VEGA: a visible spectrograph and polarimeter for CHARA

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ABSTRACT

We describe a project for the installation of a visible focal instrument at the CHARA Array, named VEGA for Visible spEctroGraph and polArimeter. This new instrument will further open the visible domain and offer both spectral and polarimetric capabilities at the CHARA Array. It will create a new and unique scientific niche for the CHARA Array[1], especially in the context of international competition. The combination of the visible domain and high spectral resolution mode combined with a good sensitivity will allow VEGA/CHARA to carve out a new piece of observational phase space and compliment many existing or planned near-infrared interferometers. VEGA will help make CHARA the interferometer with the largest spectral and spatial resolution worldwide.

Keywords: Optical interferometry, visible wavelengths, spectroscopy, polarimetry

1. INTRODUCTION

This report describes a project for a visible focal instrument for the CHARA Array , named VEGA for Visible spEctroGraph and polArimeter. The goal is to give more complete access to the visible wavelengths, and add spectral and polarimetric capabilities. It is a new scientific niche for the CHARA Array [1], and will provide access to observational phase space available no where else. By offering access to the visible band and a high spectral resolution, along with good sensitivity, VEGA is very complementary to existing or planned near-infrared instruments in many ways. First, both infrared and visible measurements are mandatory for correct and complete radiative transfer modeling. Second, the spatial resolution will reach 0.3 mas at 0.6 μm on the longest baseline of 331m. Third, many astrophysical signals investigated by interferometry have stronger signatures at visible wavelengths than in the near infra-red. All this will allow us to investigate new physical processes involved in stars, and open the field of astrophysical domains already covered by the Array. Finally, high spectral resolution is quite easy to achieve in the visible domain with VEGA, and this will be mandatory for progress in stellar activity studies.

Our previous experience has lead to the design of an instrument focusing on one mode of operation: high spectral resolution with a dispersed fringe mode called X-λ. This instrument will offer the combination of up to 4 telescopes, giving simultaneous access to 6 squared visibilities, 6 differential phases and 3 closure phases per spectral channel. The spectral resolutions offered will be 1500, 5000 and 30000 and the spectral range is from 0.45 to 0.87 μm (and if possible from 0.4 to 1.0 μm). The spectrograph is equipped with polarimetric capabilities allowing us to simultaneously record interferograms in two polarizations, either linear or circular. Finally, the field of view extension in the slit direction is 4''. This new beam combiner is based on the visible spectrograph of the GI2T interferometer, which is now de-commissioned, and offers the unique opportunity of moving the existing spectrograph to the CHARA Array for use in initial experiments. An important point is that the spectrograph already exists, is equipped with two new generation photon counting detectors and we have already observe with it on the GI2T. Furthermore, the data reduction process is

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quite mature. So all the major difficulties of the project are clearly already solved and we can now focus our attention to the implementation of VEGA at the CHARA Array and on future improvements.

In summary, the VEGA project already has a spectrograph along with calibration sources, two new generation photon counting detectors, a global control system and a data reduction pipeline. In order to deploy this instrument at the CHARA Array we will have to modify the magnification of the cameras in the spectrograph as well as the injection of the calibration sources. We will also have to develop the interface optical system, adapt the control system to fit into the CHARA framework, upgrade the software control for the 3/4 telescopes mode, and expand the data reduction pipeline. Our current plan is to install VEGA at Mt Wilson in mid 2007 and to begin operation during summer 2007. The science case of this project is described in Stee et al., at this meeting.

2. MAIN CHARACTERISTICS OF THE *VEGA* PROJECT

2.1. Operating mode

The experience we gained while operating the GI2T interferometer has lead us to focus our attention on the most consolidated mode of the REGAIN spectrograph and especially the one which requires the least development for implementation at the CHARA Array. We have a great deal of experience with the X-λ mode or dispersed fringe mode and so we have decided to put the highest priority on this operating mode at the CHARA Array in order to optimize the scientific returns. Future implementation of the COURTES mode (or Multiple Band Passes) will be possible but until Adaptive Optics are installed on the CHARA Array telescopes; the best use of the spectroscopic capabilities will be with X-λ mode. For the present configuration of the CHARA Array, we propose a visible instrument based on the multispeckle approach. Our experience, in both speckle interferometry and long baseline interferometry on the GI2T, coupled with theoretical predictions based on the typical seeing conditions at Mt Wilson, leads to a maximum spectral band of the order of 50 nm, during median to best or excellent seeing.

Calibration of multi mode visibility has already been demonstrated with the GI2T[2] at the level of $\sigma(V^2)/V^2=1.3\%$. We observed the well know A0V star Vega (α Lyrae) on different nights in June 2001, at different hour angles, different baselines and at different wavelengths. These measurements are therefore done during different atmospheric conditions. We do not use any reference star and just measured the raw visibilities. The data processing was done by using the following steps: 1) correct for the geometrical distortion of the photon counting detectors, 2) select correctly superimposed images by rejecting the sequences where tracking errors are out of bounds, 3) integrate the autocorrelation of short exposures images, in a spectral bandwidth of 9 nm centered around 645 nm, 4) calculate the raw spectral density, 5) Remove the so-called "photon counting hole" and 6) subtract the photon noise bias.

