Optical alignment of the Galileo telescope: results and on-sky test before active optics final tuning

Claudio Pernechele[a], Favio Bortoletto[a,b], Andrea Cavazza[b], Adriano Ghedina[b], Franco Paulli[b] and Roberto Ragazzoni[a]

[a]Osservatorio Astronomico di Padova, vicolo dell'Osservatorio, 5, I-35122 Padova - Italy.
[b]Telescopio Nazionale Galileo, Apartado de Correos, 565, E-38700, Santa Cruz de La Palma - Spain.

ABSTRACT

Optical alignment is a crucial step in the commitment of a telescope. The accuracy in which it is accomplished has a deep impact in the future life of the telescope. The Galileo Telescope, sited in La Palma, is a 3.58 meters telescope with active optics and has recently undergone its final optical alignment. The results of the alignment, obtained in the so-called "passive" mode, that is just before switching-on the active optics system, are here presented. The alignment consisted in the definitions of the mechanical axes of the structure and mirrors supports and of the optical axis of the entire telescope, using three high precision alignment telescopes and their relative targets. The final step has been to take some images on the sky looking at point like objects and to measure the point spread function in terms of full width at half maximum. The first star imaged in our "passive alignment" test on the sky had a FWHM of 0.8 arcsec, well inside the range of the active optics system correction, making it totally usable for the following fine-tuning of the optics.

Key words: Telescopes, Optical Alignment, Telescope Alignment.

1. INTRODUCTION

In this paper the results of the first phase of the Galileo Telescope (TNG) optical alignment are presented. The telescope has an aplanatic Cassegrain configuration with two Nasmyth focal stations. In such a configuration three mirrors should be aligned. The primary mirror (M1) is the entrance pupil, the secondary (M2) furnishes the magnification increasing the focal length, while the tertiary mirror (M3) permits to the optical beam reach one of the two Nasmyth foci. A good alignment of the three mirrors is crucial to accomplish the expected performances. The alignment of the mirrors in a modern active optics telescope consists essentially in three steps: i) mounting of the mirrors support ii) alignment of the mirros using alignment telescopes and iii) fine alignment utilizing a wavefront sensor and active optics. This paper concerns with the first two steps, *i. e.* the so-called passive alignment. The third step is accomplished utilizing a wavefront sensor, usually a curvature sensor exploiting slightly extra- and intra-focal image or a Shack-Hartmann sensor.

2. TELESCOPE CHARACTERISTICS

The Galileo Telescope is a 4 meter class Ritchey-Chretien with an ALT-AZ mount. In Tab. 1 the main optical parameters are shown. These values will be used in section 4, where a calculation of how much the actual optical alignment affects the image at the focal plane.

The passive alignment procedure consists in the two logical step, named i) and ii) in precedent section, even if these will be almost superimposed during the job.

For further information:
Claudio Pernechele - email: pernechele@pd.astro.it
Telephone: +0039-049-8754343, Fax: +0039-049-8754345

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Parameter	Description	Value
D_{M1}	Primary mirror diameter	3500 mm
R_1	Primary mirror radius of curvature	15400 mm
K_1	Primary mirror Conic constant	-1.023818
D_{M2}	Secondary mirror diameter	858 mm
M	Secondary mirror magnification	5
R_2	Secondary mirror radius of curvature	4417 mm
K_2	Secondary mirror conic constant	-2.452659
F	Telescope focal ratio	11
f	Telescope focal length	38500 mm
β	Telescope Back focal distance	0.3767

Tab. 1: Galileo Telescope main nominal optical parameters.

3. ALIGNMENT PROCEDURE

3.1 Conventions and reference system

The following conventions, shown in Fig. 1, are used during the paper. A cartesian system is chosen with the z axis lying on the AZ axis and pointing toward the gravitational direction. The y axis is choose orthogonal to z and point through the geographic north direction. The. The x axis completes the cartesian coordinate system and in a such a way pointing from Nasmyth A focus toward Nasmyth B focus and lying roughly on the EL axis. It should be noted here that the EL and AZ axes are not yet identified: these would be the ideal ones. The angles α and δ, shown in Fig. 1, define the orientation of an arbitrary axis (of versor n) in the reference system. We call *tilt* (δ) the angle between the n and the –z versor with δ defined between 0° and 90°, and *orientation* (α) the angle between the x versor and the projection of the versor n onto the x–y plane, counted counterclockwise as seeing from the –z space and going from 0° to 360°.

