SPICA, a new 6T visible beam combiner for CHARA: science, design and interfaces

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Abstract. We present the recent developments preparing the construction of a new visible 6T beam combiner for the CHARA Array, called SPICA. This instrument is designed to achieve a large survey of stellar parameters and to image surface of stars. We first detail the science justification and the general idea governing the establishment of the sample of stars and the main guidance for the optimization of the observations. After a description of the concept of the instrument, we focus our attention on the first important aspect: optimizing and stabilizing the injection of light into single mode fibers in the visible under partial adaptive optics correction. Then we present the main requirements and the preliminary design of a 6T-ABCD integrated optics phase sensor in the H-band to achieve long exposures and reach fainter magnitudes in the visible.

Keywords: visible interferometry, single mode fiber, adaptive optics, stellar parameters.

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1 Introduction

The reawakening of optical interferometry in the seventies[1] started at visible wavelengths on small apertures but, with the imperative need of going towards fainter magnitudes, the developments towards large telescopes for interferometry have taken a large priority. Although the principles of interferometry with large apertures in the visible were solidly established,[2,3] the advent of adaptive optics (AO hereafter) in the middle of the eighties opened the way for the use of the largest telescopes in construction (8 m for the VLT, 10 m for the Keck) in an interferometric mode. However, the great successes of adaptive optics for direct imaging on single telescopes opened at the same time huge expectations with the access, on ground, to the actual diffraction limit of the telescopes. Therefore adaptive optics for telescopes used in an interferometric mode were not so developed and, during a long period, large telescopes with tip/tilt correction only in the infrared were mainly used for interferometry. It is only very recently[4,5] that developing specific adaptive optics for interferometers was decided. During that time, visible interferometry continued to be developed because of the fantastic spatial resolution it permits. But the intrinsic limitations due to the atmospheric turbulence did not allow to completely use the largest aperture, except for improving the signal to noise ratio on bright stars and authorizing high spectral resolution at the same time.[6,7]

With aperture size of the order of 2 or 3 times the coherence size of the atmosphere, instruments using single mode optical fibers[8,9] have demonstrated the potential of spatial filtering for improving the accuracy and precision of the interferometric measurements. More recently, GRAVITY[10] demonstrated how coupling adaptive optics, spatial filtering, and low-noise detectors make the fundamental limits of optical interferometry at infrared wavelengths reachable. Combining all these advances (spatial filtering, adaptive optics, large telescope) appears to be a mandatory condition for doing, with the current visible interferometers, the most demanding scientific programs requiring the highest angular resolution and sensitivity. For that purpose we have developed a prototype of a visible fibered instrument: FRIEND on the CHARA Array[11,12] taking benefit of the recent program for equipping the 1 m telescope of the CHARA Array with adaptive optics.[5,13] This prototype is a pathfinder for a much more ambitious instrument, SPICA (Stellar Parameters and Images with a Cophased Array), a 6T visible fibered beam combiner for the CHARA Array.[14]

2 Scientific rationale of SPICA

2.1 Current status of fundamental stellar parameters by optical interferometry

The current version of the JMMC Measured Stellar Diameters Catalogue (JMDC[15]) gathers 1 478 measurements of angular diameters that have been published since the first experiments by Michelson, and is based on optical interferometry, intensity interferometry and lunar occultation technics. Only 11% (resp. 22%) of the stars of this catalogue have their angular diameter measured with a relative precision better than 1% (resp. 2%). It corresponds to 159 and 323 measurements respectively. With SPICA on CHARA ($\delta > -30$ deg, $\theta_{lim} \simeq 0.2$ mas, and $V < 7$), 7 786 stars can potentially have their angular diameter measured with a precision better than 1%, thanks to the principle of spatial filtering with single mode fibers. We estimate that 3 years with 70 nights per year dedicated to this survey program would be necessary to measure the angular diameter of 800 stars with a 1% precision (or better), and obtain images for 200 stars. Why is this important? Interferometry is already used to constrain Surface Brightness Color Relations (SBCR) or Differential Surface Brightness (DSB), with for instance, the JMMC Stellar Diameter Catalog (JSDC[16,17]), which provides estimated angular diameters for about 453 000 stars, with median statistical error of 1.1%. The difficulty comes actually from systematics. We can identify 23 SBCR in literature.[18] If these relations are used (taking into account their V-K domain of validity) in order to derive the angular diameter of a hypothetic star with a magnitude V of 6, then the relative dispersion of the 23 derived angular diameters ranges from 2% for V-K=3, to 9% for early-type stars (V-K=0) or late-type stars (V-K=5). It basically means that we have inconsistencies in the literature of *at least* 2% between the various SBCR relations. These relations are yet extremely useful to estimate the angular diameter of the reference stars combined in many cases with a careful analysis of the spectral energy distribution (SED) to identify possible systematic effects.