The final visibility and its formal error are calculated as described in Berio et al.[3,4]. We only include the measurements where no problems are identified during the acquisition (e.g. bad positioning of the output pupils, bad fringe tracking, and bad star tracking...). No corrections are applied to the raw visibilities.

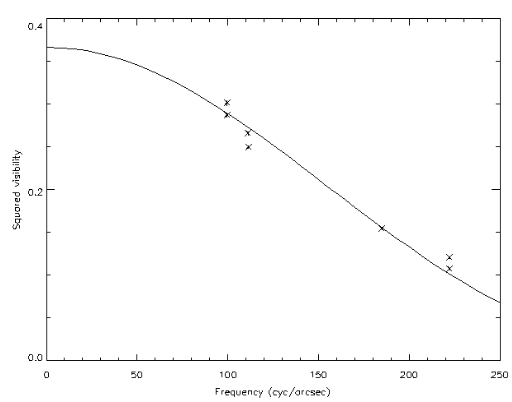

Fig. 1: Multi mode measurement of instrumental visibility of the GI2T/REGAIN interferometer.

Final adjustment of the visibility points is done using a model of a uniform disk of angular diameter Φ_{UD} multiplied by the squared instrument visibility V^2_{inst}. Both V^2_{inst} and Φ are simultaneously adjusted to fit the data. We finally get the following results:

$$V^2_{inst} = 0.367 \pm 0.005 \qquad \text{and} \qquad \Phi = 3.07 \pm 0.06$$

The angular diameter of Vega as determined here is in very good agreement with a previously published measurement (3.08±0.07) made with the Narrabri Intensity Interferometer. The most interesting result is the very good stability of the transfer function of the GI2T/REGAIN interferometer as shown on Fig. 1. This will allow visibility measurements with a final accuracy of the order of 1%. and demonstrates the feasibility of accurate visibility measurement in multimode interferometry.

The dispersed fringe concept has already been demonstrated in a large number of papers as well as the potential and accuracy of the differential phase measurements (Vakili et al.[5,6] and Bério et al.[7]). 1° of phase precision is easily obtainable, and with a better centroiding system, such as the one we intend to develop for VEGA, we estimate that 10^{-3} rd should be possible.

We propose the combination of 4 telescopes simultaneously at the CHARA Array by using the spectral+spatial encoding of the information, as explained below:

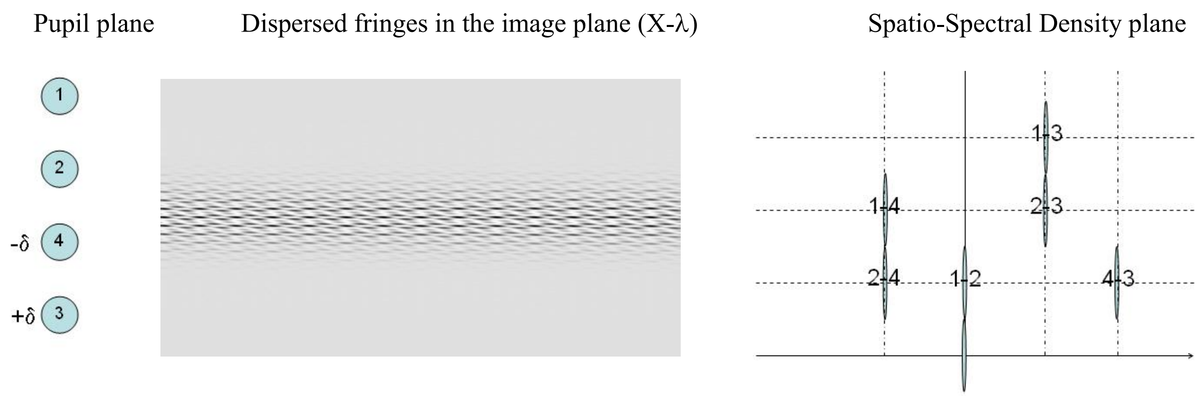

Fig. 2: schematic representation of the dispersed fringes mode of the VEGA project in the 4 telescope configuration.

The operation of REGAIN has so far been in the 2 telescopes mode, but the spectrograph has been designed to accept 3 pupils located at positions 1, 2 and 3 in figure 2. When REGAIN was first being developed, we did not foresee 4 telescope operation. Still, our currently installed internal source allows us to simulate 4 telescope operation and we plan to make intensive tests in the coming months in order to correctly establish the limits of this mode. Thanks to the dispersed fringe mode, we are able to accommodate 4 telescopes without changing the highest spatial frequency with respect to the non redundant 3T mode. In the spectral density plane, conjugate to the X-λplane, the fringe frequencies could be separated in the wave direction by simply adding a fixed delay on some of the pupils.

