Long baseline interferometry in the visible: the FRIEND project

Berio P.[a], Bresson Y.[a], Clausse J.M.[a], Mourard D.[a], Dejonghe J.[a], Duthu A.[a], Lagarde S.[a], Meilland A.[a], Perraut K.[b], Tallon-Bosc I.[c], Nardetto N.[a], Spang A.[a], Bailet C.[a], Marcotto A.[a], Chesneau O.[a], Stee P.[a], Feautrier P.[b], Balard P.[d] and Gach J.L.[d]

[a] Nice Sophia-Antipolis University, CNRS Laboratoire LAGRANGE - UMR 7293, Observatoire de la Côte d'Azur, BP 4229, 06304 Nice Cedex 4, France;
[b] Univ. Grenoble Alpes, IPAG, F-38000 Grenoble, France CNRS, IPAG, F-38000 Grenoble, France ;
[c] Université de Lyon, 69003 Lyon, Université Lyon 1, Observatoire de Lyon, 9 Avenue Charles André, 69230 Saint Genis Laval, CNRS UMR 5574, Centre de Recherche Astrophysique de Lyon, Ecole Nationale Supérieure de Lyon, 69007 Lyon, France
[d] Laboratoire d'Astrophysique de Marseille (LAM), Technopole de Chateau-Gombert-38, rue Frédéric Joliot-Curie, F-13388 Marseille, France

ABSTRACT

In the next 2 or 3 years, the two major interferometric arrays, VLTI and CHARA, will equip their telescopes of 1.8m and 1m respectively with Adaptive Optics (AO hereafter) systems. This improvement will permit to apply with a reasonable efficiency in the visible domain, the principle of spatial filtering with single mode fibers demonstrated in the near-infrared. It will clearly open new astrophysical fields by taking benefit of an improved sensitivity and state-of-the-art precision and accuracy on interferometric observables. To prepare this future possibility, we started the development of a demonstrator called FRIEND (Fibered and spectrally Resolved Interferometric Experiment - New Design). FRIEND combines the beams coming from 3 telescopes after injection in single mode optical fibers and provides some spectral capabilities for characterization purposes as well as photometric channels. It operates in the R spectral band (from $600nm$ to $750nm$) and uses the world's fastest and more sensitive analogic detector OCAM2. Tests on sky at the focus of the CHARA interferometer are scheduled for December 2014. In this paper, we present the first interferometric tests of the OCAM2 detector performed on CHARA in November 2012 and the concept, the expected performance and the opto-mechanical design of FRIEND.

Keywords: Long baseline interferometry, Visible Interferometry, Instrumentation, Optical fiber

1. INTRODUCTION

Since the first uses of optical Michelson interferometry in astronomy in the 1920's [1] and more especially after the first measurements using separated telescopes done by Labeyrie in the visible [2], several interferometers have been built in the world. Nowadays, three main interferometric arrays are in operation and produce scientific results on a regular basis: CHARA [3], NPOI [4] and VLTI. CHARA and NPOI combine up to six telescopes simultaneously. VLTI combines already 4 telescopes with the visitor instrument PIONIER [5] and will be able to combine up to 4 telescopes with the second generation instruments (GRAVITY [6] and MATISSE [7]).
Interferometric obsevations in the visible spectral band are carried out at CHARA and NPOI only. At NPOI [8], two visible beam combiners are available. They combine the light coming from up to six siderostats with an available aperture of 12cm ($D/r_0 \approx 1$ where D is the telescope diameter and r_0 is the Fried parameter). The "classic" combiner operates at low spectral resolution (16 spectral channels from 550nm to 850nm) with a limiting magnitude of $m_V \approx 6$ [9]. The second beam combiner VISION uses single-mode polarization-preserving

Further author information: (Send correspondence to Berio P.)
Berio P.: E-mail: philippe.berio@oca.eu, Telephone: +33 (0)4 92 00 31 04

fibers to spatially filter the incoming beams and a EMCCD (Electron Multiplying Charge Coupled Device) [10]. Fringes on six baselines have been obtained in January 2013. The expected limiting magnitude is $m_V \approx 7$. At CHARA, the two visible combiners operate in a totally different regime since $D/r_0 >> 1$ leading to specific concepts. The PAVO beam combiner [11] combines three 1-meter telescopes at low spectral resolution (R=40 from 650nm to 950nm). The limiting magnitude is $m_V \approx 8$. The second beam combiner VEGA [12], developped at Observatoire de la Côte d'Azur, combines up to four 1-meter telescopes. It operates at medium (R=5000) and high (R=30000) spectral resolution from 450nm to 850nm. The limiting magnitude in medium spectral resolution is similar to the PAVO one.

The early years of astrophysical exploitation of VEGA have confirmed its scientific potential. More than fifteen publications have been done in different fields of stellar physics: fundamental parameters, stellar atmospheres and circumstellar environments. The first polychromatic (across the Hα Balmer line) reconstructed image of the circumstellar disk around the Be star ϕ Per has been obtained recently [13]. Despite this potential, we have also understood the current limitations of VEGA that are mainly due to: the multi-speckle mode and the use of photon counting detector. The first one leads to a dilution of the incoming flux in the different speckles, which directly impacts the measurement Signal to Noise Ratio (SNR hereafter) and therefore the limiting magnitude. This is already true on square visibility or differential visibility but it becomes even more critical on higher order observables as the closure phase. Concerning the photon counting detectors [14] developed at Observatoire de la Côte d'Azur and Observatoire de Lyon, even if they reach undeniably the best sensitivity and remain the best at very low flux, they are however limited by a saturation at high flux and by the photon centroïding hole [15]. These two limitations lead to difficulties to measure unbiased low visibilities ($V < 0.2$) and to the inability to define a sensitive estimator of the closure phase.