These inconsistencies in the SBCR have various origins. First, the 1 478 measurements done so far are very heterogeneous in terms of technique, facility, and wavelength. Moreover, in order to derive a SCBR, one needs precise and homogeneous photometry (at least in two photometric bands), as well as a careful estimation of the extinction, which is not always easy. But the most critical aspect is probably that the 23 mentioned papers use actually their own datasets ranging from 18 to 239 stars, selected in the general catalogue of the 1 478 measurements. Another limit is that the SBCR is based on the hypothesis of perfect black bodies, which is a strong hypothesis generally not verified because of rotation, wind, environment, granulation, and also contamination due to binarity.

2.2 *The need for improved accuracy and consistency*

With SPICA, we aim to explore the fundamental properties of stars and improve our knowledge of these SBCR. This will be possible by having a global and homogeneous approach for the 800 stars, deriving their SED, checking for infrared excess (wind/environment) and/or binarity, as well as their rotation. The impact of rotation on the SBCR has already been studied in detail.[19–21] TO go further in the improvement of the SBCR, a 1% accuracy on the angular diameter is necessary for three reasons.

First, if one knows the ratio $\frac{R_\mathrm{p}}{R_\star}$ from a transiting planet from CoRoT,[22] Kepler,[23] K2,[24] TESS[25] or PLATO[26] space missions, and besides the stellar radius $R_\star$ derived from the combination of the SPICA interferometric angular diameters and the *Gaia* parallaxes, then it becomes possible to derive the radius of the planet (R_p). Separately, velocimetry provides the mass, and one can finally derive the density of the planet, its position in the habitable zone of the parent-star, and if the planet is suitable for life or not. Precise determinations of radii, masses and ages of exoplanets have been already demonstrated[27–29] but on a very small number of targets. With SPICA, our objectives are: 1) to provide direct interferometric measurements of bright stars ($V < 7$) hosting exoplanet in transit (a large number of such ones will be discovered with PLATO), 2) to provide robust SBCR, accurate at 1% in order to derive the angular diameter of *all stars (even faint)* hosting exoplanet in transit, and (3) even if the planet is not in transit, to provide accurate determination of the radius of the star as demonstrated by Ligi et al.[29] We have already identified ≈180 stars (hosting planet but without transit) according to the expected performance of SPICA, with a good repartition in spectral types (from B to M, see exoplanet.eu). The main goal for the next decade in exoplanet science is also to constrain atmospheric properties of planets, and for this, the stellar limb-darkening is of crucial importance.[30] With SPICA we aim also at measuring the limb-darkening on many stars in the visible domain.

Second, the knowledge of stellar properties (R, T_eff, M, age) is fundamental in many areas of astronomy, and more recently, thanks to the detection of oscillation in thousands of stars with WIRE,[31] MOST,[32] CoRoT,[22] and Kepler,[23] there has been a revival of stellar physics. Basic stellar physics relationships link the radius and the effective temperature to the angular diameter, and using evolution models, these quantities help to constrain mass and age. Between the angular diameter and the radius, the role of an accurate distance is central and the Data Releases of *Gaia* are already playing a crucial role. If we know the radius independently with interferometry, then we can decouple the asteroseismology mass-radius relation and determine the mass and other relevant parameters governing stellar evolution with even higher precision and more accuracy. The potential and the formalism of coupling asteroseismology and interferometry have been studied in detail.[33,34] It shows that reaching 1% accuracy on stellar radius with direct methods such as optical interferometry will permit to bring strong constraints on the stellar atmospheric and internal structure models of stars. There will be a large number of asteroseismic targets for SPICA in the future, but we already identified 400 stars accessible to SPICA among the TESS input catalogue.