For a given spatial frequency, for example the one corresponding to the three baselines 1-2, 2-4 and 4-3, the spectral separation of the fringe signals in the spectral density plane is related to the optical path delay and to the spectral bandwidth. This means that if one wants to measure the fringe visibilities in one narrow spectral channel, the three signals will be blurred and there is no way to separate them. However, by use of the cross spectral analysis, it is possible to preserve the spectral resolution of the instrument with this compact and redundant configuration. The principle of this technique is to integrate cross-correlations of short exposures between one wide spectral band and one narrow spectral channel. The fringes of baseline 1-2 in the wide spectral channel are not correlated with the fringes of baselines 2-4 and 4-3 in the narrow spectral channel but only with the 1-2 fringes. This is due to the presence of a random atmospheric phase on each baseline. Thus, as with the 2T experiment where the fringes of one speckle are only correlated with the fringes of the same speckle, in this special 4T configuration the fringes in one speckle of one baseline can be only correlated with the fringes of the same speckle and the same baseline. This permits us to separate the redundant baselines and to preserve the spectral resolution.

2.2 Spectral coverage and resolution. Sampling considerations.

The spectrograph is designed to cover the visible band from 0.45 to 0.87 µm. It is equipped with two simultaneous cameras, each one equipped with a new generation photon counting detector (intensified CCD). The blue camera covers the domain [0.45,0.75] µm and the red one the domain [0.58,0.87] µm. The spectral distance between the two cameras depends on the selected grating: The spectrograph is equipped with three different gratings allowing the resolutions set out in Table 1.

Table 1: Spectral resolution and spectral band for the three gratings of **VEGA**. Spectral separation between red and blue cameras.

Grating	X-λ mode	Spectral distance between red and blue cameras
R1: 1800tr/mm	R=35000 $\Delta\lambda$=6.7nm	18 nm
R2: 300tr/mm	R=5000 $\Delta\lambda$=40nm	140 nm
R3: 100tr/mm	R=1700 $\Delta\lambda$=120nm	Not usable simultaneously

For installation of ***VEGA*** at the CHARA Array, we plan to adapt the magnification of the cameras for the best use of the new photon counting detectors. For a correct sampling on the detector of the narrowest fringes (in the case of the 3/4Telescopes operation), we have to make a compromise between sampling of the fringes, the extension of the field of view in the slit direction, and the number of simultaneous spectral channels. Indeed, the detector characteristics (size of the entrance plane ϕ=16mm, FWHM of the photon events at the output of the intensified stages=50µm, internal magnification 1/2.5, pixel size on the CCD=10µm), gives us a number of spatial resolution elements in the spectrograph image plane which is a disk of 640 in diameter. Based on these data we have optimized the size of the slit, the magnification of the spectrograph and the extension of the field of view and obtain the following parameters:

Table 2: Parameters of the red and blue cameras of the spectrograph.

Parameters	Red camera	Blue camera
λ_{min}	0.58µm	0.45µm
λ_{max}	0.87µm	0.75µm
λ_{ref}	0.7µm	0.57µm
Slit width	61µm	50µm
Maximum field of view (center of detector)	5.4''	4.2''
Number of spectral channels	173	156
Internal magnification of the spectrograph *(between the slit and the image plane)*	1.4	1.8

2.3 Polarization capabilities

VEGA integrates a polarizing device able to simultaneously view both polarizations, either linear or circular[8] on the detectors.

The principle of SPIN **(Spectro-Polarimetric INterferometry)** is based on a Wollaston prism located (optionally) just before the grating. The prism is followed by a λ/4 plate in order to equalise the transmission of the grating after the polarizer. The Wollaston introduces an angular separation of the two polarizations, so that both dispersed images arrive on the same detector. For this SPIN operation, the slit is automatically reduced by a factor 2 in its long direction in order to avoid polarization overlaps. In front of the Wollaston, another λ/4 plate could be inserted in order to go from linear to circular polarization. The first tests of this design were made on the GI2T in 2004 on the stars β UMa, α Cep, and α Lyrae. Results are in press[9] (see fig. 3).

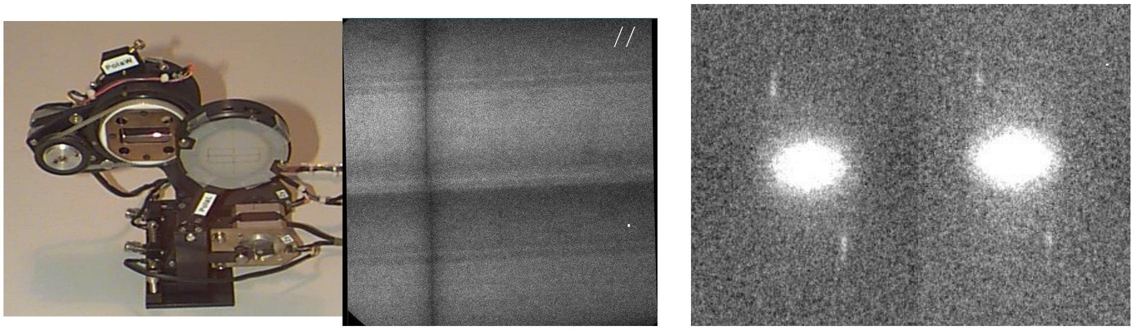

Fig. 3: left: prototype of the SPIN device. center: long exposure showing both polarizations on the same detector right: spectral density of the two parts of the images, showing the presence of fringes simultaneously on both polarizations.

