The Optical Design for the AdOpt@TNG module

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ABSTRACT

The authors describe characteristics and key results of the optical design for Adaptive Optics at the Galileo telescope. Two Off Axis Parabolae are used to image the pupil on the Deformable Mirror, and in order to keep to a minimum the number of reflections, one of them is used as Tip-Tilt mirror. The several costraints, both mechanical and optical, which led to the definitive design are reported (pupil position, effective focal ratio, off axis performances, size of the module...). Because Tip-Tilt is realized through tilting of a non-flat mirror care has been given to the deterioration and distortion of the image for a given range of misalignment of the Off Axis Parabola.

Keywords: optical design, adaptive optics, alignment

1. INTRODUCTION

The adaptive optics module is conceived to stay permanently at one of the two Nasmyth foci of the National Telescope Galileo (TNG hereafter). The optics are placed on an optical bench which rotates together with the Rotator/Adapter. When the adaptive optics correction is requested by the observer the light from the telescope is sent into the adaptive optics module via a pick up flat mirror and then relayed, after processing, to the Optical Imager Galileo (OIG) or to the Galileo IR Imager/Spectrograph (GIRIS). To insure the feasibility of this facility the alterations introduced in the optical path had to be kept to a minimum. This translates into an all reflective (strictly achromatic) system with an enlargement of the image scale from $F/11$ to $F/32$ and a 1×1 arcmin diffraction limited field of view in the near IR. Other constraints which led to the present optical layout will be briefly shown in the following.

2. OPTICS

The Adaptive Optics (AO) for the TNG (AdOpt@TNG) is one of the all reflective AO systems with less mirrors in the optical train. From Tab.1 one can see a comparison between the AdOpt@TNG system and some other AO systems.

AO System	Mirrors	Dichroics/BS	Lenses
AAT[1]	4	–	1
AdOpt@TNG[2,3]	4	1	–
CFHT Bonnette[4]	5	–	–
VLT[5]	5	–	–
Keck[6]	7	–	–
GEMINI[7]	7	1	–
COME-ON[8]	7	1	–
WHT[9]($F/55$)	8	1	1
Lick[10]	8	3	–

Table 1: Optical components for IR correction in different AO systems listed in increasing number of mirror introduced in the optical path. Dichroics are considered as mirrors if they reflect the beam directed to the scientific cameras.

It is to be pointed out that in TNG the IR camera receives the $F/11$ light through a folding mirror that is avoided when AO is switched on. This means that only three more reflections are introduced before the near IR camera, while before the OIG there is a further mirror to fold the corrected light, with a total of five reflections. Via the pick up mirror the light is fed to the first Off Axis Parabola (OAP) which acts both as Tip-Tilt mirror and as imager of the pupil into a continuous facesheet Deformable Mirror (DM). From the DM the light is sent to the second OAP, where the scale is enlarged, and from here reflected back to the two cameras; the selection is operated by a further folding mirror. It is worthwhile to point out that while this last folding mirror will have a coating optimised only for the visual the remainder of the mirrors will exhibit a coating optimised both for the visual and for the Near-IR, mostly for the Near IR portion of the spectrum where the AO correction is more effective. See Fig.1 to have a schematic explanation of the AdOpt@TNG system.

3. CONSTRAINTS

The pick up mirror is inserted at $d = 385mm$ before the Nasmith focus to send the light into the plane where most of the AdOpt@TNG module lies, and this plane is at an height $h = 85mm$ over the pick up mirror (see Fig.2 right). This means that the pick up mirror is more than 45^o folded, the exact angle depending upon the focal length f_1 of the first OAP. There are two reasons that influence the decentering of the first OAP: one is the need to reflect the light from the pick up mirror back into the plane of the adaptive optics; the other reason is that, without a lateral folding of the beam, the focused pupil would fall right above the path of light coming from the pick up mirror, leaving no space for the positioning of the DM.
A compromise had to be taken to satisfy the requests both for magnification from $F/11$ to $\approx F/35$ (the OIG has no rescaling optics) and for the size of the pupil on the DM, requests which will be seen to act in opposite directions. The image of the pupil on the DM must have the proper dimensions to cover an 8×8 correction; this means that a given size for the DM imposes the focal length for the first OAP.
By the way there is a winch at the top of the TNG fork that limits the maximum distance from the derotator axis to $r_{max} = 1900mm$. The size of the optical bench which is $d_{ob} = 150mm$ from the axis of the derotator cannot exceed this distance and it is chosen to be $l \times w = 1500mm \times 900mm$. Furthermore the focal planes of the two

