Field rotator for the GI2T interferometer

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Abstract. A field rotator dedicated to compensate for the celestial field rotation has been designed and built for the Grand Interféromètre à 2 Télescopes (GI2T) by the Laboratoire d'Astronomie Spatiale (LAS). In each interferometric arm, we introduce a three-reflection optics rotatable around the axis of the optical train. Since the visibility of the interference fringe pattern is mostly sensitive to the differential instrumental polarization, this device must fulfill not only optomechanical requirements but also polarization constraints. For this purpose, three metallic reflections at small incidences are preferred to classical K-prisms (such as Dove or Köenig-Abbe prisms) and coatings optimization leads to protected silver mirrors.
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1 Introduction

The Grand Interféromètre à 2 Télescopes[1] (GI2T) in Southern France is an optical Michelson stellar interferometer that operates in multispeckle mode thanks to its two large 1.5-m apertures. A new beam-combiner[2] REGAIN (REcombinateur pour GrAnd INterférmètre) for this instrument has been under study at the Observatoire de la Côte d'Azur (OCA) and the Laboratoire d'Astronomie Spatiale (LAS) since 1993. This new instrumentation, which is aimed at minimizing the visibility losses of the existing GI2T, ensures among other things beam combination, pupil stabilization, compensation for atmospheric dispersion, fine guiding of images and pupils, and correction for celestial field rotation. The latter compensation is mandatory for two reasons. First, the star images must be exactly superimposed, especially for multiple objects. The second reason is the minimization of the visibility losses induced by the instrumental polarization, and especially by the differential field rotations, leading to the noncoincidence of the electromagnetic fields at the beam-combination level. This coincidence is ensured at the zenith position by means of an adapted beam-combiner, whereas during the observing run, a compensation for the differential field rotations can be achieved by fitting into each interferometric arm an optical device with an odd number of reflections rotating around the optical axis.

In Sec. 2 we review the polarization constraints added to the classical optomechanical constraints of such a device. The field rotator, as built, is described in Sec. 3 and its performance in terms of optics, mechanisms, and coatings are presented and discussed. Finally, we emphasize that such a device can be used within fields other than interferometry, which are generally less constraining in terms of instrumental polarization.

2 Constraints

2.1 *Requirements Due to Instrumental Polarization*

The fringe visibility is most sensitive to the differential celestial field rotations, to the differential phase delays between the *s* and *p* fringe patterns due to oblique reflections, and to the differential transmissions.[3] Therefore the field rotator itself must induce a differential instrumental polarization as small as possible throughout the spectral range of the interferometer. For the GI2T, the instrumental polarization must be optimized for the optical combined focus (0.4 to 2.5 μm), but it also must be known for the future IR focus (i.e., to 10 μm). Thus, the polarization constraints are as follows:

1. As much as possible, there must be coincidence of the *s* and *p* polarization directions at the beamcombiner level, which is ensured by using an adapted rotation law of the device around its optical axis (see the Appendix of Ref. 2).
2. Transmissions in the *s* and *p* polarization directions must be as high as possible, which leads to a field rotator with metallic coatings rather than a total reflection design (such as a Dove or a Koënig-Abbe prism). Moreover in a near future REGAIN will also operate at IR wavelengths, and in this spectral range, dioptric components induce low-transmission coefficients, whereas metallic coatings have very high reflectivities. To optimize the optical throughput we chose a device with only three metallic reflections.
3. Transmissions in the *s* and *p* polarization directions must be as close as possible, but this is not a critical parameter. The visibility attenuation is 0.5% if the ratio between *s* and *p* transmissions remains between 0.82 and 1.22 (Ref. 3).
4. The induced phase delays must be as small as possible. In fact, the different field rotators of the inter-

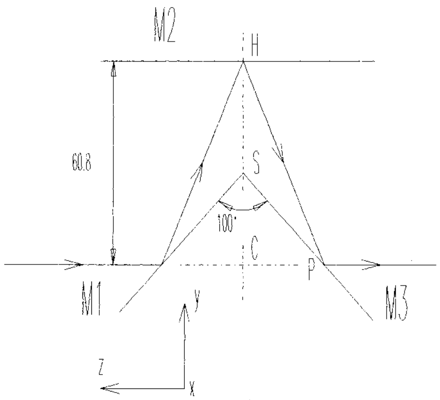

Fig. 1 Schematic of the field rotator (FR). The reference axes of the set (M1, M2, M3) are defined as follows: *X* is parallel to the edge of the prism (M1, M3), *Y* is perpendicular to mirror M2, and *Z* is perpendicular to the *X* and *Y* axes and should be parallel to the real rotation axis and to the principal ray.