2.4 Imaging capabilities

In the X−λ mode, up to 4 telescopes are recombined. With 3 closure phases, 50% of the phase information could be recovered. We do not aspire to complex imaging capabilities but simple images could be reconstructed in this configuration. If one also considers the large number of spectral channels simultaneously recorded by ***VEGA*** and the use of earth rotation to complete the (u,v) place coverage, imaging could be possible. Our groups are collaborating on the 'image reconstruction' software development (mainly the Lyon group) and we plan to integrate the specific configuration of ***VEGA*** into this general purpose user software.

2.5 Limiting magnitude and signal to noise considerations

In multimode operation, we usually consider two domains for the signal to noise ratio, depending on the number of photons per speckle per single exposure. If this number is larger than 1, then the signal to noise ratio increases as the square root of the number of photons, whereas if it is smaller than 1, the signal to noise ratio increases as the number of photons[10]. In consequence, we first defined the limiting magnitude as the magnitude giving 1 photon per speckle per single exposure. The signal to noise ratio is then equal to one and should be multiplied by the square root of the number of speckles and by the square root of the number of images. We usually consider in speckle techniques that the limiting magnitude is defined as this limit. It is clear however that the signal to noise ratio could reach high values at this limit, since one can integrate a large number of single exposures containing a large number of speckles.

In the differential regime, it has been shown by Petrov[11], that the signal to noise ratio is the geometrical mean of the signal to noise ratios in the reference channel and in the science channel. Then a good signal to noise ratio could also be achieved in a science channel where the number of photons per speckle per frame is much less than 1, thanks to the fact that we can have more than 1 photon per speckle per frame in the reference channels.

These considerations will be used for the following calculation. We also consider the following hypothesis for the calculations:

1. For a V=0 star, the number of photons received is equal to N_0=1000 ph/s/cm^2/A
2. Transmission in the visible Q_{Total}=0.15% assuming
   a. Q_{CHARA}=0.03
   b. $Q_{Instrument}$=0.15 (13 mirrors @ 0.98 + 1 grating 0.6 + the slit 0.3)
   c. $Q_{Detector}$=0.3
3. Exposure time t_0=20ms, integration time=1800s
4. r_0 estimations (for 650 nm) at Mt Wilson:
   a. Median conditions, $r_0=8.0*(650/500)^{6/5}$=11.0 cm (seeing=1.25'')
   b. Excellent conditions, $r_0=15.0*(650/500)^{6/5}$=20.6 cm (seeing 0.7'')

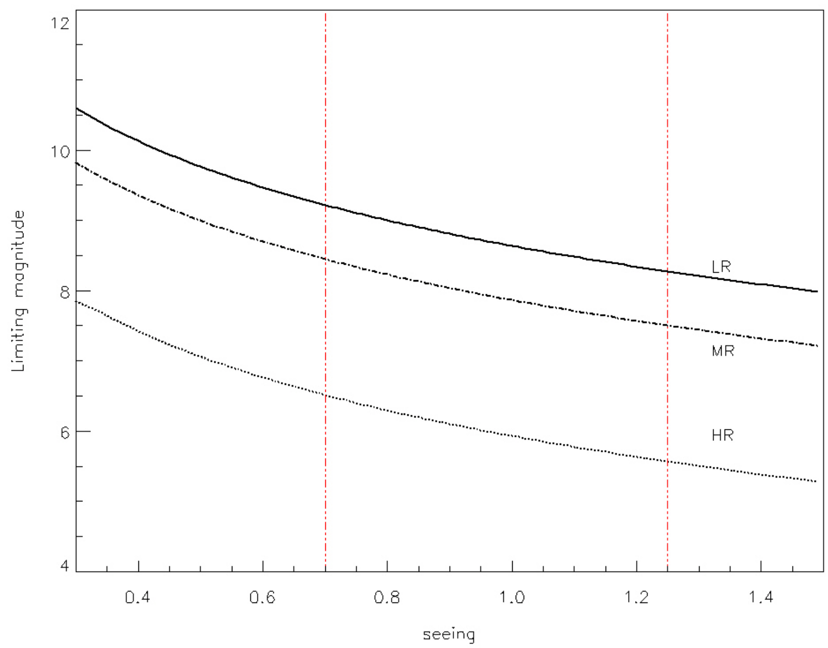

Fig. 4: Limiting magnitude for 30mn of integration, a signal to noise ratio of 10 on the differential visibility measurement with $\Delta\lambda_1$= 50 nm (resp. 40, 6.7) and $\Delta\lambda_2$= 0.4 nm (resp. 0.13, 0.02) for the Low LR (resp. medium MR, high HR) spectral resolution and a central wavelength equal to 650nm. The vertical lines correspond to the median and excellent seeing conditions.

