Title : will be set by the publisher
Editors : will be set by the publisher
EAS Publications Series, Vol. ?, 2002

THE NEAR INFRARED VLTI INSTRUMENT AMBER

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Abstract. AMBER is the General User near infrared focal instrument of the Very Large Telescope Interferometer. It is a single mode, dispersed fringes, three telescopes instrument. His limiting magnitude of the order of H=13 will allow him to tackle two dozens of extragalactic targets. His extremely high accuracy, in particular in phase closure and differential mode give good hope for very high dynamic range observation, possibly including hot extra solar planets. His relatively high spectral resolution will allow some stellar activity observations. Between this extreme goals, AMBER should have a wide range of applications including Young Stellar Objects, Evolved Stars, circumstellar material and many others. This papers tries to introduce AMBER to its future users and insists on what AMBER measures, how it calibrates it and how this could give the reader ideas for applications.

1 Introduction

1.1 The Very Large Telescope Interferometer

AMBER is the near infrared focal instrument of the Very Large Telescope Interferometer (VLTI). The VLTI (Glindeman 2002) feeds this three telescopes instrument with beams coming from any of the seven or eventually more apertures available on Paranal. For a given source, the choice of the telescopes, of their location

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DOI: (will be inserted later)

when they are movable, of the observing time and wavelengths sets the spatial frequencies of the AMBER measurements as described in section 2. Each beam is partially corrected from atmospheric wavefront perturbation thanks to Adaptive Optics (AO) modules on the 8 m Unit Telescopes (UT) or to tip-tilt correctors on the 1.8 m Auxiliary Telescopes (AT). The beams are transported to the interferometric laboratory through the telescope Coudé trains feeding Delay Lines installed in a thermally stable interferometric tunnel. In a first step, the OPD is set to zero with errors smaller than 100 μm thanks to a good global metrology of the interferometer. The inclusion of fringe sensors (Cassaing et al. 2001) in the OPD control loop allows stabilizing the fringes within a small fraction of wavelength. For each beam the pupils and the images delivered in the focal laboratory are stabilized. Eventually, a field separator implemented at each telescope will allow AO correction and fringe tracking on a reference star up to 1 arc minute away from the science source. The ultimate feature of the VLTI will be a metrology system combined with differential delay lines allowing to perform imaging through phase referencing between the off axis reference star and the science source as well as high accuracy differential astrometry. The sky coverage offered by this off axis reference star critically depends on the sensitivity of the fringe sensors. It will be poor with the first generation of sensors and fair when near infrared detectors approach the photon noise limit. The implementation of the VLTI and of its instruments will be progressive. It will start with only two telescopes and on axis fringe tracking and eventually reach the full picture evoked above.

1.2 Fundamental Amber Options

AMBER is a near infrared, three beams, dispersed fringes, single mode VLTI focal instrument. Besides a very wide scientific program, the near infrared offers the possibility to work with nearly diffraction limited images, thanks to tip-tilt correction on the ATs and a modest order Adaptive Optics system on the UTs. This allows to apply techniques well proven on smaller aperture interferometer without the necessity to correct for the rapid temporal variation of the thermal background like in the mid infrared instrument MIDI (Perrin 2002).
AMBER must combine three beams to be the first VLTI instrument with some imaging capability thanks to the possibility to compute a phase closure relation between the three simultaneous baselines. We will also see that, in addition to their imaging potential, phase closures are measures which can be particularly well calibrated and can provide strong astrophysical constraints even if only a few are measured.
However, since image reconstruction with three telescopes will be very slow, most of the astrophysical information is to be expected from the confrontation of models with a limited number of measures. In such a model fitting, analyzing the measures as a function of wavelength increases very significantly the number and the quality of measures and then the constraints imposed to the models. This pointed to a dispersed fringes instrument, similar to what has been experienced on the Plateau de Calern interferometers in France (Mourard et al. 2000).