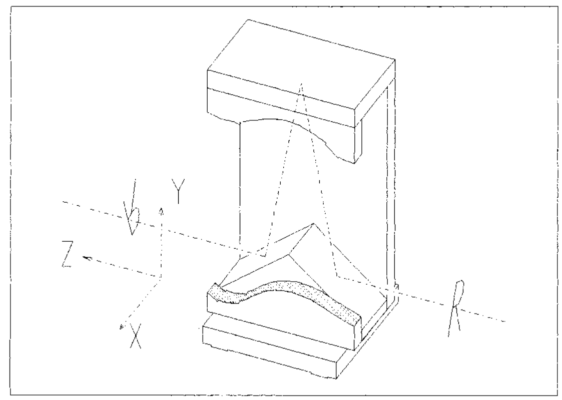

Fig. 2 Optical design of the FR including a reflective prism and a flat mirror.

ferometer follow different rotation laws, and therefore lead to different phase delays between the *s* and *p* polarization directions.[4] These differential phase delays must be minimized to avoid significant visibility attenuations (attenuations of 5% for a mere differential phase delay of 36° and of 10% for a mere differential phase delay of 52°; Ref. 3).

5. Smooth variations of the phase delay throughout the spectral range of 0.4 to 2.5 μm are required.

The requirements 4 and 5 are fulfilled by keeping incidences as small as possible (50° on M1 and M3, close to the 45° limit, and 10° on M2) (Fig. 1), and above all, by optimizing the coatings (see Sec. 3.3). Note that the polarization induced by the flat mirror M2 is negligible because of the incidence of 10° (Ref. 4).

2.2 *Optomechanical Requirements*

A preliminary analysis of adjustment error compensations shows that a misadjustment of any component can be compensated by tilting and/or translating either the set (M1, M2, M3) or the whole field rotator (FR), except the parallelism error of mirror M2 with respect to the virtual intersection of M1 and M3. Assuming a small size for mirrors M1 and M3 (28×16 mm), we consider an optical system in which mirror M3 is integral with mirror M1, hence the optical assembly is virtually composed of a mirror and a reflective prism (Fig. 2). As shown in Table 1, the rotation R_z of M2 [i.e., the parallelism of this mirror with respect to the edge of the prism (M1, M3)] has a sensitivity of 2 on the outcoming beam. Since the specification on the latter error is 30″ and because of the tolerance sharing among the three adjustment stages, this error cannot be given a tolerance greater than 5″, which is about 0.4 μm at the rim of mirror M2. Thus, before implementing the FR in the optical system, the following three steps must be carried out: (1) adjust mirror M2 with respect to the prism, which constitutes the optical set (OS); (2) cause the real rotation axis (RRA) to be the optical axis of the OS; and (3) adjust the FR inside the interferometer.

Despite this compensation capability, an analysis of the sensitivity table for the OS (Table 2) shows that the correct functioning of the FR requires the principal ray to be parallel to the RRA of the turret, holding the OS, and to pass through one of the real rotation centers (RRCs). When the OS is well fitted, the output beam remains steady (neither conic deviation nor eccentricity) during rotation of the FR. Due to possible out-of-run and roundness defaults, the RRA may differ from that intended. In the case of the out-of-run default, the RRA exists. In the case of the roundness default, the RRA does not exist. The latter default induces a residual and variable conicity default for the output beam.

3 Field Rotator as Built

3.1 *Optics*

Because the required accuracy level (see Sec. 2.2) is not easily reachable with a classical optomechanical design, an all-glass design made by optical techniques was considered.