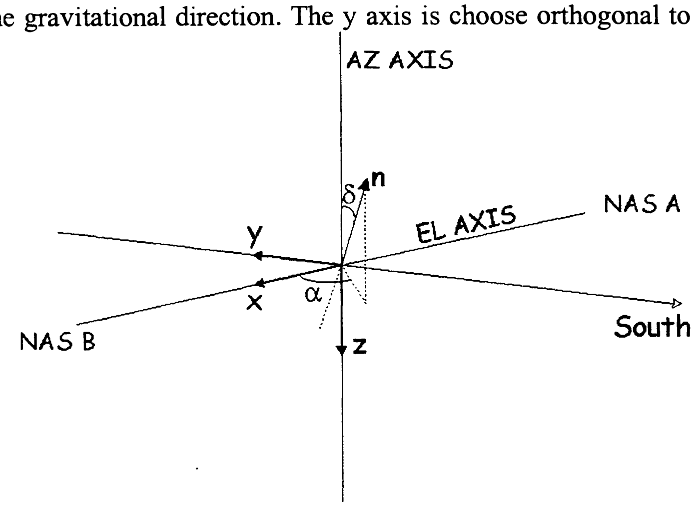

Fig. 1: tilt and orientation convention.

3.2 Identification of the main axes

The identification of most of the mechanical and optical axes was made using two autocollimators, an electronic level and several precision targets (0.2 arcsec precision), all furnished by Taylor & Hobson™ manufacturer. For the determination of mechanical axes the targets have been observed both in the so-called autoreflection and telescopic mode. The autoreflection mode is similar to the classical autocollimation in all but working with a converging beam instead of a collimated one. In such a way the measurements depend upon the telescope to target distance. All the autocollimators have been equipped with CCD cameras (provided by Electrim™), improving a lot the precision of the measurements. A sketch view of the obtained results is shown in Fig. 2, and in the next one there is a brief explanation of the figure. In the figure angles and dimensions are greatly exaggerates because it is used only for display purpose: the EL and AZ axes are really neither orthogonal nor coplanar [1].

3.2.1 Identification of gravitational axis

The alignment procedure started with the identification of the planarity of the hydrostatic bearing with respect to the gravity. This was obtained using the electronic level, whose internal precision is 1.0 arcsec. The level was placed on the central-top of the center pillar and the telescope was rotated in azimuth in steps of 9 degrees, from 0° to about 210° (redundant). In such a way the angle between the vertical and AZ axes come out straightly from the measure. The values of the measured tilt δ and orientation α of the vertical (gravitational) axis, as defined in the past section, was of 3 arcsec and 300° respectively.

3.2.2 Fixing the AZ axis

The azimuth axis was fixed using an autocollimator firmly on the center piece of the telescope tube and a target, about 4 meters apart, posed on the center pillar. The two objects are shown as TelAZ and TAZ in Fig. 3. The verticality of the telescope tube has been obtained making use of the electronic level and taking several measurements in different rectified reference surfaces of the telescope; we expect an error of alignment with the gravitational axis of the order of some tens of *arcsec*. The vision of the target through the center-pillar was disturbed a lot by seeing effect due to the high temperature gradient between the two ambients. The problem has been partially resolved separating the two ambients with a glass plate applied at the rotating-joint central hole. By rotating the telescope in azimuth of about 180 degrees it has been possible to fix the azimuth axis via the target TAZ shown in Fig. 3.

The TAZ target actually materializes the azimuth axis and fixes the z axis of the reference system shown in Fig. 1.