The use of single mode spatial filtering of each incoming beam is the first key for high accuracy measurements. After such a filtering all atmospheric and instrument wavefront perturbations before the spatial filter are reduced to only two unknowns: the flux fed into the filter, which can be monitored, and the global wavefront piston which can be frozen. This is similar to what has been used in the FLUOR/IOTA (Perrin *et al.* 1997, Coudé du Foresto *et al.* 1998) or in the PTI (Lane *et al.* 2000) interferometers.
The use of dispersed fringes has several advantages. First, most of the key astrophyical information is strongly wavelength dependant. Second, a large wavelength coverage, in addition to the possibility it offers to compare, for example, objects observed at different optical depths, strongly increases the instantaneous frequency plane coverage, which is particularly valuable when only a few number of baselines are available simultaneously. Last and certainly not least, differential measurements, comparing the visibility and phase between two or more different wavelength strongly increase the accuracy of the measurements, since this differential measure eliminates many dominant achromatic effects, such as the average residual piston produced by the atmosphere or by the instrument vibrations. This also allows to discriminate astrophysical effects of great interest from atmospheric or instrumental effects with a computable or calibrable wavelength dependance. GI2T (Mourard et al. 2000) and Differential Speckle Interferometry (Chelli & Petrov 1995) has shown that differential measurement are at least 10 times more accurate than absolute measurements, almost whatever the quality of the latest.

1.3 Basic Optical concept of Amber

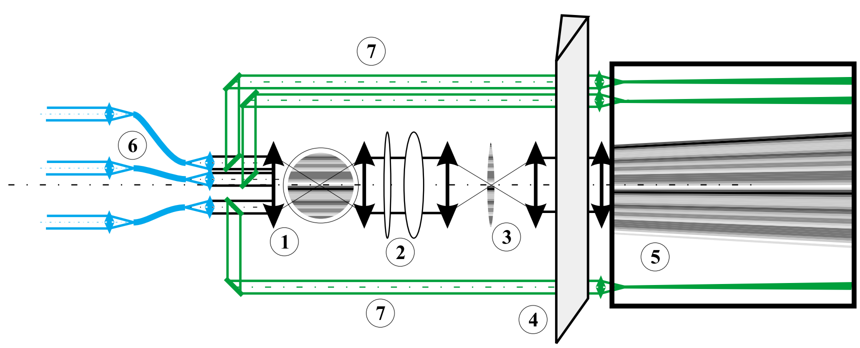

Fig. 1. Basic concept of AMBER: (1) multi axial beam combiner. (2) cylindrical optics. (3) anamorphosed focal image with fringes. (4) "long slit spectrograph". (5) dispersed fringes on 2D detector. (6) spatial filter with single mode optical fibers. (7) photometric beams.

Figure 1 summarizes the key elements of the AMBER concept.
AMBER has a multi axial beam combiner. A set of collimated and parallel beams

are focussed by a common optical element in a common Airy pattern which contains fringes (-1- in figure 1). The output baselines are in a non redundant set up, i.e. the spacing between the beams is selected for the Fourier transform of the fringe pattern to show separated fringe peaks at all wavelengths. The Airy disk needs to be sampled by a lot of pixels in the baseline direction (an average of 4 pixels in the narrowest fringe, i.e. at least 12 pixels in the baseline direction) while in the other direction only one pixel is sufficient. To minimize detector noise each spectral channel is concentrated in a single column of pixels (-3- in figure 1) by cylindrical optics (-2- in figure 1). The fringes are dispersed by a standard "long slit" spectrograph (-4- in figure 1) on a two dimensional detector (-5- in figure 1). For work in the K band with resolutions up to 10 000 the spectrograph must be cooled down to about -60 C with a cold slit in the image plane and a cold pupil stop. In practice we found it simpler to cool it down to liquid nitrogen temperature. This combination of a multi axial beam combiner with a spectrograph has been used for years in the French interferometers on the Plateau de Calern (Mourard et al. 2000).

To produce high accuracy measurements, it is necessary to spatially filter the incoming beams to force each one of them to contain only a single coherent mode. To be efficient, the spatial filter must transmit at least 10^3 more light in the guided mode than in all the secondary modes. For the kind of imperfect AO correction (Strehl ratios often $< 50\%$) available for the VLTI, the single way to achieve such high filtering quality with decent light transmission is to use single mode optical fibers (Mege et al. 2000) (-6- in figure 1). The flux transmitted by each filter must be monitored in real time in each spectral channel. This explains why a fraction of each beam is extracted before the beam combiner and send directly to the detector through a dispersive element (-7- in figure 1). The instrument must also perform some beam "cleaning" before entering the spatial filter, such as correcting for the differential atmospheric refraction in the H and J bands or, in some cases, eliminating one polarization.