Third, the SBCR are currently used to derive the distance of eclipsing binaries. Deriving distance from eclipsing binaries is simple: the radii of both components is estimated from photometry and spectroscopy, while the angular diameter estimates are calculated from the magnitude and color of stars through a SBCR. The combination of radii (in km) and angular diameters (in millisecond of arc) provides the distance. An estimation of the distance to the LMC, based on the 8 late-type eclipsing binaries,[35] achieved an unprecedented precision of 2.2%. This error is entirely due to the precision of the SBCR (applied for a V-K around 3), i.e. about 2% or 0.04 magnitude using the relation by Di Benedetto.[36] The aim is to improve this result and to reach a 1% precision or below. Besides, one would like to derive the distance of other distant galaxies like M31 or M33 hosting early-type eclipsing binaries, but unfortunately, the precision on the SCBR for early-type stars is too poor, around 8% as already mentioned. Deriving the distance of these galaxies with a 1% precision with the SBCR provided by SPICA would bring two new anchors for the determination of the Hubble constant. It is worth mentioning that the distance considered by the SHOES project,[37] i.e. 4.4% for M31[38] is currently not based on SBCR but is model-dependent.

2.3 *Feasibility of an ambitious large survey*

To achieve such a large survey program and improve the precision of the measurements to reach the 1% level, we need to be able to obtain more than 4 000 individual observations over 200 nights spread over 3 years and including multiple observations for binaries or imaging. Optimizing the strategy of observations (in terms of declination and right ascension) is thus clearly mandatory and this is the first level of optimization to which we can think in order to save slewing time and reduce as much as possible the time for fringe locking. It is, for example, simple to fix the direction in the sky during the night and just wait for the stars during the Earth rotation. This will in principle highly improve the stability of the alignment, the fringe offsets will be much more stable and finally the transfer function of the instrument should be much better defined.

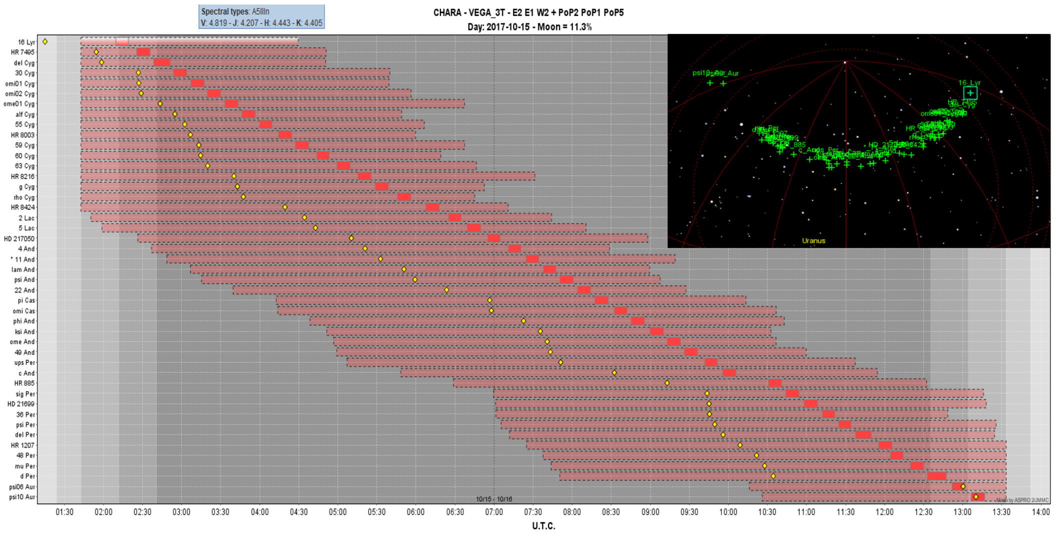

Fig 1 Running observations of 45 stars during the night of 2017 October 15 with VEGA and CLIMB used as group delay sensor, for testing a survey mode for SPICA. The red zones correspond to the time of observation of each target, the yellow dot indicates the time of transit. The top/left insert represents the position of the 45 stars on the celestial sphere. (plotted with Aspro2/JMMC).