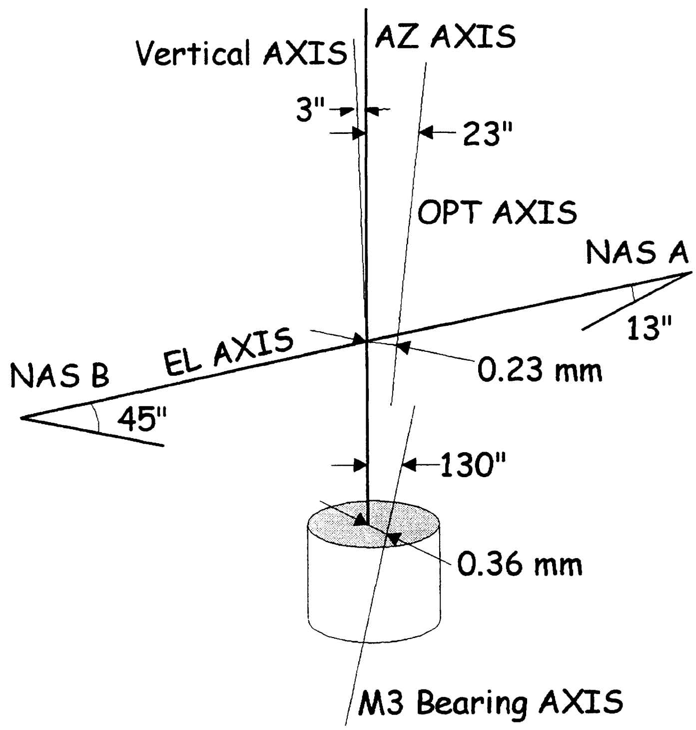

Fig. 2: Plot of the main axes fixed by the alignment. The M1 and M2 mirror are aligned along the OPT axis. The plot is not in scale.

3.2.3 Identification of EL axis

The determination of the elevation axis was performed using two targets fixed into the Nasmyth tube (rotating part) and two telescopes mounted at the two Nasmyth foci. The telescope was rotated from 10° up to 90° in elevation and the target aligned to define the elevation axis; in order to obtain a crosscheck of the measurements, each target has been observed from both the telescopes. In such a way, due to flexions of the telescope fork, two elevation axes have been found, one for each Nasmyth side. At the end a "middle" elevation axis, passing through the centers of the two aligned targets has been chosen to define the EL axis. The x–axis in Fig. 1 has been fixed as this middle elevation axis, except for the non-coplanarity and non-orthogonality. The Nasmyth A and Nasmyth B EL axes have been found to be tilted with respect to this middle EL axis by about 13 and 45 arcsec respectively, with the direction vectors lying on the plane parallel to the x–y plane and containing the middle elevation axis.

3.2.4 Identification of OPT axis

The optical axis has been defined as the one orthogonal to the elevation axis. To do this a pentaprism was placed approximately where the EL axis crosses the AZ axis (see Fig. 3) and the autocollimator in the Nasmyth B has been used to look into the azimuth target in the center pillar (TAZ in Fig. 3). The procedure for the cross-check of the non-co-planarity and non-orthogonality between the EL and AZ axes was based on reference [1]. Unfortunately we found that the alignment based on the pentaprism wedge, following the ESO procedure [1], was very difficult to perform, because the TAZ target, as seen from the NAS-B telescope was barely detectable, due to a number of light dispersion we encountered with commercial target (ESO adopted custom target). The problem has been solved placing a second target defining the azimuth axis close to the bottom face of the pentaprism shown as TM3 in Fig. 3. The TM3 target has been fixed on the M3 bearing. In this way the AZ axis has been redefined as the straight line passing through the centers of the two targets TAZ and TM3, both well visible in telescopic mode from the NAS-B through the pentaprism. The optical axis has then been defined as that one orthogonal to the EL axis, in accord with the ESO/NTT alignment procedure [1]. In such a way we can determine the discrepancy from the OPT axis defined by the pentaprism and the azimuth axis defined by the TAZ target. The resulting non-co-planarity between the AZ and OPT axes has been found to be of 230 μm all along the –y direction on the reference system (see Fig. 1). The tilt δ of the OPT axis has been found to be 23 arcsec with an orientation α of 180°.