In the coming years, we will be able to overcome these two limiting factors : [i] the new generation of low noise EMCCD could be used in a photon counting mode without the photon centroïding hole and [ii] the CHARA telescopes will be equipped with AO [16,17,18]. The principle of spatial filtering by the use of single mode optical fibers can therefore be applied in the visible domain as done in the near-infrared. It will open new astrophysical fields by taking benefit of an improved sensitivity and state-of-the-art precision and accuracy of interferometric observables. So our goal is to develop a demonstrator instrument (called FRIEND) that combines the beams coming from 3 telescopes by applying a spatial filtering with single mode optical fibers. It will operate in the R spectral band (from 600nm to 750nm) and will use the world's fastest and most sensitive analogic camera system OCAM2 [19]. This instrument will be installed at the focus of the CHARA array. It will allow us to test a visible interferometric instrument operating with telescopes for which $D/r_0 >> 1$ and equipped with AO systems for the first time.

In this paper, we present the OCAM2 detector including the first tests realized in November 2012 at the VEGA focus in section 2, the concept of FRIEND in section 3, the expected performance of FRIEND in section 4 and the conclusions and perspectives in the last section.

2. OCAM2 DETECTOR

2.1 Main Characteristics

The OCAM2 detector is a high speed low noise camera able to run at 2067 fps with sub-electron readout noise [20]. OCAM2 uses a custom CCD (240x240 pixels) developped by e2v Technologies. The best performance has been achieved at 1300 fps and a multiplication gain of 1000: mean rms noise $< 0.2e^-$, mean dark current close to $0.001e^-/pixel/frame$ and a peak Quantum Efficiency (QE) of 94% at $650nm$. OCAM2 is now commercialized by Firstlight Imaging*.

*http://www.firstlight.fr

2.2 Photon Counting Mode

In EMCCD, the statistical behavior of the gain adds a Excess Noise Factor (ENF). Hynecek & Nishiwaki [21] demonstrated that this excess noise has the same amplitude as the photon noise. Therefore in terms of SNR, this ENF could be expressed as if the QE of the EMCCD would be halved. This ENF could be completely removed by considering the pixel binary and by applying a single threshold to the pixel value [22]. In this photon-couting mode, one consider that a pixel has detected a single photon if its value is higher than the threshold and none otherwise. In this mode, the flux should be low in order to avoid photon coincidence losses, and the ratio $G/RON_{G=1}$ (G is the EMCCD gain and $RON_{G=1}$ is the read-out noise (RON) at $G = 1$) should be high in order to minimize the proportion of events lost in RON (due to the threshold). Besides, even if RON and ENF are completely removed in photon counting mode, the noise due to Clock Induced Charges (CIC) is still present and could be dominant under very low fluxes. The CIC occur as a result of impact ionization during charge transfers, either in sensor pixel or shift/gain registers.

2.3 First Interferometric Test

The OCAM2 detector has been built to provide the very best wavefront sensing device available. Since visible interferometry requires also high speed low noise camera, we decided to test an OCAM2 detector at the focus of VEGA. We used an engineering grade OCAM2 borrowed by Firstlight Imaging and the LAM laboratory. We organised a technical run at CHARA in November 2012. More than 10 stars have been observed in 2-telescopes or 3-telescopes mode with the medium spectral resolution (R=5000). Despite the bad atmospheric conditions ($r_0 \approx 5cm$) and the fact than only half of the VEGA speckle pattern and a reduced spectral band could be recorded on OCAM2 240x240 pixels, we found fringes up to stars with $m_V = 5.2$.
As the VEGA interferograms are recorded at low flux (typically $< 0.1 photon/pixel/frame$) on the OCAM2 detector, we decided to process the data in a photon counting mode. All the data have been recorded at high gain $G = 1000$, therefore $G/RON_{G=1} = 20$. We applied a $5 \times RON_{G=1000}$ threshold (with $RON_{G=1000} \approx 0.17e^-$, mean value estimated on dark frames). So as explained by Daigle et al. [22], about 22% of photons should be lost in the photon counting process. After this first step of photon counting pre-processing, we applied the classical VEGA data reduction methods which are fully described in Mourard et al. [12]. As an illustration, we present the averaged power spectrum and bispectrum obtained for HD5349 (γ Cas) in Figure 1. Three high frequency peaks corresponding to three baselines could be seen in the power spectrum. In addition, the power spectrum presents some artefacts which are probably due to spatial structures in the bias of this engineering grade detector. These structures present a temporal variation and therefore could not be easily removed by substracting an average bias. In the bispectrum, the high frequency peak could be detected and gives an estimated closure phase $\Delta\phi = 0.6 \pm 3\,\mathrm{deg}$. This value is in good agreeement with what is expected for this Be star in the continuum at $800nm$. Let's note that this closure phase estimation is not possible with the classical photon counting detectors due to saturation for stars brighter than $m_V = 3$ and to the photon centroïding hole artefact.

In order to check the quality of the visibility measurements, we decided to observe a star with a well known angular diameter. We choosed α Per. Its angular diameter has been accurately measured in the K band with FLUOR, $\theta_{LD} = 3.13 \pm 0.007mas$ [23]. We observed α Per with the E1E2 baseline. The comparison between our visibility point and a quadratic limb-darkening model is presented in Figure 2. The limb-darkening angular diameter has been fixed to the value estimated by FLUOR while the R-band limb-darkening coefficients are derived from Claret [24] using $T_{eff} = 6250K$, $log(g) = 1.5$, a microturbulence of $4km/s$ and a solar metallicity. As in the case of the closure phase estimation, let's note that this kind of low and accurate visibility could not be obtained with the classical photon counting detectors whatever the star magnitude.