To test the realism of such an optimized observing strategy, we dedicated a VEGA night on 15 October 2017. We selected stars observable at this time of the year, with magnitude brighter than 5.5 and with declination between $45°$ and $49°$. Among the 52 objects, we decided to schedule 45 stars on E1E2W2, this number corresponding to the average requirement for SPICA. In Fig. 1 we present the night achievement. The raw V^2 measurements for the three baselines are presented in Fig. 2. Some of the stars are fully resolved in the visible, even on the shortest baseline but we

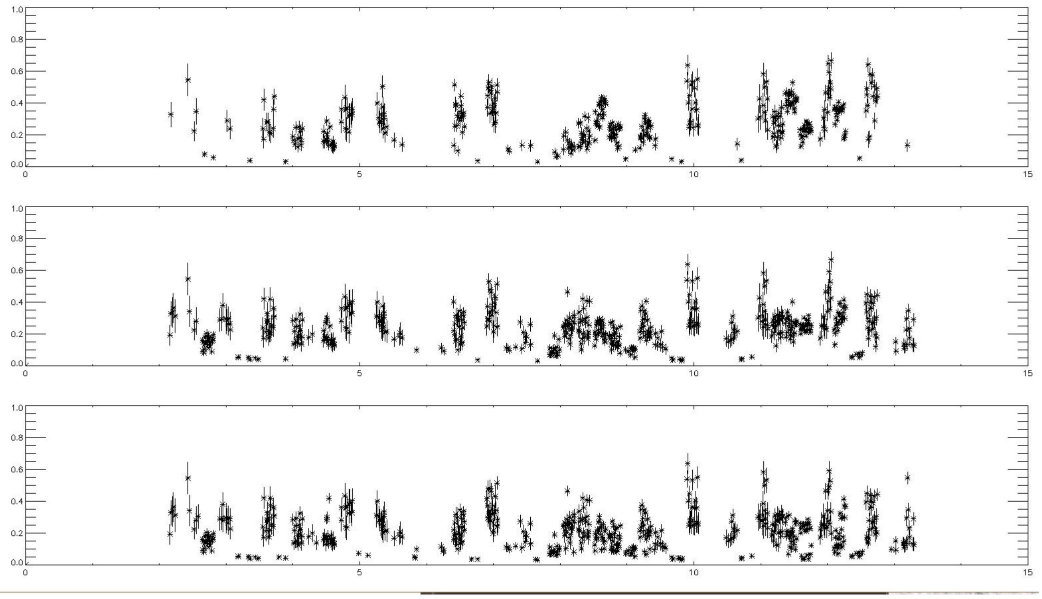

Fig 2 Raw V^2 measurements for the 45 stars of the test night, as a function of the UT time. The baselines are (from top to bottom) E1E2 (≈65 m), E2W2 (≈155 m), and E1W2 (≈220 m). Each star is observed during 10mn (24 different sequences of 25 s).

can easily identify a certain number of stars that could be used to estimate the smooth variation of the transfer function along the night. This night has showed that this strategy guarantees an excellent stability for the optical alignment of VEGA (almost no lateral pupil alignment needed) and CLIMB (only one alignment during the night after a crash of the control software, whereas the usual frequency is once an hour). Moreover fringe offsets stay within 150 μm during the whole night, which has also greatly improved the efficiency when slewing to a new target.

Deriving the angular diameter of 800 objects and the images of 200 others (1 000 stars in total) will have a tremendous impact in the field of exoplanet host stars, asteroseismology, fundamental parameters, distance scale in the universe, and stellar activity (binarity, rotation, pulsation, granulation). The step forward, which aims at deriving a robust SCBR from these 800 diameters, will need additional photometric and spectroscopic campaigns. Our aim is to provide a full modeling of stars including 3D limb-darkening, full SED, extinction calculations, wind and/or environment, impact of binarity. The 200 images will be used to better constrain stellar activity in our models. This way, the derived SBCR will gain in robustness and will, in particular, take into account the impact of stellar activity.