2 Amber Measurements and Science

As explained in the general introduction given at this Winter School (Haniff 2002) long baseline interferometry generally does not provide directly an image of the astronomical source. Instead it yields values of its complex Fourier transform, also called visibility function. Measuring the modulus and the phase of the visibility up to a spatial frequency B/λ, where B is the baseline of the interferometer and λ the observation wavelength, with a regular frequency sampling f_0 would allow, through an inverse Fourier transform, to obtain an image of size $1/f_0$ (the field) with spatial resolution λ/B. For example, reconstructing a 230 mas image (AT Airy disk at 2 μm) with the maximum resolution permitted at this wavelength (2 mas for $B = 200$ m) would require about 6000 measurements at different spatial frequencies, i.e. 2000 different 3 telescopes set ups. This can be relaxed using the natural variation of the baseline projection on the sky due to earth rotation and called super synthesis. If the source is expected to have an almost achromatic image, the variation of the spatial frequency B/λ with wavelength can also increase the number of spatial frequencies examined during a given observation run with a fixed telescope configuration. Still, in general, the filling factor of the u-v plane patch needed for a given result (also called u-v plane coverage) will be very poor for most acceptable lengths of observing time. A second limiting factor, is that, even when the atmospheric piston is adaptively compensated, the measurements of the object visibility phase at a given spatial frequency have little meaning unless one has a metrology of the global interferometer (giant telescopes on hectares size mountain top) with a few nanometers accuracy. This is an extremely tough technological challenge, which the VLTI might eventually match but certainly not before quite a few additional years. In the meantime, the single phase information provided by AMBER is color differential phase (for each baseline) or the phase closure of the three simultaneous AMBER baselines. Although this quantities are of great scientific interest, as it will be explained below, color differential phase can be used for imaging only in specific cases, while phase closure can contain all the necessary phase information but with an even slower aperture synthesis. This reasons explain why, in spite of its imaging potential, AMBER is basically an instrument designed to constrain models of astrophysical sources thanks to a limited number of wavelength dependent measurements. The following explains what are the key measures AMBER can perform, together with some of the main source information they can provide and with their main calibration requirements.

2.1 Amber Measurements

For each elementary frame and in each AMBER spectral channel, i.e. in each column of the detector, we have an interferometric and three photometric signals which have been processed by the same optics and the same dispersive elements. A generalization of the ABCD algorithm used in the PTI interferometer (Lane 2000) has been developed (Chelli 2002) to establish a linear relation between the values measured in each pixel and the complex coherence for each baseline. The "pixel to visibility matrix" (PTVM) is calibrated using the artificial source unit in the instrument. This matrix combines the effects of many parameters which affect the measurement such as the detector gain table and the exact shape of the beams after the fiber output and the pupil stop in the spectrograph. To calibrate this matrix we must combine measures of the full three beams interferogram, measures of the signals detected when only one beam is open and measures of the interferograms obtained when one of the beams is affected by a known delay close to $\pi/4$. To achieve the goal on a visibility uncertainty smaller than 10^{-4} this calibration phase delay must be reproducible with a 10^{-4} radians accuracy.
For each baseline l-m, we obtain in each spectral channel, a measure of the visibility $V_{lm}(\lambda)$ and of the phase $\Phi_{lm}(\lambda)$. This is used to derive the various parameters measured by AMBER. It is important to note that the measurement is integrated over a certain patch around the B_{lm}/λ spatial frequency, because of the spatial filtering. The weight of the various frequency points in the patch depends from the

product of the fiber input acceptance projected on the sky by the instantaneous PSF of each telescope Adaptive Optics. If the object is not small with regard to the Airy disk of the individual aperture, this variable convolution can introduce small errors on the visibility measurement.