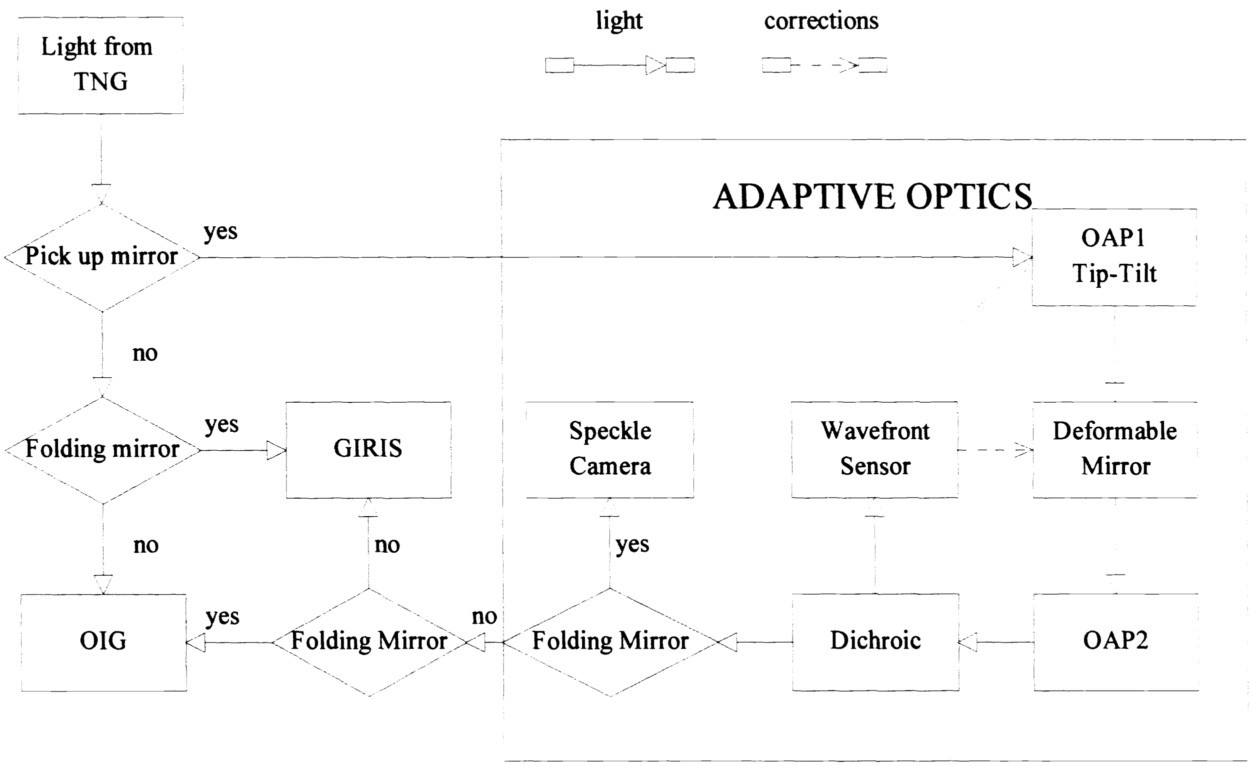

Figure 1: Flowchart of the AdOpt@TNG system

imaging cameras are $c = 300mm$ from the point where the optical train meets again the axis of the derotator. Keeping all these things in mind and allowing enough space for the thickness of the OAP with its mount and movement devices it is easily seen that the focal length of the second OAP cannot be grater than $f_2 \leq 1800mm$. This focal length, at the requested $F/35$, would mean to reimage a very little pupil, $D = 55mm$ in diameter. On the other hand a $D = 60mm$ pupil diameter would need, always at $F/35$, a too long focal length $f_2 = 2100mm$ for the OAP. Hence, the best compromise is to have a lower magnification. Another figure to be derived is the new position of the exit pupil. The infrared camera has a Lyot stop to clean the pupil image and, for this stop to work properly, the position of the pupil EP_p should not change when the adaptive optics system is on. The exit pupil of the TNG is placed $EP_p = 10443.4mm$ before the Nasmyth focal plane and has to be reimaged on the DM by the first OAP. The second OAP then creates a new image of the pupil, which should still be at EP_p before the rescaled focal plane. With the conjugate points law one can easily find the distance b of the DM from the second OAP as a function of the focal length f_2 of the latter: with $f_2 = 1800mm$ the DM is placed at $b = 1490mm$: too far away if one still wants to keep the pupil at a distance EP_p and at the same time the DM and its mechanics on the AO bench. On the other hand the distance a of the DM from the first OAP is directly determined by the f_1 chice. Furthermore, in order to analyse the behaviour of the DM (for example hysteresis in the response of the piezoelectric actuators will act as a source of noise) an autocollimation interfometer will be placed in front of it: thus the light path at its surface must be folded back with an angle wide enough to leave enough space for the interferometer. From Fig.3 one can see the ellipticity of the pupil image on the DM.

The exact position of the DM is specified also by the off axis angle of the first OAP and, on its turn, it sets the off axis angle of the second OAP. To keep the aberrations to a minimum, the ratio between the off axis angles of the two parabolic mirrors should be equal to the ratio between their F/numbers[12]. Notice, however, that in our situation the theory can't be followed. Beside the amount of decentering in the two OAPs there is also to say that the direction of the decentering should be the same (there is a vectorial relation between the two). It will be clear in the following that the direction of decentering for the first OAP is not in the plane of the AO but it