3 Conceptual design of SPICA

To achieve the science program presented above, we did a preliminary study of the main characteristics of the instrument and computed its expected performance.[14] To reach the required limiting magnitude, it has been shown that long exposures are mandatory and SPICA is therefore considered as fed by 6 beams cophased by a near infrared fringe sensor and a fast servo loop on the main delay lines of the CHARA Array. The fringe sensor will use the H-band fibers and injection system of MIRCx to feed an integrated optic component based on the ABCD scheme on the 15 baselines of the 6T array. A low dispersion (R=5) spectrograph will illuminate the Selex/Saphira detector currently used in MIRCx. More details are given in Sect. 5.

The SPICA instrument itself is based on the principles that we have studied in the FRIEND prototype.[12] We form dispersed fringes in the image plane on the detector (an ANDOR Ixon 897) after a linear non redundant rearrangement of the 6 collimated outputs of the fibers. The entrance part of the instrument is dedicated to the correction of the birefringence of the fibers, and the optimization of the injection. Additional modules are conceived for alignment or controls. The fibers permit an easy transportation towards a V-groove, corresponding to the first element of the spectrograph. An optical setup is presented in Fig. 3.

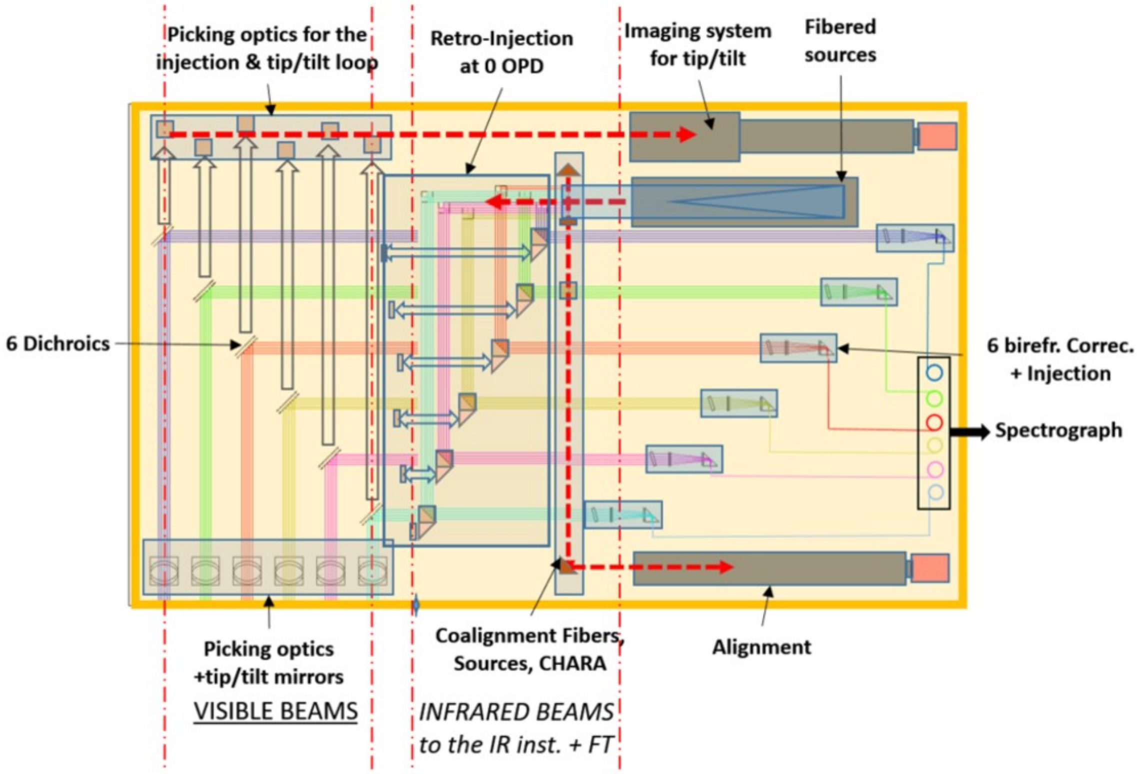

Fig 3 Optical setup of the SPICA instrument. The 6 visible beams coming from the bottom-left part of the figure are directed towards the compensator and injection system by the picking optics (2 mirrors in a periscopic setup with one fast tip/tilt actuator) and a dichroic. The smallest wavelengths (550-600 nm) are sent in different parts of an imaging camera for the control of the fast tip/tilt mirror controlling the injection. Before the injection, a compensator of the birefringence of the fibers is installed on each beam to maximize the instrumental visibility. Additional systems permit to control the alignment on sky or with internal sources. The spectrograph is not represented in this view. The infrared beams are not concerned by the SPICA table and go directly to the MIRCx table (not represented).