Table 1 Sensitivity of M2 with respect to the prism (M1, M3).

Translation of M2	Translation of the Exiting Beam		
	T_x	T_y	T_z
T_x	0	0	0
T_y	0	−0.35	0
T_z	0	0	0

Rotation of M2 about *H*	Translational of *P* (mm deg^{-1})		Rotation of the Exiting Beam	
	T_x	T_y	R_x	R_y
R_x	0	−2.25	−2	0
R_y	0	0	0	0
R_z	−2.12	0	0	1.97

P and *H* are defined in Fig. 1.

Table 2 Sensitivity of the set (M1, M2, M3).

Translation of the Set	Translation of the Exiting Beam T_x	T_y
T_x	0	0
T_y	0	2

Rotation of the Set About C	Translation of P (mm deg^{-1}) T_x	T_y	Rotation of the Exiting Beam R_x	R_y
R_x	0	1.93	2	0
R_y	1.97	0	0	0

P and *H* are defined in Fig. 1.

Mirror M2 is held by a pair of glass plates bonded to the sides of the prism (Fig. 3). To ensure the stability of this assembly with time, the components are fastened together by optical contact. Both optical manufacturing and assembling were carried out by Stigma-Optique, which made three optical sets with the following performance: the wavefront error (WFE) on the exiting beam is lower than λ/12 and the residual slope of the exiting beam (due to a parallelism error of mirror M2 with respect to the edge of the prism) is lower than 8″ (see the measurement principle in Fig. 4).

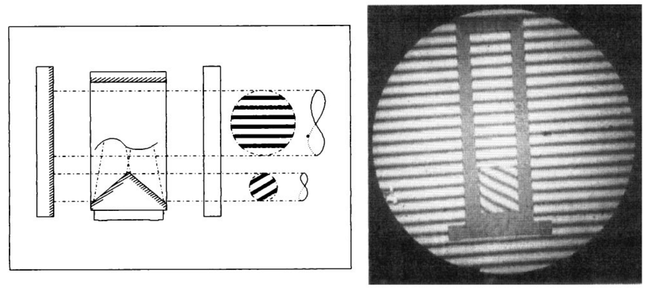

Fig. 4 Interferometric verification of the parallelism of mirror M2 with respect to the edge of the prism. A pattern of straight fringes is produced by the reflection of a collimated laser source on two plane test plates, slightly tilted about X (reference beam). As the FR is inserted between the plates (measurement beam), it deviates the fringes in the beam zone, which goes through it. Since the sensitivity of this deviation with respect to the prism edge is 1.97, and since the beam goes through the field rotator twice, the measurement of the fringe deviation in Y gives the angle of mirror M2 with respect to the prism edge as follows: $\alpha=\tan^{-1}[\lambda(\delta Y/D)]/3.94$, where δY is the fringe deviation in Y, $D=16$ mm is the prism width, and $\lambda=0.6328$ μm. The angular errors for the three built samples are less than 4″.

3.2 *Adjustment of the OS in the Turret*

A pitch plate holds the OS and, using spring washers, it is pressed again three sets of nuts and swiveling washers. The nuts are screwed onto three bolts attached to the yaw plate. The latter is fixed to the turret and can be adjusted along R_y while the pitch plate allows adjustments along Y, R_x, and R_y.

Rotating the turret enables us to materialize the RRA by means of two reticles (no out-of-run default) and an adjustable flat mirror (any reflected beam remains steady). In the alignment process, we use a reference beam, which is collimated and adjusted to be perpendicular to the flat mirror. Due to the nondecoupling between the degrees of freedom, the adjustment process is iterative. In the first step, we must minimize the deviation of the output beam by the differential rotation of the three nuts. Then looking in the exact direction of the reference beam, we must superpose the image of the entrance reticle with the output reticle by translating the OS along X and Y.