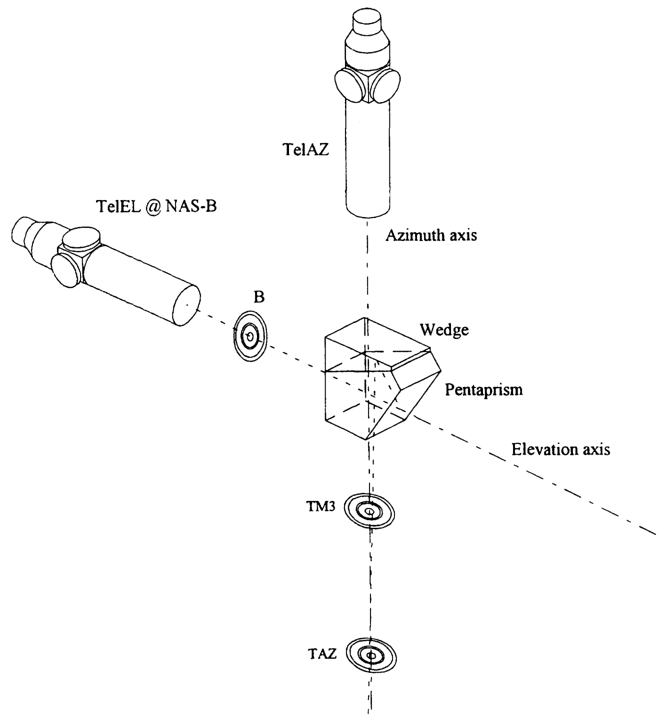

Fig. 3: Fixing AZ and OPT axes.

3.2.5 Identification of M3 bearing axis

The bearing axis of the tertiary mirror has been aligned at this stage. The target placed inside the M3 bearing is visible in Fig. 3 and was the same already used during the identification of the OPT axis (TM3 target). This operations has been preceded by the dismount of the telescope placed on the center-piece (TelAZ in Fig. 3) and posing it inside the center pillar by replacing the target TAZ. The tilt of the M3 bearing has been measured by rotating it around its axis while observing the target TM3. Before this operation the telescope tube has been placed in vertical using the electronic level following the same procedure described in paragraph 3.2.3. The axis of M3 has then been adjusted to be parallel to the AZ one inserting plates of different thickness at the contact points between the barrel of M3 and the spiders and checking the result both with the pillar telescope and with the electronic level placed on the top surface of the M3 bearing. Finally the M3 bearing was fixed in a position with tilt δ nearly 130 arcsec with an orientation α of 90°.

3.2.6 Mount of the mirrors

After the identification of the main axes, the mirrors were mounted at the telescope inside their proper mounts. The primary mirror was mounted and aligned inside its cell. Once mounted the primary mirror cell the alignment with respect to the OPT axis was performed and a final decentering of the cell of 430 μm along a direction of +116° has been measured. The secondary mirror has been aligned along the OPT axis with a decentering of 120 μm along a direction +55° apart from the x–axiz. The M2 optical axis has a tilt of δ=2.5 arcsec and orientation δ=+90°.

The M3 mirror was simply mounted on the bearing, and no adjustment was performed; in such a way a decentering of 160 μm remains with respect to the OPT axis. Some values reported on Fig. 2 and useful for the next discussion on section 4 are shown in Tab. 2. All the values are referred to the convention exposed on paragraph 3.1. Care is necessary in the interpretation of the numbers in Tab. 2 because of their definition with respect to the OPT axis instead of the AZ axis. The decentering is the distance between the center of the mirror sag and the azimuth axis while the orientation of the decentering direction follows the same convention of the parameter α in Fig. 1. The tilt measurements are affected substantially by the environmental seeing (about ±10 arcsec) and by the instrument precision, which depends on the telescope to target distance. The decentering measurements are mainly affected by the instrument precision (also depending on the distance).