3. FRIEND CONCEPT

3.1 Main Specifications

From a technical point-of-view, the main goal of FRIEND is to validate spectrally-resolved interferometric observations in the visible in the case of partial correction by AO. In terms of astrophysics, a first and non-exhaustive analysis has confirmed the need to reach a 10th limiting magnitude at least in the case of low spectral

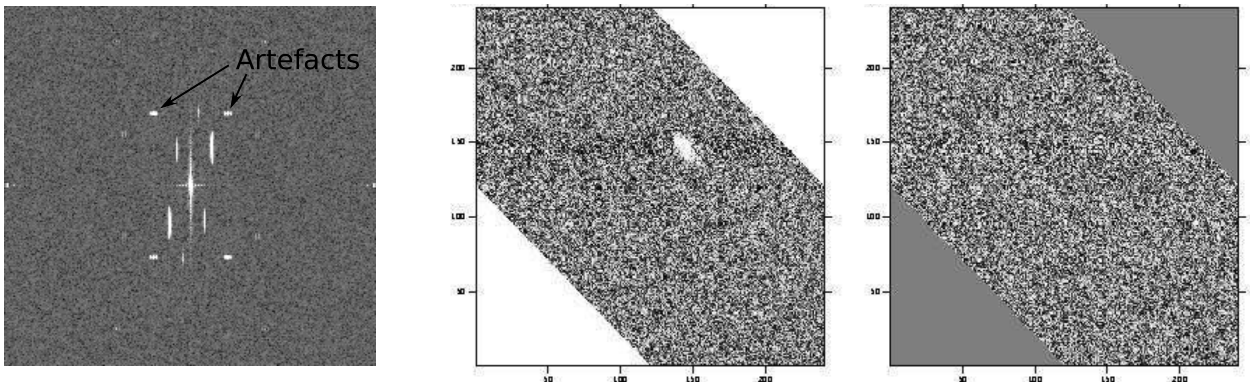

Figure 1. Averaged power spectrum (left) and bispectrum, real part (middle) and imaginary part (right), obtained with OCAM2 for HD5394 (Observation parameters: $DIT = 10ms$, 90000 frames, central wavelength $\lambda_0 = 800nm$ with a spectral band $\Delta\lambda = 15nm$ and 3T observations with the telescopes E1, E2 and W2).

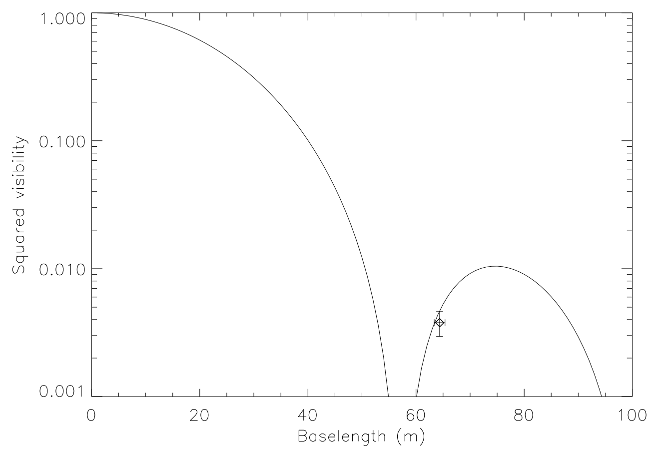

Figure 2. Squared visibility measured on α Per with the E1E2 baseline compared to a quadratic limb-darkening model.

resolution observations and to keep high spectral resolution capabilities. So, we decided to use the well-known multi-axial 'all-in-one' beam recombination scheme. This scheme has already proved its high spectral resolution capabilities in VEGA and AMBER [25].

In partial AO correction regime, the visibility calibration is one of the main difficulties. So, we decided to spatially filter each incoming beam by using single-mode polarization-preserving fibers. This filtering transfoms the phase fluctuations of the incoming beams into intensity fluctuations of the light injected into the fibers. Therefore, the visibility calibration requires simultaneous measures of the photometry of each beam at the output of the fibers. In addition and based on the success of the first test of the OCAM2 detector at the focus of VEGA (see section 2), we decided to buy one science grade OCAM2 detector for FRIEND. In our case, the main drawback of this camera is its size, only 240x240 pixels. Therefore considering the recombination scheme and the small number of pixels, we can define the maximal number of input telescopes. No more than 3 telescopes could be used in order to ensure a good sampling[†] of the fringes whatever the wavelength between $600nm$ and $750nm$.

So the main specifications of FRIEND are the following:

- 3 telescopes visible beam combiner
- a multi-axial 'all-in-one' beam recombination scheme with high spectral resolution capabilities

[†]3 pixels per fringe at least.

- spatially filtering of each incoming beam by using single-mode polarization-preserving fibers
- photometry of each beam simultaneously recorded with the interferogram
- a fast and low noise OCAM2 detector

3.2 Implantation in CHARA

FRIEND is divided in two modules: the injection module and the combiner module described in sub-sections 3.3 and 3.4 respectively. Both modules will be installed on the VEGA spectrograph table (see figure 3). So the beams $V1$, $V2$ and $V3$ coming from the telescopes will be injected in the optical fibers after the VEGA interface table. In this way, FRIEND will benefit from the alignment (pupils and images) and source devices of VEGA. These devices will be used to align FRIEND on CHARA and then to control the image and pupil positions during observations.