2.1.1 Calibrated visibility as a function of wavelength $V_{lm}(\lambda)$

After time averaging and various bias corrections and calibration steps (correction of residual piston effects using the fringe tracker residuals, use of a star with known visibility), $V_{lm}(\lambda)$ yields the calibrated visibility in each spectral channel for the baseline l-m. For a simple object, $V_{lm}(\lambda)$ will give constrains on its angular size in the direction of the baseline B_{lm}. If a certain range of spatial frequencies B_{lm}/λ is explored, thanks to baseline changes or to the spectral coverage, visibility measurements yield the different scales which are present in the source. In very general terms, an attenuation of the visibility indicates that the source has been at least partially resolved. Several levels of attenuation at different spatial frequencies can indicate that structures of various sizes are present. For example the supergiant star Betelgeuse can show a strong drop of visibility at low frequencies which can be the signature of an extended dust envelope, then a fraction of visibility curve which can be fitted by a limb darkened disk model and finally non zero visibility at higher frequencies, where the disk visibility function is expected to be very low. This can be tentatively interpreted as the signature of a structure smaller than the stellar disk such as for example a stellar spot.

Even if algorithms have been proposed to reconstruct images from visibility modulus only, thanks to some additional constrains like positivity and finite support of the image, these methods are likely to be quite unreliable with the poor u-v coverage and sometimes low SNR of long baseline interferometry measurements.

The use of measurements at different wavelengths is important, because it increases the frequency coverage and, mainly, because the spectral information can orient the interpretation. For example, in a circumstellar envelope, one can compare the visibility in two narrow spectral channels in a spectral line. Each spectral channel can correspond to an area of given radial velocity. The comparison between the two visibility and therefore the sizes of the two equal velocities area can constrain the source velocity field (Stee *et al.* 1995).

The accuracy of the visibility measurements is critical. A few % accuracy yields gross size information (which in a limited number of cases can be very valuable). But the differences between object models very often lead to very small visibility differences. This is true for example for limb darkening or for discriminating different radial distribution of material in an envelope or in a dust torus. Then the typical accuracy is on the order of 1%. Detecting features which are faint or small with regard to a main source (binary stars with a strong magnitude difference and ultimately extra solar planets, star spots, structures in envelopes or disks) is particularly demanding in terms of accuracy. In particular, even the hotest giant extra solar planets such as 51 Peg, have visibility signatures smaller than 10^{-4}.

The same will apply for "planetary gaps" in accretion disks, or for stellar structures on otherwise quite unresolved stars. In spite of all precautions: single mode spatial filtering, frozen piston, short exposures, dispersion correction, the visibility will still be sensitive to instrumental and atmospheric effects. The main tool to calibrate these effects is to observe as often as possible a reference star with unit or known visibility. The fundamental limit of this calibration is the limited speed with which is it possible to switch from locked AOs and fringe trackers on a science source to the same on a reference source. Our best expectation for the period of such a calibration cycle is 10 minutes.

2.1.2 Differential visibility as a function of wavelength $V_{lm}(\lambda)/V_{lm}(\lambda_0)$

One or several spectral channels can be defined as being a reference channel (when several wavelengths are used, the information is averaged over λ). Then the ratio between the visibility in each spectral channel and the visibility in the reference channel yields the differential visibility $V_{lm}(\lambda)/V_{lm}(\lambda_0)$. The interest is that $V_{lm}(\lambda)$ and $V_{lm}(\lambda_0)$ are measured simultaneously which increase the accuracy of the calibration since many effects will affect all the channels in the same way (or in ways related by known relations).

2.1.3 Differential phase as a function of wavelength $\Phi_{lm}(\lambda) - \Phi_{lm}(\lambda_0)$

The absolute phase $\Phi_{lm}(\lambda)$ has no meaning unless the phase referencing (Glindeman 2002) equipment is available. However, it is immediately possible to measure the absolute phase differences between any spectral channel and the reference channel: $\Phi_{lm}(\lambda) - \Phi_{lm}(\lambda_0)$. The Differential Phase can bring specific astrophysical information. For example, if one observes in different channels of a line as described above, the Differential Phase will constrain the angular distance between the equal velocity areas. For sources with relatively simple or partially known velocity fields (multiple system with small number of stars, envelopes combining a global rotation and a global expansion, knobs in a jet with a similar global direction but different velocities) combining the variation of the visibility modulus and phase with wavelength is particularly interesting: the modulus variation will constrain the relative sizes and intensities of the equal velocity zones while the phase will constrain their relative positions. The combination of these values with some a priori or spectroscopic physical knowledge of the velocity field can allow to almost reconstruct images. A good example is likely to be the envelopes of hot stars (Be, WR) observed in emission lines (Stee 2002).
Both Differential measurements are particularly interesting when the object is known to be unresolved in some spectral channels and resolved in others. Then, if the channel containing an unresolved source is used for reference, the differential complex visibility in the other channels is the exact object visibility and the image reconstruction process can be as efficient as if we had a "phase referencing system".
The second interest of the Differential Phase is that, unlike the differential mod-