4 Injection in single mode fibers under partial AO correction

The new adaptive optics setup of the CHARA telescopes is presented in ten Brummelaar et al. (these proceedings). A first deformable mirror with 60 actuators and a wavefront sensor (visible or IR, depending on the choice of the dichroic plate) are installed in the telescope itself and constitute the fast adaptive loop to correct for the effects of the atmospheric turbulence (TELAO). A second deformable mirror with 37 actuators is installed in the lab, just before feeding the instruments (LABAO). It is controlled by a second wavefront sensor and is dedicated to the corrections of the Non Common Path Aberrations. The complete system has been designed to achieve a Strehl ratio of 85% in the H band, corresponding, under the best conditions, to 25% in the R band. Therefore one important point to address for the development of SPICA is the quality of the injection into a single mode fiber under partial AO corrections. We need indeed to optimize the quantity of light injected into the fibers and its temporal stability to avoid frequent low photometry in any of the 6 beams.

A first test was performed on 2017 October 16 ($r_0 \simeq 10$ cm) with the star Capella on S1, S2, and W2 telescopes equipped with LABAO only. The brightness of the star enables us to run the LABAO systems at a frequency of 40 Hz, which already improved the Strehl ratio and permitted to demonstrate that the flux injected into the FRIEND fibers was multiplied by a factor 3 (Martinod et al. 2018, to be published). This test showed however that the fluctuations of photometry in the fibers were even larger with the AO closed loop. This is obviously due to a residual speckle pattern. To go further and waiting for the installation of the final deformable mirror in the telescope, we decided to simulate the behavior of the injection in single mode fibers in the visible under the partial AO conditions of CHARA. We used the code developed by M. Ireland[5,13] and included the coupling process. It can be easily seen in fact that the residual pattern, composed of 1 to 3 or 4 bright speckles has a stabilized photocenter that does not coincide rigorously with the position of the fiber. We decided to include an additional tip/tilt correction to lock the AO system on the brightest speckle. The numerical results are presented in Tab. 1. They demonstrated a clear improvement of the coupling efficiency in all the seeing conditions. To demonstrate the improvement of the stability, we simulate sequences of corrected images for different magnitudes and different conditions of turbulence and applied our rejection criteria of an individual image when, at least, one of the photometric channels is below a threshold equal to 1.5 times the dark current of the detector (see Martinod et al. 2018 to be published). We used the FRIEND parameters and present in Fig. 4 the results for a 3T observation.

Table 1 Average coupling efficiency (CE) without and with additional tip/tilt correction (TT).

r_0 (cm)	CE (no TT)	CE (TT)
6	1.37 ± 1.37	2.16 ± 1.85
10	11.4 ± 7.49	16.6 ± 6.61
12	21.4 ± 7.04	25.6 ± 5.9

These results demonstrate the importance of this additional tip/tilt correction for optimizing the injection into single mode fibers under partial AO corrections. We have designed a dedicated system, called CESAR, that will be installed in June 2018 inside the VEGA table to test this additional tip/tilt correction. It should be noted that correcting this additional tip/tilt error on the deformable mirror itself is possible but we demonstrated in the simulation that it will degrade the quality of the injection in the H band. Therefore the tip/tilt correction has to be in the visible beam only. It is important to note however that the AO control loop is designed, as usual, to minimize the wavefront sensor measurements, i.e. the residual wavefront slopes, and not to maximize the coupling efficiency. NCPA may induce a loss of coupling efficiency that may even evolve due to thermomechanical drifts. For the purpose of optical communication between ground and satellites (Saab 2018, under submission), it has been demonstrated that the AO control loop can be opti-