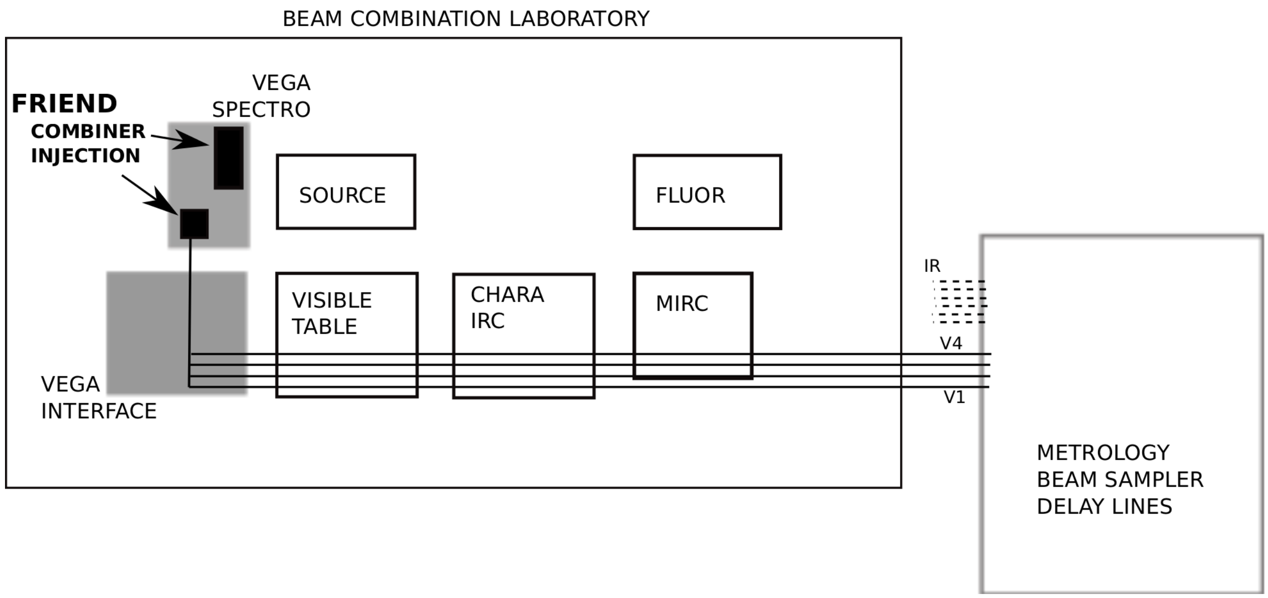

Figure 3. FRIEND implantation in the CHARA focal laboratory. The VEGA interface and spectrograph tables are represented in grey. The FRIEND injection and combiner modules are represented in black.

For aligning FRIEND on CHARA, we align it on VEGA, previously aligned on CHARA, i.e. the beams coming from the telescopes and the VEGA artifical source are aligned. This source can indeed be sent towards the telescopes and simultaneously towards the VEGA spectrograph table, and then the entrance of FRIEND. Thus, the FRIEND alignment procedure is:

- Use of the VEGA artifical source backwards (towards the telescopes).
- Use of an alignment tool for controlling the image and pupil positions. This tool is installed on the VEGA interface table close to the pupil plane.
- Keep these positions as references.
- Light injection into the FRIEND fibers backwards (from the combiner module to the injection module).
- Control of the image and pupil positions with the alignment tool.

- Correction of these positions with respect to the reference ones by moving the FRIEND injection table (big corrections) and by acting on the linear XYZ piezo-stages (see sub-section 3.3) on which the fibers are mounted (faint corrections).

This procedure should garantee a beam orientation at $10''$ in such a way that the light coming from the VEGA artifical source or from the sky are injected at least partially into the fibers. Then, the injection could be optimized by controlling the flux on the FRIEND camera and by acting on the linear XYZ piezo-stages.

3.3 Injection Module

The goal of this module is to inject three incoming beams into the single-mode optical fibers. This module will be installed on the VEGA spectrograph table and is represented in figure 6. Three prisms intercept 3 of the 4 entrance beams coming from the VEGA interface table. The whole three prisms is held on a motorized linear stage in order to be able to easily switch between VEGA and FRIEND. This functionality should be very useful during observations in order to control the fringe positions for example.
The three beams are then injected into the fibers thanks to a system which combines an achromatic doublet and a prism. We studied such system in order to minimize the chromatism aberrations and to keep the coupling efficiency very close to 80% in the whole spectral band (from $600nm$ to $750nm$). The fibers are mounted on linear XYZ piezo-stages for coupling optimization. Two of the three sub-modules supporting the whole 'fiber-doublet-prism' are mounted on motorized linear stages for the internal cophasing of the three beams. Finally, the injection module is also equipped with three motorized shutters.

3.4 Combiner Module

At the entrance of the combiner module, the fibers are positioned into a silicon *V-groove*. In the *V-groove*, the fibers are precisely positioned along a line with a $250\mu m$ pitch, enabling the arrangement of the fibers according to the desired non-redundant exit pupil configuration. Then, 3 doublets collimate the output beams before applying a pupil mask. The reconfigured pupil is thus created. The distances between each pair of sub-pupils are $3\times$, $6\times$ and $9\times$ the sub-pupil diameter (see figure 4). This configuration has been choosed in order to minimize the cross-talks between fringe peaks in the power spectrum but also to be able to correctly estimate and substract the photon bias during the data reduction.

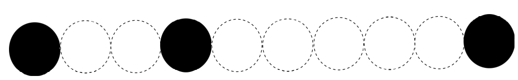

Figure 4. Non-redundant reconfigured pupil.

