the intput and output beams and are measured from independent coordinate axes for each module. For instance, the IROT tolerances are measured with respect to an origin which sits just inside the dewar window. X, Y, and Z, have the usual definitions as discussed for all earlier tolerance tables and as defined in Zemax. The super module IROT/FCON is also defined with respect to this same origin. The FCON origin is just a bit after the filter. The OAPC origin is at the center of the illuminated aperture, and the z-axis is parallel to the input beam on this element. The echelle origin is at the very center of the echelle. It is tilted so that the z-axis bisects the input and output beams. The same is true for the cross-disperser. The TMA reference axes are defined by the input beam to the TMA. The FPA axes originate at the center of the array, and they are oriented with respect to the edges of the array.

Table 5: NIRSPEC Opto-mechanical Alignment Tolerances

Tolerance	units	IROT	FCON	Super	OAPC	Echelle/ LRFLAT	CD	TMA	FPA
x-tilt	mrad	0.3iw	2.6b	0.8b	0.3b	1.7b	1.2b	0.7b	3.6p
	asec	62	536	165	62	351	248	144	743
y-tilt	mrad	0.3iw	2.6b	0.8b	0.3b	0.3b	-	0.7b	3.6p
	asec	62	536	165	62	62	-	144	743
z-tilt (clocking)	mrad	-	30m	30m	30m	30m	30m	15m	30m
	asec	0	6188	6188	6188	6188	6188	3094	6188
x-decenter	mm	0.3pw	0.7b	0.3b	1.0b	1.0b	1.0b	1.0b	1..0b
y-decenter	mm	0.3pw	0.7b	0.3b	0.4b	0.5b	1.0b	1.0b	1.0b
z-decenter	mm	1.0m	1.0m	1.0m	0.5p	2.0m	1.4b	5.0m	0.05p

Tolerances are measured with respect to local coordinate axes. The z-axis is normal to the clear aperture tangent plane. The x-axis is out of the page in Figure 1. The y-axis is orthogonal to the x- and z-axes.

Tolerance codes:

p - image performance gives 90% ESE within a 97 :m per side square for slit field points, and 80% ESE for SCAM FOV corner field points
iw - image wander radius = 97 :m at slit plane
b - 1.0 mm offset of beam footprint on any element
m - mechanical clearance
pw - pupil wander radius = 267 :m (1% of pupil diameter)
s - negligible scattering between 8 = 1 and 5 :m