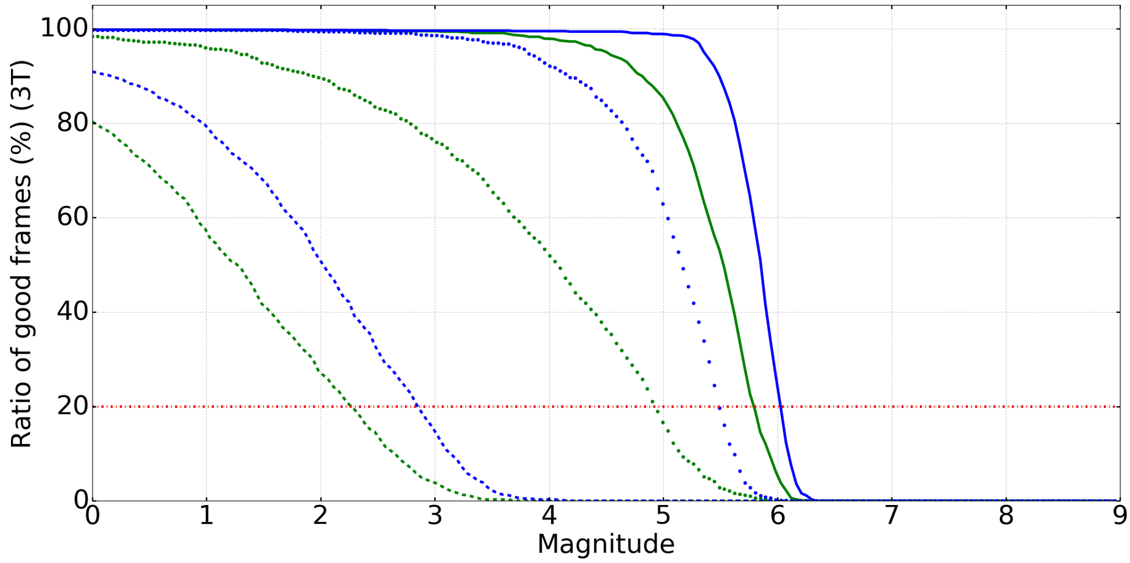

Fig 4 Evolution of the fraction of good images (flux in each photometric channel larger than 1.5 times the dark current) as a function of the magnitude for three different conditions of turbulence (plain line: $r_0 \simeq 12$ cm, dotted line: $r_0 \simeq 10$ cm, and dashed line: $r_0 \simeq 6$ cm). The blue curves correspond to the injection with additional tip/tilt correction, whereas the green ones are with the AO system only.

mized with respect to coupling efficiency. This optimization can even be updated on a regular time basis, in presence of residual turbulence, to account for thermomechanical drifts. We consider in the future going further by optimizing directly the AO control strategy with respect to the coupling efficiency. Managing together the infrared and the visible domain will probably require an additional tip/tilt correction in the visible. This will be the second test that we will perform with the CESAR experiment. These tests will permit to correctly define the entrance modules of SPICA and the additional control loops required for the optimization and the stabilization of the injection.

5 Fringe tracking considerations

In the CHARA system, the fast control loop of the delay lines permits, in principle, to achieve fringe tracking at a frequency up to 1 kHz, as demonstrated in the past by the CHAMP experiment.[39] Therefore developing a fringe tracker (FT) is mainly to define the best fringe sensor (FS) for achieving the required science performance. As general user requirements, robustness, residual error, rapidity, and sensitivity are the main guiders.

The design of fringe-trackers (FTs) has been addressed for about 40 years in stellar interferometry.[40] In the case of SPICA, we decided to analyze the recommendations brought by the CHAMP[39] and by the GRAVITY[10] instruments and to adapt them for the visible science combiner. The SPICA design is rather specific since the spectral domain used for wavefront sensing has a wavelength longer (about 2x) than the one used for the scientific instrument, unlike most active systems including AO. Therefore, for a good tracking (about $\lambda/10$) in the visible, an excellent tracking (about $\lambda/20$) is required in J or H or even $\lambda/30$ in K. It is therefore critical to optimize the FS to push as high as possible the limiting magnitude for coherent integration in the visible.