Then an anamorphic system made of 2 cylindrical mirrors enlarged the beams by a factor 12 in the direction perpendicular to the fiber line, i.e. in the direction perpendicular to the spectral dispersion. The beams are then spectrally dispersed by a plane reflection grating. And finally, the interferogram is formed on the OCAM2 detector thanks to a focusing lens.
For this prototype, we decided to use standard and cheap gratings. Using a $1200gr/mm$ grating gives access to a spectral resolution of $R = 2600$. This resolution is a good compromise between sensitivity (see sub-section 3.5) and astrophysical capabilities. For instance, this resolution is well adapted for spectro-interferometric studies across spectral lines of fast-rotating stars. A higher spectral resolution would have required the use of a zooming optical system in order to increase the current size ($1.4mm$) of the collimated beams. Finally, FRIEND could be operated in three modes:

- Medium Resolution: a $1200gr/mm$ reflection grating gives access to a spectral resolution of $R = 2600$. In this mode, a spectral band of $30nm$ will be imaged on the detector. The central wavelength (from $600nm$ to $750nm$) could be choosed by slightly rotating ($\pm 3\deg$) the grating. The coherence length will be around $1.8mm$, so large enough for searching the fringes in good conditions. Besides, CLIMB (one of the CHARA IR beam combiners) could be used as fringe coherencer since its level of coherencing ($< 20\mu m$) is well adapted to the coherence length of this mode.

- Low Resolution: a $300gr/mm$ reflection grating gives access to a spectral resolution of $R = 400$. The coherence length will be around $0.3mm$. In this mode, the full spectral band (from $630nm$ to $750nm$) will be imaged on the detector simultaneously. Therefore this mode will be relevant for instrument characterization.
- No spectral resolution: the grating will be replaced by a plane mirror. This mode will be used for alignment purposes only, and more especially for optimizing the flux injection into fibers.

The two gratings and the mirror will be installed on a motorized rotation stage. Thus, we could change the mode at any time during observation.
In addition, a part of each beam will be used for photometric channels. 20% of each beam is taken thanks to a beamsplitter which is located just before the anamorphic system. Then, the photometric beams propagate towards the grating stage thanks to a small number of plane mirrors. Thus the three photometric channels are spectrally dispersed as the interferometric one and then imaged onto the OCAM2 detector. A global overview of the FRIEND combiner module is presented in figure 7.

3.5 First tests in laboratory

The full integration of FRIEND is still in progres in laboratory at Observatoire de la Côte d'Azur. However, we already performed some tests in order to check the instrumental visibility of FRIEND. The first FRIEND measurements obtained in laboratory are presented in figure 5. We measured the visibility of the three fringe systems and the closure phase in a spectral band from $600nm$ to $700nm$. These results show that the instrumental

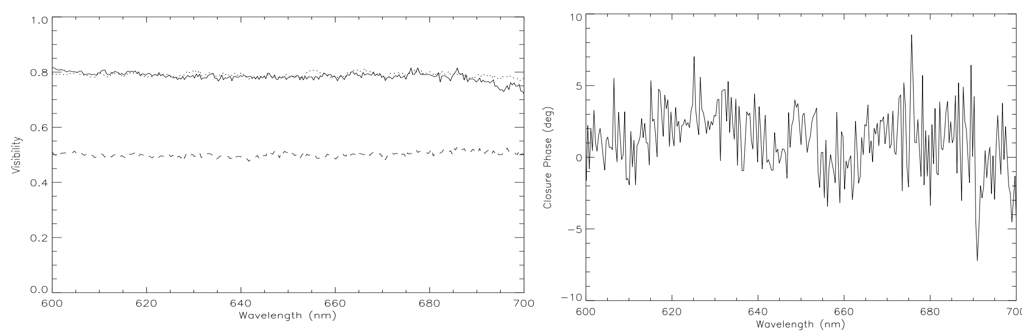

Figure 5. First FRIEND measurements obtained in laboratory : Visibility (left) and Closure Phase (right) measured in each spectral channel from $600nm$ to $700nm$.

visibilities are rather stable (less than 5% over λ), as well as the closure phase ($\Delta\phi = 0 \pm 3\,\mathrm{deg}$), in the whole spectral band. However, the levels of visibility are not very good and more especially for the fringes corresponding to the reconfigured baseline of $9D$ (with D the sub-pupil diameter). With the *No spectral dispersion* mode, we identified that this problem comes from a bad superposition of the three images. This could be resolved by improving the positioning of the three small doublets used for collimating the beams at the output of the optical fibers. These doublets are glued on a plate with three holes whereby the beams propagate. The *V-groove* is pressed on the other side of the plate. The thickness of the plate is equal to the focal length of the doublets. A picture of the opto-mechanical setup is shown in figure 8. The sticking of the doublets on the plate (with UV glue) is done under optical control. Since the first sticking attempt, we built a new tool for holding the doublets during the UV flash. So we think we can significantly improve the quality of the doublet positioning and therefore increase the instrumental visibilities. Our goal is to reach $V_{inst} > 0.9$ for the three fringe systems.

4. EXPECTED PERFORMANCE

The FRIEND performance strongly depends on the quality of the AO correction. We used a simulator developped for the AO of CHARA [16] to estimate the coupling into a single mode fiber at $\lambda = 700nm$. We considered one seeing condition (effective $r_0 = 12cm$ and $t_0 = 10ms$ at $\lambda = 0.5\mu m$) corresponding to the 80th percentile of the summer seeing at Mount Wilson. We considered also two conditions of AO corrections: *Tip-Tilt only* and *Full AO*. We found a mean coupling of 3% and 25% for the *Tip-Tilt only* and *Full AO* conditions, respectively.