Axis	Tilt δ (")	Orientation α (")	Decentering (μm)	Orientation of Decentering (°)
M1	——	——	430	+116
M2	2.5±10	+90	120±310	+55
M3	130±18	+143	160±100	+16

Tab. 2: Some useful results of the main optical axes. The values are with respect to the OPT axis.

4. EFFECTS OF THE ACTUAL ALIGNMENT ON IMAGE QUALITY

The results of the alignment induce two main effects on the focal plane image: a shift with respect to the nominal position and an optical aberration. These effects may be only partially removed in a subsequent active correction of the mirrors. Given the parameters in Tab. 2, the effect of telescope misalignments are summarized in Tab. 3. Most dangerous misalignment concern only with the M1 to M2, having M3 no optical power.

	Effect	
Misalignment	**Blur**	**Shift**
Decentering of 1 μm	0.19 μm or 0.001"	4.0 μm or 0.021"
Tilt of 1 arcsec	1.59 μm or 0.0085"	85.7 μm or 0.46"

Tab. 3: Effect of M1–M2 misalignment.

The misalignment of M3, it does not matter if it is due to tilt or decentering, just produces a displacement of the image on the focal plane. Looking into the M1 and M2 tilt column of Tab. 2, and utilizing Tab. 3, a blur less than 0.1 arcsec is expected due to the M1-M2 tilt misalignment. Considering the M1 and M2 decentering column in Tab. 2, the result is a net decentering value of 385 μm between the two mirrors. With the aim of the Tab. 3 that value implies a blur of the image of 73 μm, or 0.4 arcsec. This is the worst values found in the alignment. Anyway this value may be corrected using active optics, in particular using the hexapod support of the secondary mirror introducing a decentering of M2 in such a way to align it with M1. As far as the shift of the image due to M1-M2 misalignment is concerned, using Tab. 2 and Tab. 3, it is found a value of 8 arcsec due to decentering, and 1 arcsec due to tilt. These shifts will also be corrected aligning the mirrors via active optics. The effect of M3 misalignment is explained through Fig. 4 and Tab. 4. In Fig. 4 a rotation of θ degrees around the major axis of the M3 elliptical surface is shown. n and n' represent, respectively, the mirror normal before and after the rotation. Ri is the versor of the incident ray while Rr and Rr' are the ones of the reflected rays before and after the rotation, making an angle ϕ. Xfp and Yfp represent the coordinate system on the focal plane, where the nominal nasmyth focus is also shown. The generic position of the image after the rotation θ has coordinate ΔXfp and ΔYfp. In Tab. 4 the values of the angle ϕ and the image position in terms of ΔXfp, ΔYfp and ΔZfp (defocus) as function of any kind of M3 rotation are shown. The bearing rotation is done around the Ri versor in Fig. 4, while the minor axis of M3 is coincident with the x axis in the same figure. It may easily be proved that for a small rotation around the major axis, as is our case, $\Delta Yfp \approx 0$ and $\phi = 2^{1/2}\theta$. The piston

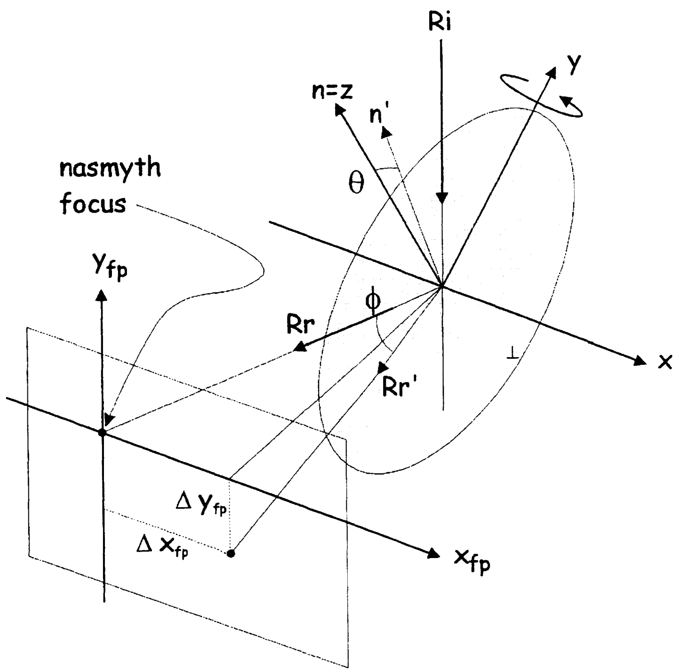

Fig. 4: Effect of M3 movement on the focal plane image. Rotation θ occour around the M3major axis.