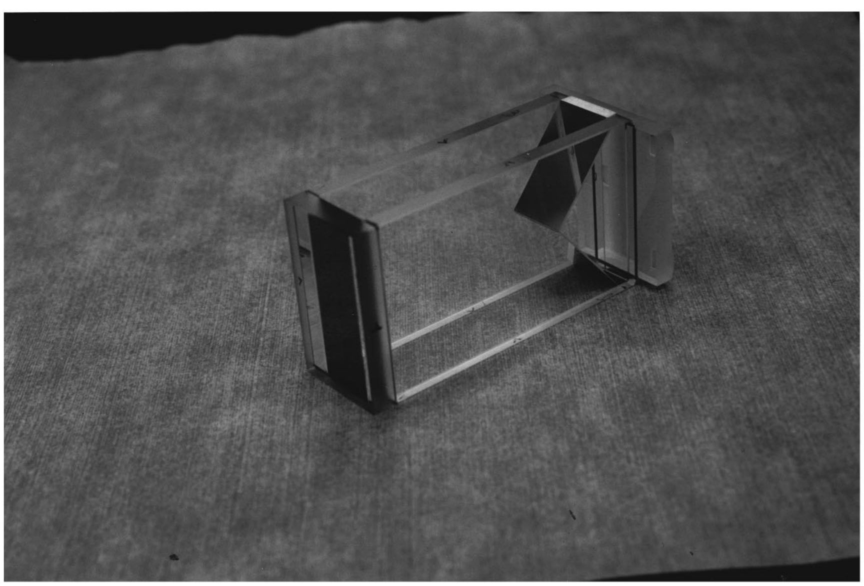

Fig. 3 Photograph of the FR studied at LAS. Optical manufacturing and assembling were carried out by Stigma-Optique. Tofico realized the coatings.

Table 3 Measured phase delays Φ_m between the *s* and *p* polarization directions for a coated silver mirror (Tofico), a "Silflex" coated mirror (Balzers), and an aluminum mirror coated with ZnSe (OCA, Nice, France). Measurements are made at an incidence of 50° for three wavelengths (0.475, 0.540, and 0.650 μm).

	Wavelength (μm)	Silver Coating (Tofico)	Silver Coating (Balzers)	Aluminum +ZnSe (OCA)
Φ_m (°)	0.475	8.05±0.6	−4.4±0.3	5.6±0.2
	0.540	20.74±0.05	−12.1±0.3	22.3±0.3
	0.650	24.3 ±0.1	−26.2±0.3	42.3±0.3

3.3 *Mounting into the Optical System*

The REGAIN reference ray, used to adjust the FR, must have a reference reticle centered on it. The adjustment of the FR on the optical bench consists of tilting it to avoid any deviation of the output ray from the direction of the reference ray, and then using translations to avoid any displacement of the image of the reference reticle when the FR rotates.

3.4 *Coatings*

Various coatings have been measured at 50° using a polarimeter built[3] at LAS: a coated silver mirror (Tofico), a "Silflex" coated mirror (Balzers), and an aluminum mirror coated with ZnSe (OCA, Nice, France). The smallest phase delays are obtained for coated silver mirrors (Table 3). As expected, multilayer coatings are not appropriate for our purpose since the introduced phase delay is large and can describe all the angles between 0° and 360° throughout a large spectral range.[5] The ratios of the reflection coefficients are given in Table 4 for coated silver mirrors.

Tofico achieved the coatings for the FRs. By measuring the evaporation samples we obtained the polarization characteristics of the three identical FRs (Table 5). By modeling the visibility function of a stellar interferometer in polarized light,[3] we obtained the responses of the GI2T with and without REGAIN versus hour angle for two declinations (Figs. 5 and 6). Without FRs, for a declination of 20°, observations become troublesome 1 h after the meridian transit ($H=15°$) since the visibility attenuations then attain 15%. For a declination of 70°, the resulting attenuations are less but remain critical since they equal 10% 2 h after the meridian transit. When the differential field rotations are compensated by FRs, the visibility attenuations are greatly reduced and whatever the declination, they do not exceed 9% 4 h after the meridian transit. Adding FRs inside the focal instrumentation of the GI2T interferometer enables us to increase the observation time by more than 3 h. Thus earth-rotation synthesis will become possible,[6] which will constitute a strong means of investigation for astrophysicists.