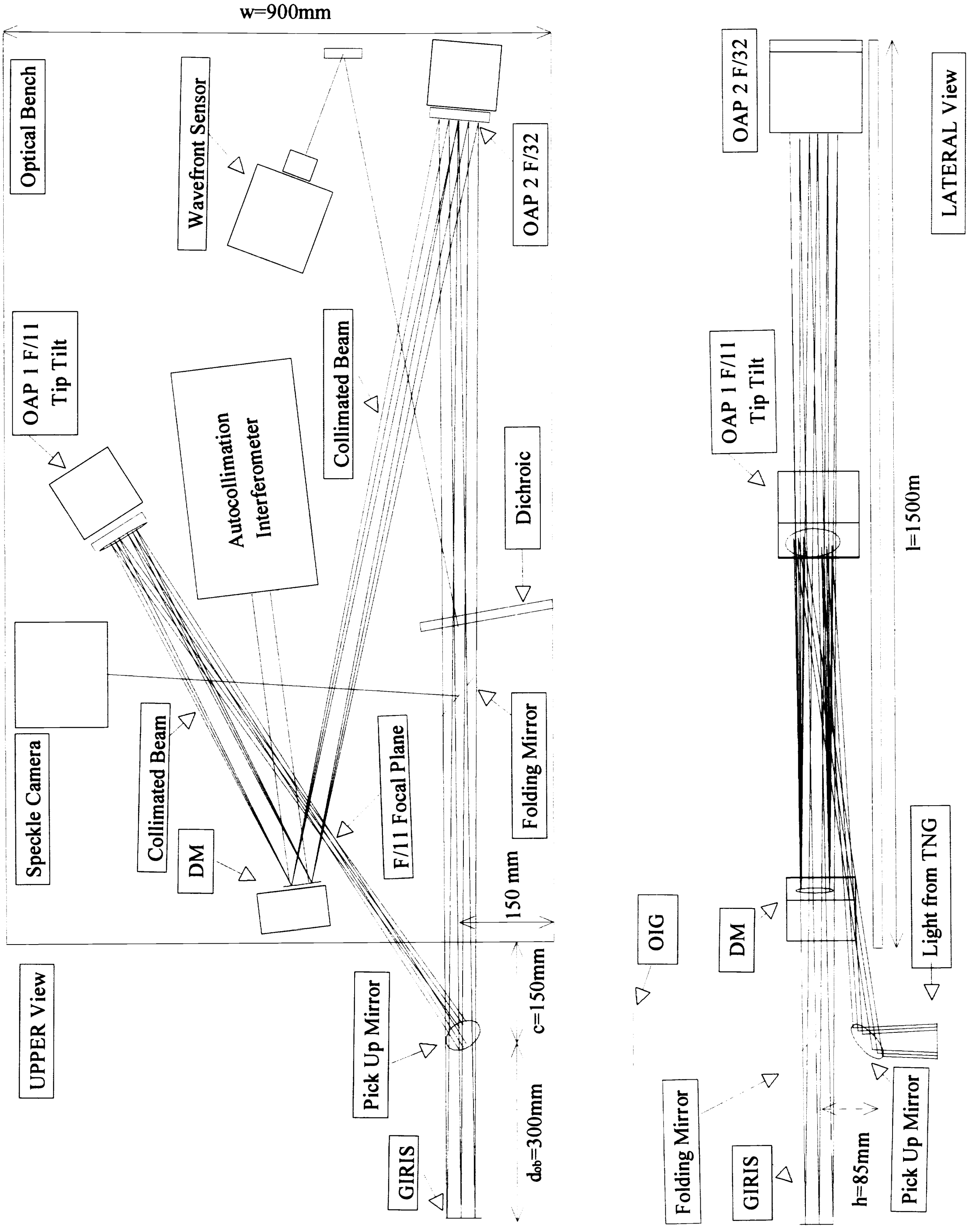

Figure 2: Upper (left) and lateral (right) views of the AdOpt@TNG module

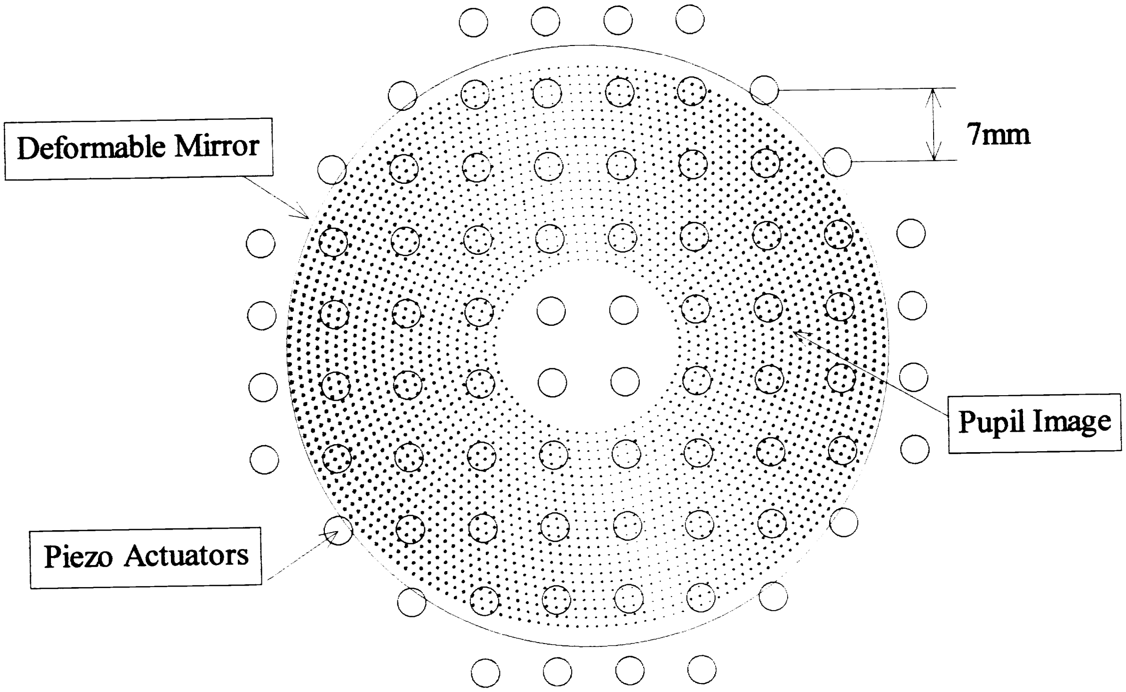

Figure 3: Image of the pupil on the DM. The eccentricity of the shape due to the non orthogonal incidence of the beam is clearly visible. Also the positions of the piezoelectric actuators are shown

points towards below the optical table. To balance the aberrations the second OAP should be decentered in the opposite versus but mechanical constraints forces us to keep the beam parallel to the optical bench: one can also say that this is a direct consequence of the fact that we want to use the same cameras both for $F/11$ and $F/32$. It is clear how, in order to have the lowest number of reflections, fixing one of the parameters inevitabily freezes the others and the whole optical design. The actual optical layout of the adaptive optics module is a harmonious whole of compromises that had to be adopted in order to satisfy the requests and the constraints.

4. TECHNICAL SPECIFICATIONS

Some care has to be paid to the manufacturing costs of the two OAPs. As a matter of fact an OAP cutted from a standard focal length parental mirror is nearly half in price than a custom one. When the off axis angle is