ulus, it can be calibrated using an internal modulation instead of an external reference star. The measured phase difference $\Delta\Phi_{lm}(\lambda)$ will be the sum of:

$$\Delta\Phi_{lm}(\lambda) = \Delta\Phi_{lm*}(\lambda) + \Delta\Phi_{lm\mathrm{a}}(\lambda) + \Delta\Phi_{lm\mathrm{I}}(\lambda)$$

where $\Delta\Phi_{lm*}(\lambda)$ is due to the source, $\Delta\Phi_{lm\mathrm{a}}(\lambda)$ is the contribution of the atmosphere, which is very strongly dominated by the differential dispersion in the tunnels and $\Delta\Phi_{lm\mathrm{I}}(\lambda)$ is the instrumental chromatic phase difference between the beams l and m. The dominant and most difficult to eliminate term is the instrumental one $\Delta\Phi_{lm\mathrm{I}}(\lambda)$. AMBER plans to solve this problem by inverting the beams as close as possible to the entrance of the instrument, before any chromatic optics in AMBER (dichroics, fibers, beam splitters, cryostat windows, spectrograph chamber, detector). Then we obtain a new phase difference $\Delta\Phi_{ml}(\lambda)$:

$$\Delta\Phi_{ml}(\lambda) = -\Delta\Phi_{lm*}(\lambda) - \Delta\Phi_{lm\mathrm{a}}(\lambda) + \Delta\Phi_{lm\mathrm{I}}(\lambda)$$

The difference eliminates the instrumental term $\Delta\Phi_{lm\mathrm{I}}(\lambda)$. The atmospheric term $\Delta\Phi_{lm\mathrm{a}}(\lambda)$ depends upon the differences in average temperature, pressure and water vapor between the two beams. The first two terms have a globally multiplicative effect and can be fitted in the data itself particularly if we use a large spectral coverage. The water vapor term can have a strong effect in the water vapor absorption lines. We are examining if this can be calibrated from the difference between the spectra of each beam, which can be very precise because of the beam commutation allowing to use the same pixels to measure the two spectra, and which should permit to quantify the difference in the total water vapor in each one of the beams.
It has been shown (Vannier 2001) that if we have differential phase measurements with the UTs, at low spectral resolution over the full J,H,K spectral coverage, limited only by photon, background and detector noise, the variation of phase with wavelength produced by the presence of a Jupiter mass hot extra solar planet around a sun like star at 10 pc can be detected with a SNR higher than 20 for 51 Peg (separation = 0.05 au) and with a SNR of the order of two for a separation of about 0.2 au. Such an observation will yield the orbital parameters and therefore the mass and the spectrum and therefore the temperature and composition of the atmosphere of the extra solar planet. It is one of the most ambitious AMBER goals, since the corresponding phase variations range between a few 10^{-5} and a few 10^{-4} radians. The condition to achieve such an extreme accuracy is that the instrumental and atmospheric variation must be smaller than the photon noise over the calibration period. After a systematic study of all factors affecting this measurement (Vannier 2001) it appears that the result is achievable with a 30s calibration cycle based on an internal beam commutation and out of reach if one has to use the 300s cycle using a reference star. The single term which might affect the measurement can come from the atmosphere which is not calibrated by the beam commutation. We explained above, that with two telescopes we expect to compute this term from the data itself. If we have three telescopes this term can be eliminated using the phase closure relation.

2.2 Phase closure $\Phi_{123}(\lambda)$

In the phase closure relation $\Phi_{123}(\lambda) = \Phi_{12}(\lambda) + \Phi_{23}(\lambda) + \Phi_{31}(\lambda)$, all atmospheric and most of instrumental terms are cancelled. The only terms which are not corrected in the phase closure result directly from the fringe detection process (error in the PTV matrix). Fortunately, we recently discovered (Petrov *et al.* 2002) that commuting two of the three beams allows to calibrate the phase closure relation. Let's assume that we measure the phases for the three baselines B_{12}, B_{23} and B_{31}. Each beam i is affected by an OPD which translates in a phase Φ_i. The spatial frequency $u_{lm} = B_{lm}/\lambda$ yields a source phase $\varphi_*(u_{lm})$ to which must be added a detection phase error $\varphi_{\rm d}(u_{lm})$ resulting for example from a drift of the PTV matrix. The measured phase closure for the three baselines very classically is given by:

$\Phi_{123}(\lambda) = \Phi_1 - \Phi_2 + \varphi_*(u_{12}) + \varphi_{\rm d}(u_{12}) + \Phi_2 - \Phi_3 + \varphi_*(u_{23}) + \varphi_{\rm d}(u_{23}) + \Phi_3 - \Phi_1 + \varphi_*(u_{31}) + \varphi_{\rm d}(u_{31})$
i.e.:

$$\Phi_{123}(\lambda) = \varphi_*(u_{12}) + \varphi_{\rm d}(u_{12}) + \varphi_*(u_{23}) + \varphi_{\rm d}(u_{23}) + \varphi_*(u_{31}) + \varphi_{\rm d}(u_{31})$$

where the terms introduced by the path delay in each beam are classically eliminated but where the "detection" term remains.

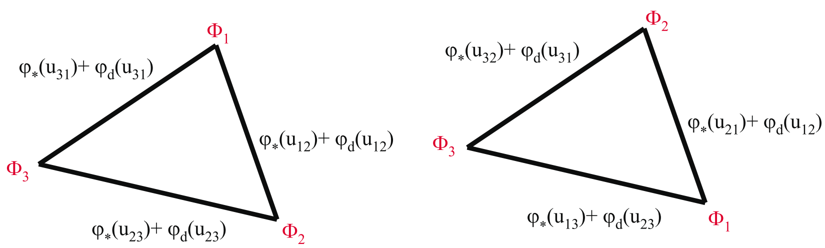

Fig. 2. Phase closure before and after beam commutation

If, we commute the beams 1 and 2, the new phase closure relation is:

$\Phi'_{123}(\lambda) = \Phi_2 - \Phi_1 - \varphi_*(u_{12}) + \varphi_{\rm d}(u_{12}) + \Phi_1 - \Phi_3 - \varphi_*(u_{31}) + \varphi_{\rm d}(u_{23}) + \Phi_3 - \Phi_2 - \varphi_*(u_{23}) + \varphi_{\rm d}(u_{31})$

i.e. :

$$\Phi'_{123}(\lambda) = -\varphi_*(u_{12}) + \varphi_{\rm d}(u_{12}) - \varphi_*(u_{31}) + \varphi_{\rm d}(u_{23}) - \varphi_*(u_{23}) + \varphi_{\rm d}(u_{31})$$

We see that the astronomical phase closure is inverted while the detection terms are unchanged : the detector "does not know" that the beams have beam inverted before the spatial filter. The half difference between the two phase closure relations yields

$$[\Phi_{123}(\lambda) - \Phi'_{123}(\lambda)]/2 = \varphi_*(u_{12}) + \varphi_*(u_{23}) + \varphi_*(u_{31}) = \varphi_{*123}(\lambda)$$

where $\varphi_{*123}(\lambda)$ is an astronomical phase closure measurement free from any atmospheric or instrumental effect, if the beam commutation have been made fast enough for the instrumental terms to remain unchanged. This way to obtain a perfectly calibrated phase closure is unique to the VLTI because its three large telescopes and to AMBER because of its beam commuting device. Such a phase closure measurement might well be the key of successful early spectroscopy of hot giant extra solar planets (Ségransan 2000).

2.2.1 Differential photocenter

When the source is non resolved (i.e. is smaller than B/λ) the phase tends to be proportional to the photocenter of the object at that given wavelength:

$$\Phi_{lm}(\lambda) = 2\pi(\vec{B}_{lm}/\lambda)\vec{\epsilon}(\lambda)$$

where both $\vec{B}_{lm}$ and $\vec{\epsilon}\lambda)$ are vectors, which the above product being a scalar one. The photocenter is defined as the barycenter of the object brightness distribution $o(\vec{r}, \lambda)$ at the wavelength λ:

$$\vec{\epsilon}(\lambda) = \int \vec{r} o(\vec{r}, \lambda) dr / \int o(\vec{r}, \lambda) \vec{dr}$$

Since phase differences can be measured even when they are extremely small compared to 2π, this allows to extract from differential phases, variation of objects photocenter as a function of wavelength even when the source is much smaller than the resolution limit. For example, for a magnitude 5 source observed with a resolution 1000 during 5 hours with an UT, one can measure photocenter displacement of about 0.1 mas. For a magnitude 10 star with UTs or a magnitude 7 star with ATs the accuracy on the photocenter displacement remains 1 mas. This allows to obtain information on sources or structures much smaller than the resolution limit, such as stellar spots.