Table 4 Measured ratios R_p/R_s of the reflection coefficients for a coated silver mirror (Tofico) and a "Silflex" coated mirror (Balzers). Measurements are made at an incidence of 50° for three wavelengths (0.475, 0.540, and 0.650 μm).

	Wavelength (μm)	Silver Coating (Tofico)	Silver Coating (Balzers)
R_p/R_s	0.475	1.02±0.01	0.95±0.01
	0.540	0.99±0.01	1.00±0.01
	0.650	0.96±0.01	1.00±0.01

Table 5 Measured reflection coefficients R_s and R_p and phase delay Φ_m between the *s* and *p* directions for the FRs as built at 0.475, 0.540, and 0.650 μm.

Wavelength (μm)	R_s	R_p	Φ_m (deg)
0.475	0.887±0.009	0.92 ±0.01	−2.2±0.2
0.540	0.93 ±0.01	0.910±0.009	23.4±0.3
0.650	0.98 ±0.01	0.903±0.009	45.4±0.2

3.5 *Performances of the FRs*

Two FRs were built and adjusted in accordance with the previous procedure. The maximum allowable errors after mounting on the REGAIN optical bench are a conical deviation of ±30″ (60″ peak to peak) and a beam offset of ±0.1 mm (0.2 mm peak to peak). After adjustment in laboratory (see Sec. 3.2) the defaults are ±8″ and ±0.013 mm for FR 1 and ±10″ and ±0.02 mm for FR 2. After integration in the REGAIN optical train (see Sec. 3.3) the beam offsets are less than ±0.1 mm and the conical deviations do not exceed ±25″.

4 Conclusion

We have designed and built a FR to compensate for the differential field rotations induced by the telescopes of the GI2T interferometer. To minimize the visibility attenuations due to instrumental polarization, we have chosen an optics with three protected silver coated mirrors. To fulfill the movement accuracies, the optics has been realized by

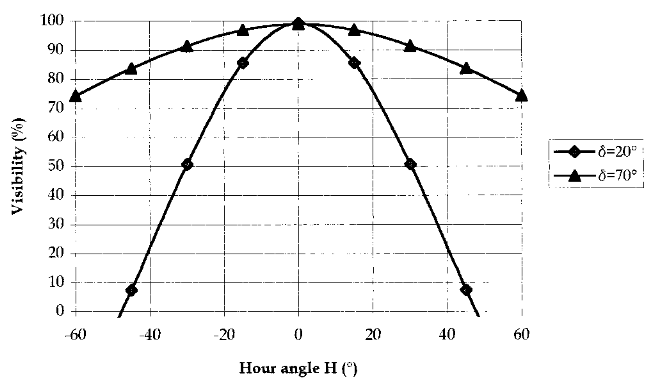

Fig. 5 Expected visibility of the GI2T interferometer without FRs versus hour angle for two declinations (20 and 70°). The visibility is calculated for the latitude of the Plateau de Calern (43°45′) and for a wavelength of 0.650 μm. It is expressed as a percentage of the coherence degree of the source.

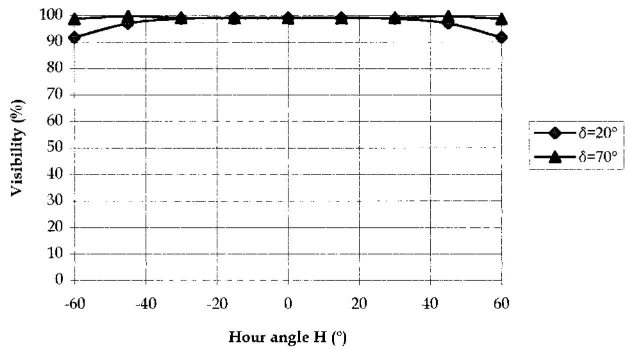

Fig. 6 Expected visibility of the GI2T interferometer with FRs versus hour angle at 0.650 μm for declinations (20 and 70°). The visibility is calculated for the latitude of the Plateau de Calern (43°45′) and for a wavelength of 0.650 μm. It is expressed as a percentage of the coherence degree of the source.

optical contact. When such a device is introduced into each interferometric arm, the potential of the GI2T is greatly improved: the attenuation bias is significantly reduced, and above all, the observation run can last 4 h before and after the meridian transit, which makes possible earth-rotation synthesis. Our FR has been optimized for the GI2T interferometer, but note that such a device can be used for other stellar interferometers or optical aperture synthesis arrays and more generally for others scientific applications.