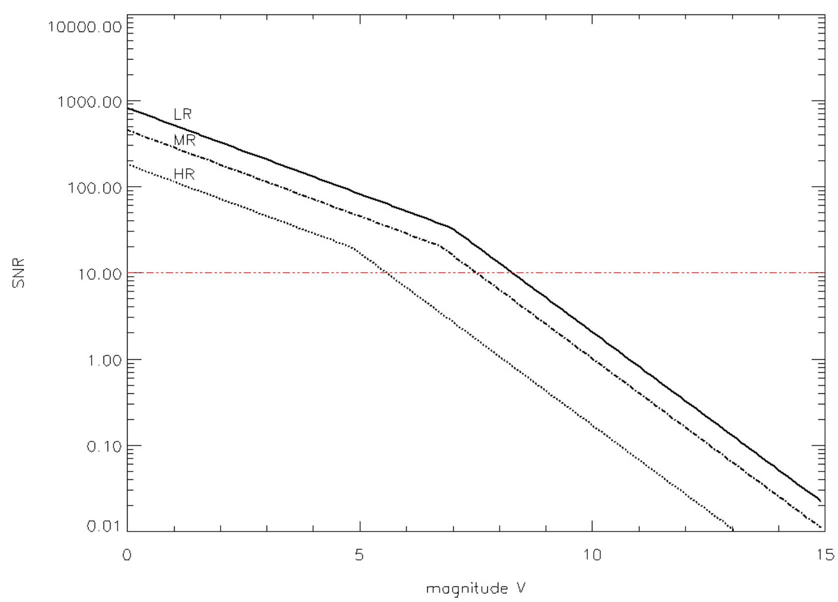

Fig. 5: SNR calculations for the three different spectral resolutions. The hypotheses on the spectral bands are the same than in figure 4. The calculations are made for a seeing of 1.25" (median conditions) and 30mn of integration time.

As already described above, the principle of multimode operation relies on a coherence (group delay) tracker and not on a fringe (phase) tracker. Therefore the previous calculations do not assume an external fringe tracker system but only a coherence tracking system able to stabilize the optical path difference to less than 2 microns over the duration of the integration of short exposures. A good model of baselines and an optical path difference measurement at a period of a few seconds are enough for correct operation of ***VEGA.*** Real time processing of the data is used for optical delay stabilisation, a technique that has already been demonstrated on the GI2T with the RAFT experience[12].

3 FUNCTIONAL ANALYSIS

3.1 Functional Analysis and product breakdown

We can break down the ***VEGA*** instrument into two sub-systems, the Interface Optics (Acronym: IOP) and the Spectrograph (Acronym: SPE)

The main functions of the Interface Optics sub-system are to:

- inject the beams coming from CHARA to ***VEGA***
- adjust the pupil location (see Annex A)
- reduce the size of the beams (from 3/4 inches to 5 mm)
- configure the beams at the entrance of the spectrograph (vertical separation of 10mm)
- provide artificial beams to calibrate and align the instrument
- adjust the optical path difference (the zero OPD plan will be the same as the current CHARA visible combiner)

The high spectral dispersion of the ***VEGA*** instrument means that it is not necessary to correct for the chromatic image shift caused by atmospheric refraction. In addition, the fact that the main part of the optical path between the telescopes and the instrument is inside vacuum tubes allows us to avoid the use of a longitudinal OPD compensator (see Annex B).
The main functions of the Spectrograph sub-system are to combine the beams, disperse the fringe signal, optimize the fringe sampling and to select the polarization
The following diagram shows the different modules which make up the sub-systems:

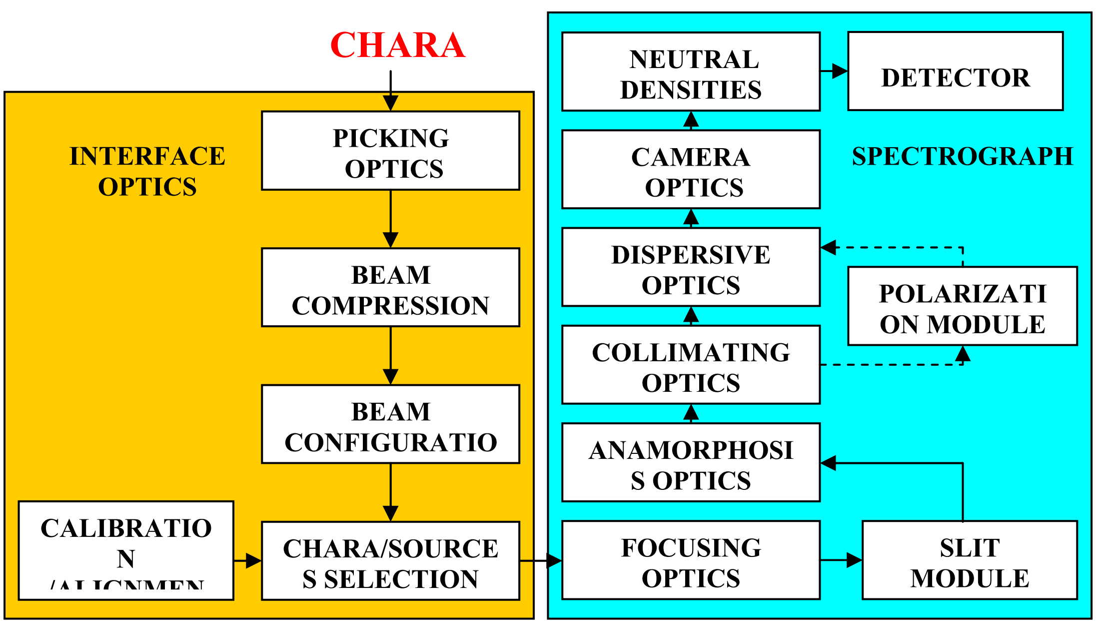

Fig. 6: Sub system decomposition of **VEGA**

The following table summarizes the different functions of each module:

Table 3: Functional analysis of the different subsystems of **VEGA**.

MODULE NAME	ACR.	COMPOSITION	M#	FONCTIONS
SUB-SYSTEM : INTERFACE OPTICS (IOP)				
Picking Optics	PGO	Set of 4 periscopes	*	Injects the beam coming from CHARA into ***VEGA*** Avoids beam vignetting due to the mounts of the optical elements of the CHARA visible combiner
Beam Compression	BCP	Parabolic and spherical mirrors		Reduces the beam size (0.75 inches → 5 mm) Adjusts the pupil location Adjusts the ZOPD
Beam Configuration	BCF	Set of 4 flat mirrors		Configures the beam (with a beam separation of 10 mm) Puts the beam in a vertical configuration
Calibration and Alignment Unit	CAU	Artificial sources (spectral and halogen lamps, laser) Collimator Mask	*	Produces light for internal alignment and for the co-alignment between the instrument and CHARA Produces light for the calibration (flat-field, distortion grid, spectral calibration, …)
CHARA/Sources Selector	CSS	Beam splitter Flat mirror	*	Feeds the spectrograph with the internal sources or with the beams coming from CHARA
SUB-SYSTEM : SPECTROGRAPH (SPE)				
MODULE NAME	**ACR.**	**COMPOSITION**	**M#**	**FONCTIONS**
Focusing Optics	FOC	Parabolic mirror		Produces an image at the spectrograph slits level
Slit Module	SLM	Slits	*	Selects a part of the image
Anamorphosis Optics	ANO	2 cylindrical mirrors		Optimizes the sampling (ratio 12 between the spectral and the spatial directions)
Collimating Optics	COL	Parabolic mirror		Collimates the beams
Polarization Module	POL	Wallaston prism $\lambda/4$ blades	*	Allows to separate the 2 polarization directions
Dispersive Optics	DIS	3 gratings	*	Disperses the light Selects between 3 different spectral resolutions (1700, 5000, 35000)
Camera Optics	DFC	Parabolic and flat mirrors		Produces a dispersed fringes image at the detector level
Neutral Densities	NDN	Neutral densities	*	Attenuates the flux
Detector	DET	Detector	*	Detects the dispersed image

#: if *, motorized or remotely controlled module

3.2 Implantation

We have studied two possible implantations for the ***VEGA*** spectrograph at the CHARA Array. The first option was to remove the current CHARA visible table and to replace it by a larger one able to host the ***VEGA*** interface optic. Unfortunately, this solution has a large impact on the current configuration of the CHARA Array and does not minimize the number of reflections for ***VEGA***. We present here the preferred solution for the location of ***VEGA***.