too wide, which means a very fast mirror to polish, the OAP is polished from a stand-alone mirror. This is what is actually done for the second OAP. The first OAP is cut out from a standard $f_1 = 600mm$ focal length parental paraboloid. From the value of f_1 one can derive the angle α to fill the gap between the pick up mirror and the

	OAP1	OAP2
Focal Length (mm)	600	1770
OAD to Edge (mm)	45	320
Angle to Center (deg)	8.57	12
SemiDiameter (mm)	45	50
Clear Aperture (mm)	85	95

Table 2: Data for the two Off Axis Parabolae.

adaptive optics bench:

$$\alpha = \arcsin\left(\frac{h}{d_p + f_1}\right) \tag{1}$$

with $\alpha = 4.95^o$. When the light reaches the first OAP it is folded sideways to the DM. As we said before, to allow enough room on the optical table for the mechanics of the mirror and for the movements of a slide in the $F/11$ focal plane the off axis angle is fixed to $\beta = 7^o$. Adding it to the α angle one can see that the whole off axis Angle to Center in the first OAP is $ATC_1 = 8.57^o$, and this angle is defined as the off axis angle from the focus of the paraboloid to the center of the off axis parabolic mirror. The linear decentering is usually expressed as the Off Axis Distance either to the Center or, when the diameter of the mirror is given, to the internal Edge of the parabola, both measured along a perpendicular to the optical axis. Tab.2 summarizes the data for the two OAPs.

With a $f_1 = 600mm$ focal length the pupil diameter will be of $D = 56mm$. The position of the actuators behind the DM is shown in Fig.3, with the image of the pupil superimposed. For the second OAP the $f_2 = 1770mm$ focal length is a compromise between the magnification, the position of the pupil at $a = 634.5mm$ and the length l of the optical bench. With this focal length the resulting F/number is set to $F/31.6$. The definitive position for the DM, and hence its distance b from the second OAP, is a function of the position of the first OAP over the bench, taking into account also that enough room must be left for the speckle camera, the interferometer and the mechanics of both Tip Tilt and Deformable mirrors. As a consequence the angle between the two off axis parabolic mirrors at the pick up mirror, looking from above the plane where all the optics are, is defined to be $\gamma = 34.2^o$. From here we still have three parameters to sort out but one, the angle δ at the DM is a function of the others two, the distance b from the DM to the refocusing OAP and the decentering ATC_2 of this parabola