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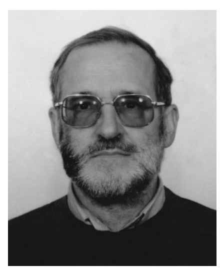
Karine Rousselet-Perraut received her PhD degree in optics from the University of Marseille, France, in May 1996. She graduated from the Physics School of Marseille in 1993. She was the scientist in charge of the REGAIN project at the Laboratoire d'Astronomie Spatiale, Marseille. She has been in charge of the Integrated Optics Near Infrared Interferometric Combiner (IONIC) at the Observatoire de Grenoble since October 1997. Her research areas include optical aberrations, optical long baseline interferometry, polarimetry, and high resolution angular observations. She is a member of the French Society of Optics (SFO).

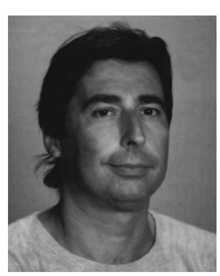
Lucien Hill is a graduate of the Ecole Nationale Superieure de Physique de Marseille. He was with Laboratoire d'Astronomie Spatiale from 1972 to early 1997 and was in charge of some optical systems developed by this institute, such as the recent LASCO coronograph of the ESA's SOHO mission. In the past, he also collaborated on both improvement and adaptation of specific software modules aimed at modeling various optical systems. In the frame of the REGAIN interferometric project, he contributed to the development of some optical subsystems. Now, with Observatoire de Haute-Provence, he collaborates on the development of the VIRMOS focal instrument to be mounted on the ESO's Very Large Telescope.

Gabrielle Lasselin-Waultier received her degrees in physics from Marseille University in 1967 and 1968. She specializes in optic instrumentation. She contributed to the definitions, integrations, and alignments of several international spatial instruments such as LASCO-SOHO and she is now participating in the development of telescopes such as the Very Large Telescope.



Jean-Lucien Boit received his engineering degree in mechanics in 1965 from Ecole Nationale d'Electricite et de Mecanique, Nancy, France. He has been responsible for the mechanical team involved in many space projects such as the UV imaging telescope FAUST (French rocket and Spacelab 1), the UV spectrometer UFT on a Soviet satellite, the UV Very Wide Field Camera (Spacelab 1), the infrared Long Wavelength Spectrometer on the ISO satellite, the solar coronograph LASCO and the far UV imager EIT on the SOHO satellite. He participated in some ground projects, such as the solar power plant PERICLES and the improvement of the two large telescope interferometers GI2T (the REGAIN project).

Gerard Rousset has been working at LAS since 1970. Involved in several spatial experiments, he was responsible for the mechanical design of the Very Wide Field Camera on the Spacelab 1 mission. He was the product assurance manager at LAS for the LASCO C2 coronograph of the ESA SOHO program. He is now deputy project manager for the OSIRIS-NAC telescope of the ESA ROSETTA mission.



Jean-Claude Blanc was first employed with SOPEMEA and ONERA. In 1978 he joined the LAS. He had been part of the mechanical team in charge of many instruments used in space projects, such as VWFC, LWS, LASCO, and the Swedish satellite Odin. He is now involved in the camera OSIRIS (for the ESA satellite ROSETTA).

Gabriel Moreaux has been with LAS since 1968. He was responsible for optical components. He is presently in charge of the optical metrology laboratory where he performs interferometric and

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J. M. Corneloup: Biography and photograph not available.

S. List: Biography and photograph not available.

Clotaire Voët worked as a mechanical engineer from 1965 to 1990 on several space astronomical instruments. He has worked as a quality assurance manager since 1990. He was the project manager at LAS for REGAIN.