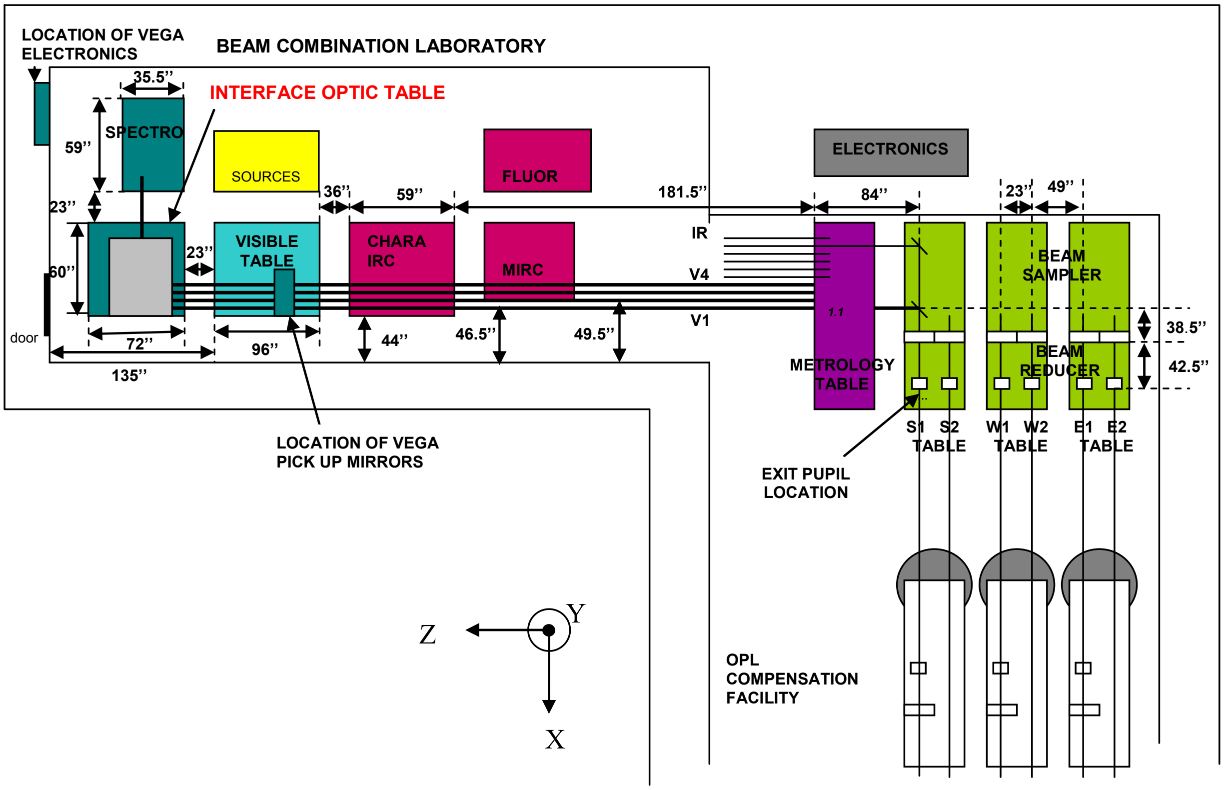

Fig. 7: **VEGA** implantation in the CHARA focal laboratory.

3.3 Interfaces with CHARA

The existing elements of the CHARA interferometer will provide some functions necessary for the ***VEGA*** instrument. These functions are the following:

- Telescope control.
- Tilt/tilt measurement and correction
- Optical path length equalization
- Optical path difference and delay line control
- Differential field rotation compensation
- Telescope selection (thanks to the Beam Sampler)
- Beam selection (thanks to the shutters located on the CHARA visible combiner)
- Instrument/Interferometer co-alignment (thanks to the different artificial sources, integration tools and optical targets located in the beam combination laboratory)

3.4 Software aspects

All the software aspects of ***VEGA*** are based on PC with WindowsXP and Visual C++. We dedicate one PC (single or bi-processor) for each main subsystem (motors, cameras, fringe tracking and main control) so to ensure real time processing.

Each subsystem controller has the same structure (see software structure diagram below):

A server which controls the device(s) according to the reception of high-level commands (change state command or information request, etc).

A client which can be launched locally on the same computer (for debugging or local use) or launched on another computer connected through a standard network remote operation.

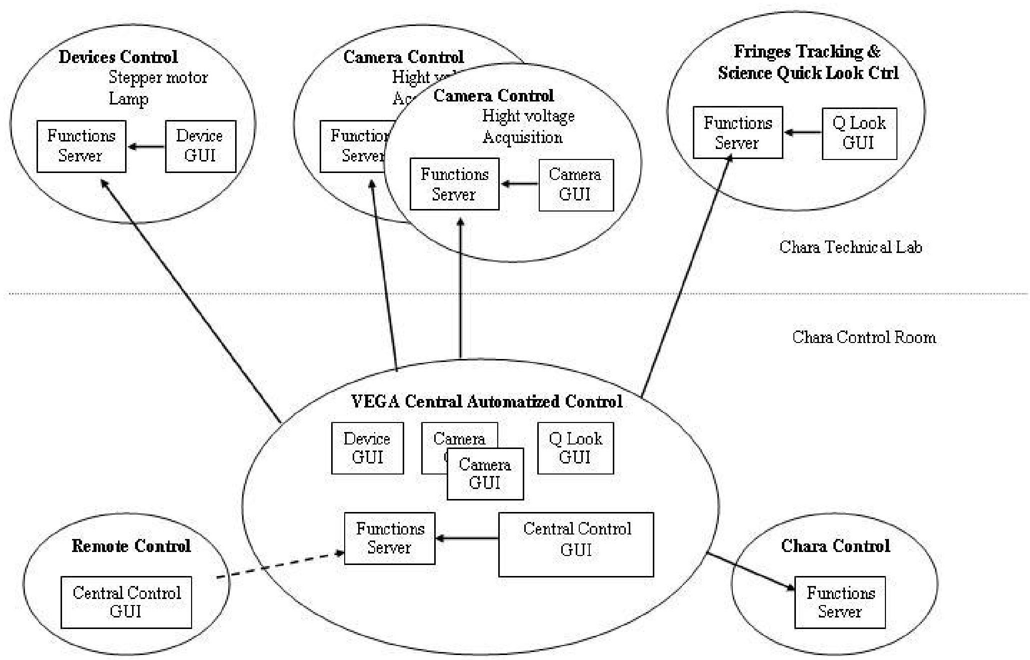

Fig. 8 **VEGA** software structure inside the CHARA organisation

The main control of sequencing is based on an observing script file composed of elementary commands organized in blocks. These commands are sent one by one to the specified devices. The script file can be easily read and edited in a standard text editor but a dedicated observing preparation tool allows coherent editing of this file. The central control is also responsible for collecting various information representative of the observing conditions and logs them in a file.