$$b\cos ATC_2 = (f_2 - c) - (d + f_1)\cos\alpha\cos\gamma + a\cos(\gamma - \beta) \tag{2}$$

$$b\sin ATC_2 = (f_1 + d)\cos\alpha\sin\gamma - a\sin(\gamma - \beta) \tag{3}$$

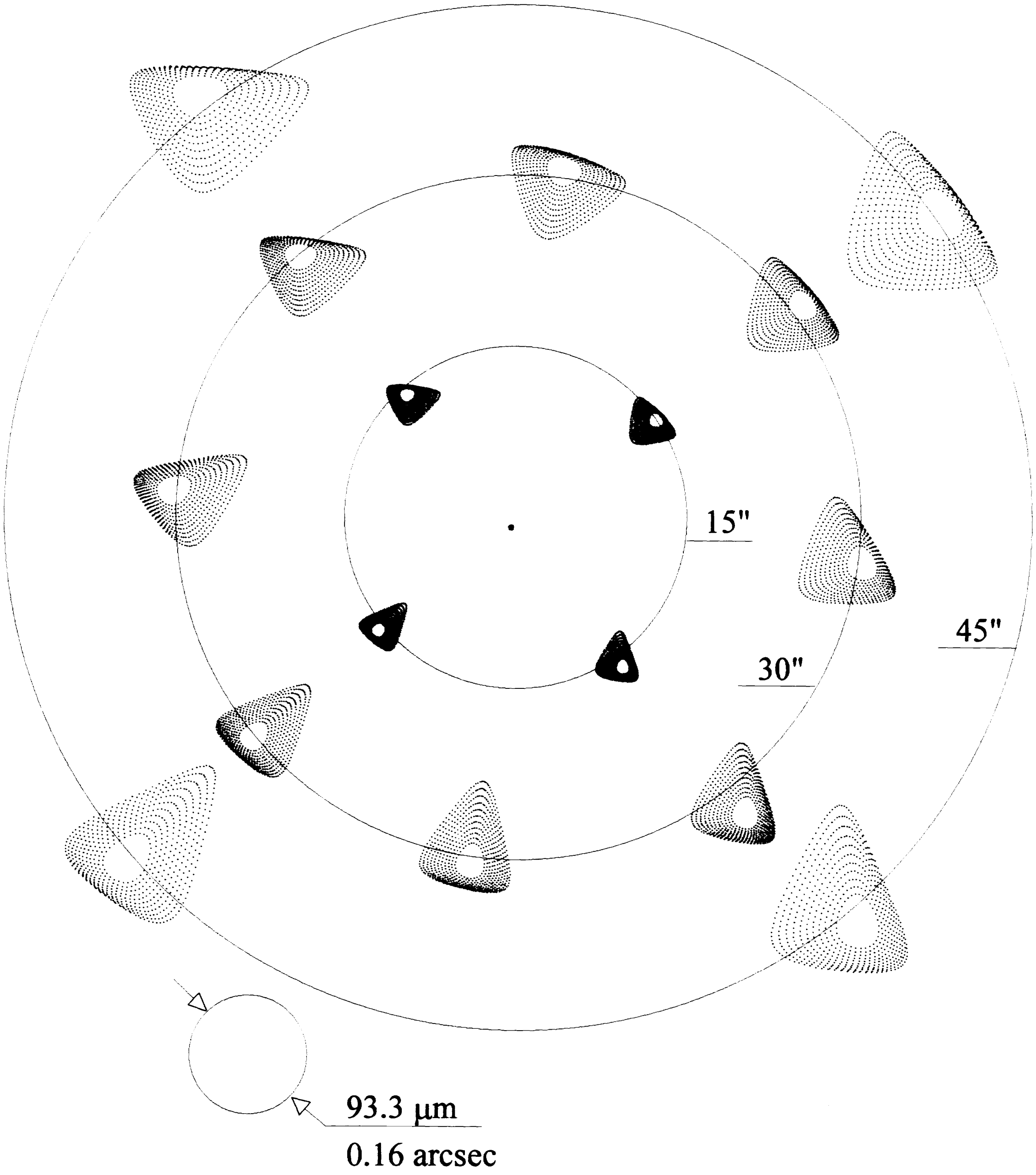

Figure 4: Enlarged Spot Diagram for the F/32 beam. The circle is the Airy disk for $\lambda = 1.2$ microns. One can see that the 1×1 arcmin field is nearly diffraction limited. Spots dimensions and field are not in scale.

From here we find that $ATC_2 = 12.1^o$ and $b = 1250.3mm$: finally the angle at the DM is $\delta = 39.3^o$.

5. ALIGNMENT

Using OAPs the image out of the optical axis degrades steeply if the system is not perfectly aligned. The high accuracy requested for the alignment of the optics forces us to have a versatile system to check regulary the correct position of the optical elements. This system must be permanently mounted in the AO module so to avoid the insertion of other optics or instruments. The alignment of the AO module will start with a rough alignment based on the positions of the mirrors in the optical design. A second step will consider the use of a laser beam and image analysis to increase the accuracy of the alignment. The final tuning of the AO system will then make use of the Shack-Hartmann wavefront sensor in an iterative fashion. This final approach (now under development) will be the one used to check for the correct alignment of the optics on a regular basis. On the slide at the Nasmith focus four illuminated optical fibers will simulate point sources and, with the wavefront sensor, Zernike coefficients of the generated wavefront will be measured. These coefficients will be compared to the theoretical ones, deduced from simulated linear misalignment (tilt and decentering of the two OAPs) in the optical design; a matrix inversion will then give the corrections to get the system optimized.