For the fringe sensor (FS) design, many concepts have to be considered, including pair-based or collective combination; pupil or focal plane detection; spatial or temporal modulation; single- or multi-mode operation; phase and/or group delay tracking. In ground-based stellar interferometry, single-mode coupling is an elegant way to convert (at the price of some SNR loss) atmospheric turbulence to fast amplitude fluctuations, canceled out by spatial modulation and low-noise detectors. The main issue is to define the combination scheme (which baseline, which flux division,...). A previous study made for the GRAVITY 4T combiner[41] showed that a good choice is to measure the OPD over the 6 possible baselines (whereas there are only 3 independent OPDs to track), leading to an integrated optics component similar to the one used for the scientific channel; on-sky results confirmed this was a good choice.[42] The situation may be different for a 6T combiner, as there are 15 possible baselines for 5 independent OPDs. We are currently continuing to compare various 6T designs, taking into account hardware constraints such as detector performance and chip transmission.

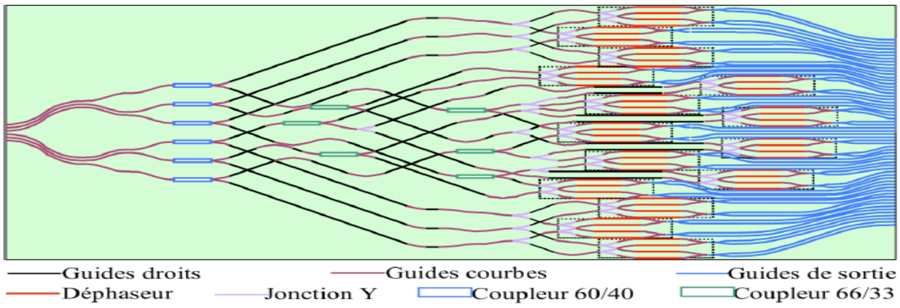

Fig 5 Design of a 6T-Hband-ABCD integrated optics component. Each input beam is shared in 5 equalized flux beams to be combined by pairs with the other beams. Four quadrature phase states (ABCD) are recorded for each baseline, giving access to all the information without temporal scanning. From Labeye PhD.

For the OPD controller, GRAVITY results also confirm the interest of a Kalman control, which can apply a predictive correction during intensity drop-outs,[41] based on a model including potential vibrations but also an real-time adjusted model of the atmospheric turbulence. To test the FT algorithms and compare different FS architecture, we will use the end-to-end temporal-domain FT simulator developed for GRAVITY.

As the baseline concept for the fringe sensor, it was decided to use a H-band, 6T-ABCD integrated optics beam combiner. It will use the H-band fibers of the MIRCx instrument (see Monnier et al., these proceedings) as well as its fast and low-noise Selex/SAPHIRA detector. We will use the flexibility of fibers and integrated optics chip to easily interface this new sensor into the optical setup of MIRCx. Depending on the additional studies essentially done for pushing the sensitivity, we will design and build a second sensor, for example based on the Hierarchical Fringe Tracker concept.[43] Together with the manufacturing companies, we studied the transmission performance of the IO chip designed in the past by Pierre Labeye (PhD thesis report) and presented in Fig. 5. Our initial estimations, before manufacturing, result in a transmission between 40 and 50% over the whole H-band if one uses the 2% PLC technology based on Silicon dioxide. A validation testbed is now under development.

6 Conclusion

The recent progresses made with the FRIEND prototype have permitted to validate the main subsystems of the future SPICA instrument. Thanks to the additional studies for optimum coupling between single mode fibers and partially corrected wavefronts, the SPICA conceptual design is now well advanced. The addition of a fringe sensor to the CHARA Array is progressing on two aspects: the important upgrade of MIRC and the possibility of building a dedicated integrated optic device as phase sensor in the H-band. Finally, an important part of the SPICA project is dedicated to the actual preparation of an innovative survey mode in optical interferometry with new principles of observations (from the preparation to the execution), data reduction, and data interpretation based on large samples. By combining all these efforts, we consider that we can reach the performance needed to complete the ambitious survey program that has been presented.

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