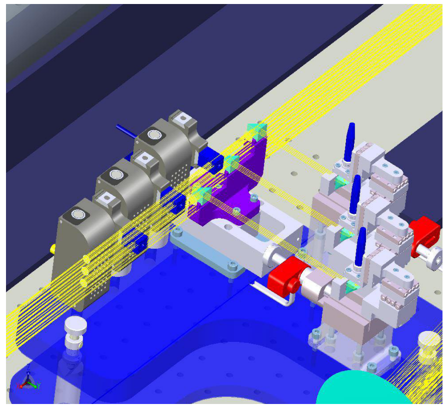

Figure 6. Injection module of FRIEND.The beams come from the VEGA interface table (bottom-left). They are intercepted by 3 prisms (in turquoise) mounted on a single mechanical support (in purple) which is held on a motorized linear stage. Then the beams propagate into 3 identical injection sub-modules made of a doublet, a prism and a single mode polarisation-preserving fiber mounted on a linear XYZ piezo-stage (the fiber heads are represented in blue). Two of the injection sub-modules are held on a liner motorized stage (the motors are represented in red). The last devices of this module are the motorized shutters (in dark grey) which are located just before the 3 intercepting prisms.

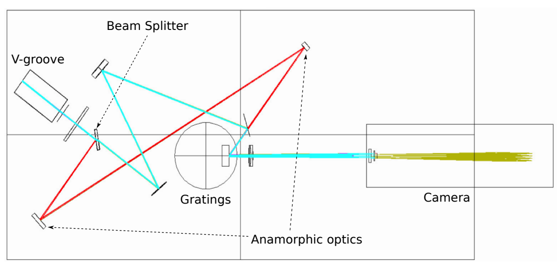

Figure 7. Representation of the FRIEND combiner module. (turquoise: photometric beams, red: interferometric beams).

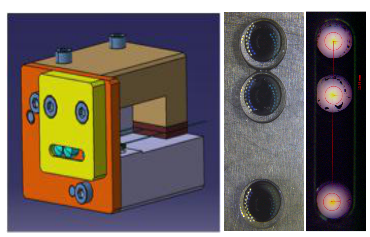

Figure 8. Left: Mechanical drawing of the module supporting the *V-groove* and the doublets. The plate on which the doublets (in turquoise) are glued is in orange. Middle: picture of the three doublets glued on a plate (with three holes) on which the *V-groove* is pressed on the other side. Right: same picture when a white source is injected into the three fibers simultaneously. The red circles (diameter of $1.4mm$) represent the parts of the beams which pass through the pupil mask. The dark spots on the beams are glue residues.

The FRIEND performance has been derived at $R = 2600$. We derived the expression of the squared visibility considering [i] a photon counting pre-processing of the images recorded with the OCAM2 detector as explained in section 2.2, [ii] an estimation of the squared visibility in the average power spectrum of each spectral channel and [iii] an average of the visibility over the whole spectral channels. Thus the SNR could be expressed as follows:

$$SNR_{V^2} = \frac{\sqrt{N_c M} N^2 V_{inst}^2 V_*^2}{\sqrt{N^4 V_{inst}^4 V_*^4 + 2N^3 n_{tel} V_{inst}^2 V_*^2 + n_{tel}^2 N^2 + n_{pix}^2 N_{CIC}^2}} \quad (1)$$

where $n_{tel} = 3$ is the number of telescopes, $N_c = 80$ is the number of spectral channels, M is the number of frames, V_{inst} is the instrumental visibility, V_* is the target visibility, $n_{pix} = 360$ is the number of pixels for one spectral channel (3 pixels width and 120 pixels heigth), $N_{CIC} = 0.0023 ph/px/fr$ is the number of CIC detected in the photon counting process and N is the number of photons reaching the detector for one telescope in one spectral channel:

$$N = T_{inst} \times \eta \times T_{PC} \times QE \times S_{tel} \times \delta\lambda \times DIT \times 10^{-0.4m} \times \phi_0 \frac{\lambda}{hc} \quad (2)$$

where $T_{inst} = 6.7\%$ is the instrumental transmission from the telescope to the detector, η is the coupling efficiency, $T_{PC} = 78\%$ is the percentage of photons kept in the photon counting process, S_{tel} is the telescope surface, $\delta\lambda = \lambda/R$ is the spectral bandwidth of one spectral channel and DIT is the integration time. Figure 9 shows the expected SNR of squared visibility with respect to the star magnitude for two conditions of AO correction in the case of an unresolved star.

From a theoretical point-of-view (i.e. considering photon and detector noise only), it clearly appears that a 10th

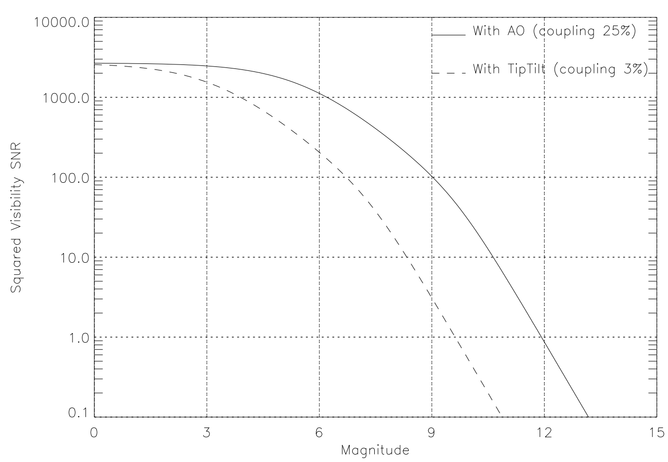

Figure 9. Expected SNR of the squared visibility with FRIEND in the medium spectral resolution mode for an unresolved star. Used parameters: $\lambda = 700nm$, $\Delta\lambda = 30nm$, $R = 2600$, $DIT = 10ms$, $QE = 90\%$, $M = 30000$ (i.e. 5 minutes of observation), $V_{inst} = 0.9$ and $V_* = 1$.

limiting magnitude‡ could be reached by averaging the visibility estimates over a spectral band of $30nm$ in the case of *Full AO* correction. This value is well within our specifications. In the case of *Tip-Tilt only* correction, the limiting magnitude could not exceed the 8th magnitude.