The PC and digital camera(s) structure is based on a multicast dialog which allows us to have the same frame on 2 or more computer at the same time. We can than clearly separate real time functions (intensified camera security, data acquisition, fringe tracking, science Quick Look). For this purpose we need one, or better yet 2, gigabit dedicated fiber links between the technical lab and the control room. A one gigabit link is quiet enough for the dataflow of one camera (1000 pixels *1000 pixels * 8bits * 150 frames per second).

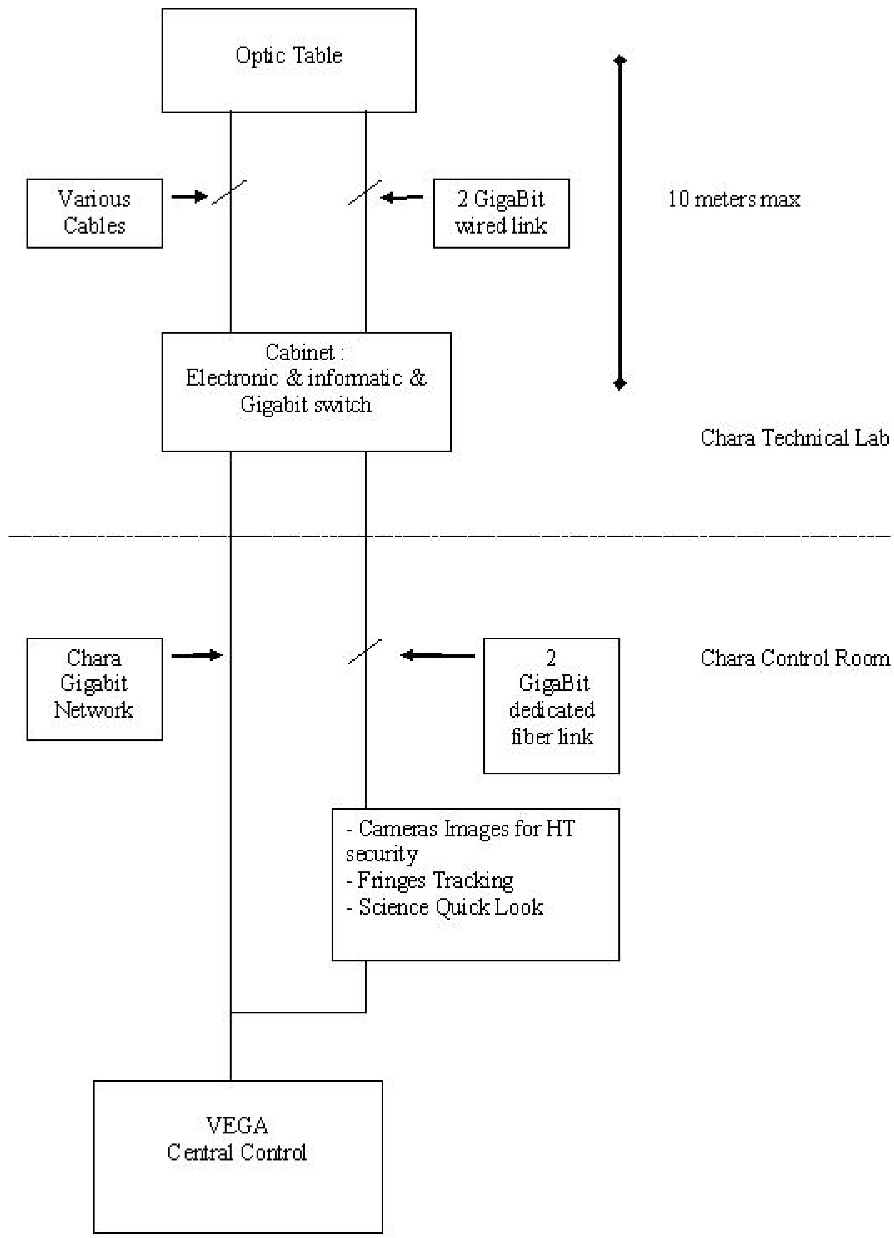

Fig. 9: Hardware implementation of the **VEGA** control system

The data reduction principles have been published in two main papers[3,4]. A complete description of the current data reduction pipeline (the GI2T one) is available. Adaptations are foreseen for a larger use of this facility and for more automatic processing. Of course adaptations will be made for the 3T and 4T configuration.

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