displacement happens when a M3 translation along the M3 normal is present. The values of ΔXfp, ΔYfp and ΔZfp are in micron for a rotation θ of 1 arcsec around the correspondent axis and a piston movement of 1 micron. The distance between the mirror center and the nominal position of the image is 4100.6 mm. The total image displacement due both to M3 bearing tilt and decentering is: ΔXfp=1.8 mm, ΔYfp=3.6 μm and ΔZfp=160 μm. The values of ΔXfp and ΔYfp correspond, respectively, to 9 and 19 arcsec on the sky and those values can not be corrected by the M3 active optics. In fact, a system of three piezo-electric actuators allows the rotation around the minor and major axes and the piston movement. The ranges are of about 20 arcsec for the rotations and 40 μm for the piston. Considering the M3 active optics ranges and the described misalignment values it should be noticed the impossibility of correcting the M3 misalignment.

M3 Misalignment	ϕ	ΔX_{fp} (μm)	ΔY_{fp} (μm)	ΔZ_{fp} (μm)
Rot Bearing (θ)	θ	20	0	≈0
Rot minor axis (θ)	2θ	0	40	≈0
Rot mayor axis (θ)	$\approx 2^{1/2}\theta$	28	≈0	≈0
Piston	0	0	1.4142	1.4142

Tab 4: Effect of M3 misalignment. ΔXfp, ΔYfp and ΔZfp are in micrometer for θ of 1 arcsec and piston of 1 micrometer.

This fact should be taken into account at the moment of mounting the instruments in both the Nasmyth stations and when modeling the telescope pointing system.

5. ON-SKY TEST

The final step of the alignment has been a preliminary visual check at the Nasmyth B focal plane looking at the sky on a point-like source. The very first picture was taken during the night of the 9^{th} of June, 1998, and it is here shown in Fig. 5. The object was the ε Lyr 1 binary system in the B band with a 10 s exposure. The separation of the two stars is of 2.6 arcsec and a computation of it using pixel match showed a good agreement with the telescope scale.

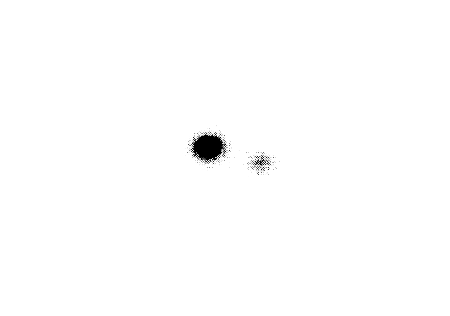

Fig. 5: Picture of the "first light" image. The FWHM of the stars is 0.8 arcsec.

The measured seeing at the time of the exposure was 0.8 arcsec (IAC–DIMM courtesy), also in agreement with the FWHM measured on both the stars. Take into account that M1 and M2 are, at this stage, slightly misaligned, because the active optics was not even switched–on. A residual decentering coma aberration of 0.4 arcsec should be present on the image in Fig. 5. However it should be taken into account as the measurement imprecision, also listed in Tab. 2, are somewhat greater than the measurement and this fact may play a determinant role in foresight calculation of expected aberration.

6. CONCLUSIONS

The passive alignment of the Galileo telescope has been performed and the uncertainties values in the misalignment, as regards the implication on the image quality, are inside the range of the active optics capabilities. The final alignment has been tested pointing the telescope to a binary stars system separated by 2.6 arcsec. A FWHM of the two stars of about 0.8 arcsec has proved the goodness of the passive alignment, as predicted by the uncertainties found during the alignment itself.

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8. REFERENCES

[1] ESO-NTT, Basic Optical Alignment, Final version, August 1988.