5. CONCLUSION AND PERSPECTIVE

FRIEND is currently in integration at Observatoire de la côte d'Azur. A full characterization in laboratory of the whole instrument and detector will be done in the next months. Then a first test on sky at CHARA is planned in December 2014. At this time, only the Phase I AO system will be installed. The Phase I AO will

‡we define the limiting magnitude as the magnitude corresponding to $SNR_{V^2} = 10$

perform a *Tip-Tilt only* correction even if optical feed system and wavefront sensor are already installed on the telescopes.
The real tests of FRIEND in AO correction conditions could not be done before the Phase II AO system where a fast deformable mirror is implemented to close the loop for *Full AO* correction. Meanwhile, FRIEND will remain installed in the focal laboratory of CHARA. Depending on the first tests and more especially on the data quality in the case of *Tip-Tilt only* correction, we plan to carry out dedicated astrophysical programs with FRIEND in 2015.

ACKNOWLEDGMENTS

The FRIEND project is funded by the Institut National des Sciences de l'Univers (INSU), Observatoire de la Côte d'Azur, the LAGRANGE Laboratory and the european funding program FEDER.

REFERENCES

[1] Michelson, A. and Pease, F., "Measurement of the diameter of α orionis with interferometer," *Astrophysical Journal* **53**, 249–259 (1920).

[2] Labeyrie, A., "Interference fringes obtained on vega with two optical telescopes," *Astrophysical Journal* **196**, L71–L75 (1975).

[3] ten Brummelaar, T., McAlister, H., Ridgway, S., Bagnuolo, W., Turner, N., Sturmann, L., Sturmann, J., Berger, D., Ogden, C., Cadman, R., Hartkopf, W., Hopper, C., and Shure, M., "First results from the chara array. ii. a description of the instrument," *Astrophysical Journal* **628**, 453–465 (2005).

[4] Armstrong, J., Mozurkewich, D., Rickard, L., Hutter, D., Benson, J., Bowers, P., Elias, N., Hummel, C., Johnston, K., Buscher, D., Clark, J., Ha, L., Ling, L., White, N., and Simon, R., "The navy prototype optical interferometer," *Astrophysical Journal* **496**, 496–550 (1998).

[5] LeBouquin, J.-B., Berger, J.-P., Lazareff, B., Zins, G., Haguenauer, P., Jocou, L., Kern, P., Millan-Gabet, R., Traub, W., Absil, O., Augereau, J.-C., Benisty, M., Blind, N., Gitton, P., Gillier, D., Kiekebusch, M., Kluska, J., Knudstrup, J., Labeye, P., Lizon, J.-L., Monin, J.-L., Magnard, Y., Malbet, F., Maurel, D., Ménard, F., Micallef, M., Montagnier, L. M. G., Morel, S., Moulin, T., Perraut, K., Popovic, D., Rabou, P., Rochat, S., Rojas, C., Roussel, F., Roux, A., Stadler, E., Stefl, S., Tatulli, E., and Ventura, N., "Pionier: a 4-telescope visitor instrument at vlti," *Astronomy and Astrophysics* **535**, A67 (2011).

[6] Eisenhauer, F., Perrin, G., Brandner, W., Straubmeier, C., Perraut, K., and al., "Gravity: Observing the universe in motion," in [*The Messenger*], ESO, ed., **143**, 16–24 (2011).

[7] Lagarde, S., Robbe-Dubois, S., Petrov, R., Lopez, B., Jaffe, W., Venema, L., Berio, P., Antonelli, P., Beckmann, U., Bettonvil, F., Graser, U., Navarro, R., and Matter, A., "Matisse: concept, specifications, and performances," in [*Optical and Infrared Interferometry III*], Delplancke, F., Rajagopal, J., and F.Malbet, eds., *Proc. SPIE* **8445**, 84452J (2012).

[8] Armstrong, J., Hutter, D., Baines, E., Benson, J., Bevilacqua, R., Buschmann, T., Clark, J., Ghasempour, A., Hall, J., Hindsley, R., Johnston, K., Jorgensen, A., Mozurkewich, D., Muterspauch, M., Restaino, S., Shanklandh, P., Schmitt, H., C.Tycner, Vanbelle, G., and Zavala, R., "The navy prototype optical interferometer (npoi): an update," *Journal of Astronomical Instrumentation* **2**, 1340002 (2013).

[9] Mozurkewich, D., "Hybrid design for a six-way beam combiner," in [*Amplitude and Intensity Spatial Interferometry II*], Breckinridge, J., ed., *Proc. SPIE* **2200**, 76 (1994).

[10] Ghasempour, A., Muterspaugh, M., Hutter, D., Monnier, J., Armstrong, T., Benson, J., Mozurkewich, D., Williamson, M., Fall, S., Harrison, C., and Sergeyous, C., "Vision: The next generation science camera for the navy optical interferometer," in [*Optical and Infrared Interferometry III*], Delplancke, F., Rajagopal, J., and F.Malbet, eds., *Proc. SPIE* **8445**, 84450M (2012).