6. PERFORMANCES

With the insertion of the AO module the scale of the telescope is brought from $scale_{F/11} = 0.19$ mm/arcsec to $scale_{F/32} = 0.55$ mm/arcsec. From Fig.4 one can see that when the system is perfectly aligned in the IR the requested 1×1 arcmin field is diffraction limited and the system is nearly diffraction limited still over a 45 arcsec off axis field. Using a non flat mirror as Tip Tilt let us reduce the number of reflections but it can produce deteriorations in the final image. Fig.5 shows the 1×1 arcmin field for different tilting of the first OAP. The value in the tilt of the Tip Tilt mirror is the maximum tilt available at the first OAP of $\Delta\epsilon = \pm 1.2$ milliradians. This tilt at the rescaled focal plane of the TNG would be seen as a jittering of the image of $\Delta r = 4.3mm$ which, in the sky, is the same as having $\Delta\rho = \pm 7.8$ arcsec. Obviously these are the external bounds of the tilt. To correct 1 arcsec of Tip Tilt only 0.15 milliradians of tilt in the mirror are necessary, so the deteriorations in the final image are greatly reduced as regards to the distortions one can see in Fig.5.

7. CONCLUSION

The optical layout of the AdOpt@TNG system has been presented. Several constraints forced us to reach an arrangement between the different optical components to satisfy the system requirements. In spite of all that we could find a solution which let us minimize the number of reflections, but at the same time to have a diffraction limited system in the Near-IR over a 1×1 arcmin field of view. One can see that using an off-axis parabola as Tip Tilt mirror introduces deteriorations in the image at the $F/32$ focal plane but these deteriorations still let the system to have diffraction limited performances.

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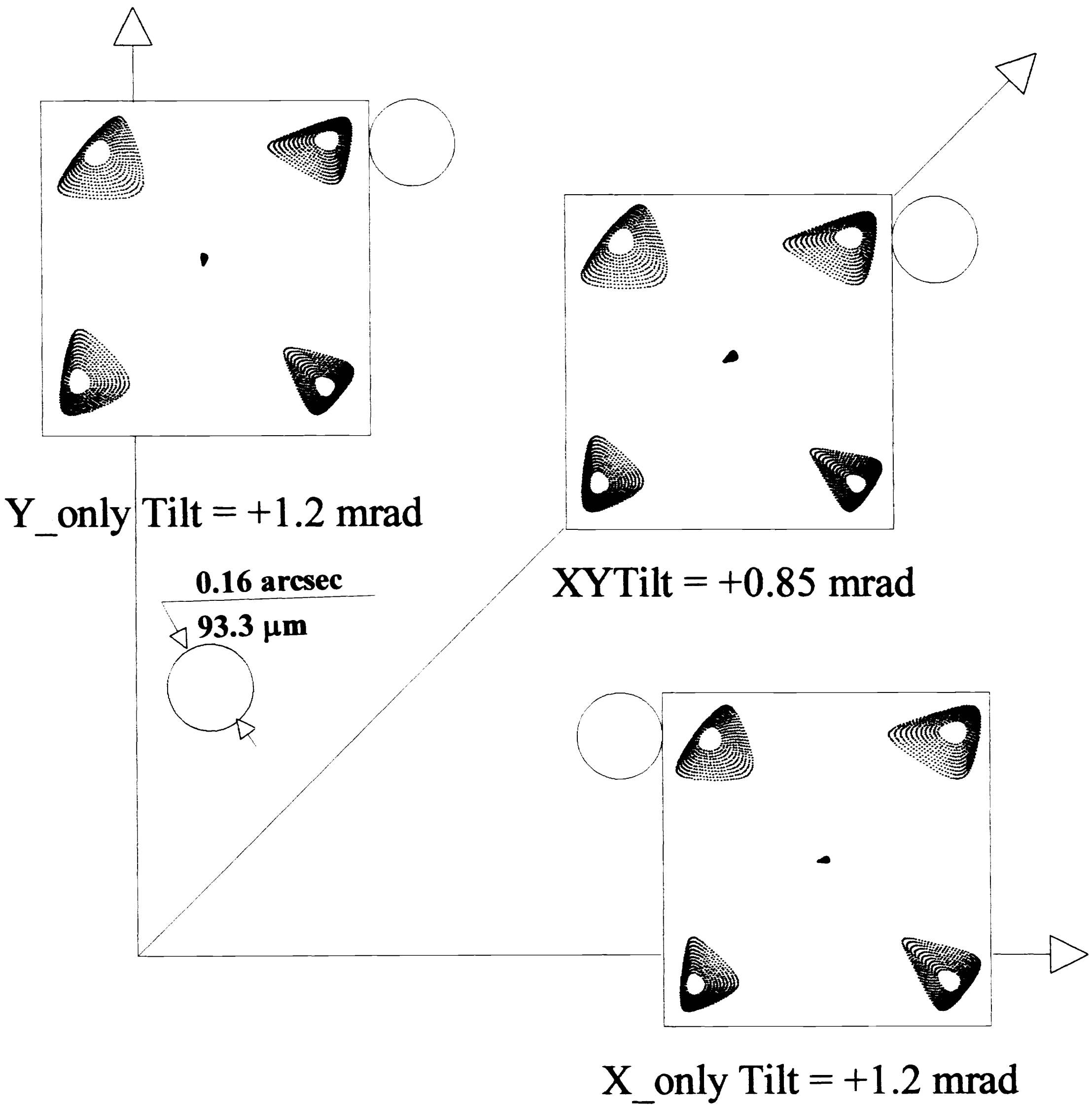

Figure 5: Spot diagram for the tilted OAP. Xtilt is positive tilting the mirror towards below the optical bench; Ytilt is positive rotating the mirror clockwise. Circles are the Airy disks @$\lambda = 1.2$ microns.

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