[11] Ireland, M., Mérand, A., ten Brummelaar, T., Tuthill, P., Schaefer, G., Turner, N., Sturmann, J., Sturmann, L., and McAlister, H., "Sensitive visible interferometry with pavo," in [*Optical and Infrared Interferometry*], Scholler, M., Danchi, W., and Delplancke, F., eds., *Proc. SPIE* **7013**, 10 (2008).

[12] Mourard, D., Clausse, J., Marcotto, A., Perraut, K., Tallon-Bosc, I., Berio, P., Blazit, A., Bonneau, D., Bosio, S., Bresson, Y., Chesneau, O., Delaa, O., Hénault, F., Hughes, Y., Lagarde, S., Merlin, G., Roussel, A., Spang, A., Stee, P., Tallon, M., Antonelli, P., Foy, R., Kervella, P., Petrov, R., Thiebaut, E., Vakili, F., McAlister, H., ten Brummelaar, T., Sturmann, J., Sturmann, L., Turner, N., Farrington, C., and Goldfinger, P., "Vega: Visible spectrograph and polarimeter for the chara array: principle and performance," *Astronomy and Astrophysics* **508**, 1073–1083 (2009).

[13] Mourard, D., Monnier, J., Che, X., Millour, F., Schaefer, G., Gies, F., McAlister, H., ten Brummelaar, T., Ridgway, S., Sturmann, J., STurmann, L., Turner, N., and Farrington, C., "Spectral and spatial imaging of the be system of ϕ persei," *Astronomy and Astrophysics* **in preparation** (2014).

[14] Blazit, A., Rondeau, X., Thiébaut, E., Abe, L., Bernengo, J., Chevassut, J., Clausse, J., Dubois, J., Foy, R., Mourard, D., Patru, F., Spang, A., Tallon-Bosc, I., Tallon, M., Tourneur, Y., and Vakili, F., "New generation photon-counting cameras: algol and cpng," *Applied Optics* **47**, 1141–1151 (2008).

[15] Berio, P., Vakili, F., Mourard, D., and Bonneau, D., "Removing the photon-centroiding hole in optical stellar interferometry," *Astronomy and Astrophysics Supplement* **129**, 609–615 (1998).

[16] Che, X., Sturmann, L., Monnier, J., ten Brummelaar, T., Sturmann, J., Ridgway, S., Ireland, M., Turner, N., and McAlister, H., "Optical and mechanical design of teh chara array adaptative optics," *Journal of Astronomical Instrumentation* **2**, 1340007–1–1340007–16 (2013).

[17] Che, X., Sturmann, L., Monnier, J., ten Brummelaar, T., Sturmann, J., Ridgway, S., Ireland, M., Turner, N., and McAlister, H., "The chara array adaptive optics i: common-path optical and mechanical design, and preliminary on-sky results," in [*Optical and Infrared Interferometry IV*], Rajagopal, J., Creech-Eakman, M., and F.Malbet, eds., *Proc. SPIE* **9148**, 108 (2014).

[18] ten Brummelaar, T., Che, X., McAlister, H., Ireland, M., Monnier, J., Mourard, D., Ridgway, S., Sturmann, J., Sturmann, L., Turner, N., and Tuthill, P., "Chara array adaptive optics ii: non-common-path correction and downstream optics," in [*Optical and Infrared Interferometry IV*], Rajagopal, J., Creech-Eakman, M., and F.Malbet, eds., *Proc. SPIE* **9148**, 183 (2014).

[19] Gach, J., Balard, P., Stadler, E., Guillaume, C., and Feautrier, P., "Ocam2: world's fastest and most sensitive camera system for advanced adaptive optics wavefront sensing," in [*Second International Conference on Adaptive Optics for Extremely Large Telescopes*], (2011).

[20] Feautrier, P., Gach, J., Balard, P., Guillaume, C., Downing, M., Hubin, N., Stadler, E., Magnard, Y., Skegg, M., Robbins, M., Denney, S., Suske, W., Jorden, P., Wheeler, P., Pool, P., Bell, R., Burt, D., Davies, I., Reyes, J., Meyer, M., Baade, D., Kasper, M., Arsenault, R., Fusco, T., and Garcia, J. J. D., "Ocam with ccd220, the fastest and most sensitive camera to date for ao wavefront sensing," *PASP* **123**, 263–274 (2011).

[21] Hynecek, J. and Nishiwaki, T., "Excess noise and other important characteristics of low light level imaging using charge multiplying ccds," *IEEE Trans. Electron Devices* **50**, 239–245 (2003).

[22] Daigle, O., Carignan, C., Gach, J., Guillaume, C., Lessard, S., Fortin, C., and Blais-Ouellette, S., "Extreme faint flux imaging with an emccd," *PASP* **121**, 866–864 (2009).

[23] Mérand, A., Aufdenberg, J., Kervella, P., du foresto, V. C., ten Brummelaar, T., McAlister, H., Sturmann, L., Sturmann, J., and Turner, N., "Extended envelopes around galactic cepheids. iii. y ophiuchi and α persei from near-infrared interferometry with chara/fluor," *Astrophysical Journal* **664**, 1093–1101 (2007).

[24] Claret, A., "A new non-linear limb-darkening law for lte stellar atmosphere models. calculations for $-5.0 <= log[m/h] <= +1$, $2000k <= teff <= 50000k$ at several surface gravities," *Astronomy and Astrophysics* **363**, 1081–1190 (2000).

[25] Petrov, R. G., Malbet, F., Weigelt, G., Antonelli, P., Beckmann, U., Bresson, Y., Chelli, A., Dugué, M., Duvert, G., Gennari, S., Gluck, L., Kern, P., Lagarde, S., and Coarer, E. L., "Amber, the near-infrared spectro-interferometric three-telescope vlti instrument," *Astronomy and Astrophysics* **464**, 1–12 (2007).