One of the most interesting application is likely to be the study of the Broad Line Regions (BLR) of Active Galactic Nuclei. Usually this structures are quite smaller than the VLTI resolution limit. However, if one follows the photocenter through narrow channels in the broad wings of an emission line, he can obtain the size of the BLR (maximum amplitude of photocenter variation), its orientation (direction of the photocenter vector), and strong constraints on the kinematics (photocenter displacement for a certain Doppler velocity shift). This could confirm the existence of central black holes, constrain their masses, and permit to study the interaction between the BLR and the most inner parts of the NLR. The SNR estimates show that all Quasars and Seyfert Galaxies bright enough to allow the operation of the interferometer (H=13 with the first fringe tracker, probably 14 later), will be good

candidates for this technique.
The study of the photocenter has numerous other applications, too long to list here. The key fact to remember is that for objects with spatially structured spectral features, the limiting resolution of the AMBER/VLTI can be much smaller than the classical B/λ (1 or 2 mas) limit.

2.3 Observing and calibration cycles of Amber

The observing modes of AMBER are set by:

- The number of telescopes used (2 or 3)
- The spectrograph set up (resolution: -low=35, medium=1000, high=10000-; spectral coverage; central wavelength)
- The presence or not of a fringe tracker. It seems that all first observations of AMBER will use an on axis fringe tracker (FINITO). In a second phase, we could implement a blind observation mode, but this assumes some advanced study of the stability of both the VLTI and AMBER
- The accuracy needed: for very precise measurements of the visibility modulus, one should use very short frame times, even if the fringes are stabilized by a fringe tracker. The minimum frame time is of the order of 10 ms for 40 spectral channels (J,H and K band in the low resolution mode). For lower accuracy or differential phase observations one could use longer frame times (50 to 100 ms) even if the fringe tracker is performing poorly. Finally for high spectral resolution, it is needed to have a correct fringe tracking and to use long frame times, from a few seconds to a few tens of seconds.
- The kind of calibration selected: visibility measurements will give priority to frequent calibration using one or more reference stars. Differential measurement will use relatively fast internal beam commutation and use external reference stars only from time to time to check the instrument.

All these observing modes are extremely similar. In each case we set up the instrument and perform the corresponding PTVM calibration. Then we read frames, with frame times selected as explained above, and we combine them in exposures (successive frames recorded on the same source with the same instrument set up). Each exposure yields measurements of the complex coherence but a complete calibration needs combining exposures on different sources (science target, reference star, sky background, calibration lamps) or with different beam commutation (Mouillet *et al.* 2000).
All operations needed to perform a given measurement, i.e. a given exposure cycle are automatically unrolled by the instrument. The sequences are described in standard templates, with parameters set by the User as a function of its scientific objectives. To each given exposure cycle corresponds a standard way to reduce

Table 1. Summary of the specifications and expected performances of AMBER

Characteristic	Specification	Goal (or performance)
Number of beams	3	3
Minimum spectral resolution	35 in K	$\approx$ 35 in J
Medium spectral resolution in K	$500 < \Re < 1000$	
Highest spectral resolution in K		$10000 < \Re < 15000$
Spectral resolution in H and J	As it results from the K band equipment. Use order 2 in J.	
Spectral coverage	J,H,K' from 1 to 2.3 μm	J,H,K from 1 to 2.4 μm
Instantaneous spectral coverage	Simultaneous observation of the full spectral domain for $\Re = 35$	
Absolute visibility accuracy	$3\sigma_V = 0.01$	$\sigma_V = 10^{-4}$
Differential visibility accuracy	$3\sigma_{V/V_0} = 10^{-3}$	$3\sigma_{V/V_0} = 10^{-4}$
Differential phase accuracy	$3\sigma_{\Delta\Phi} = 10^{-3}$ rad	$\sigma_{\Delta\Phi} = 10^{-5}$ rad
Limiting magnitude for fringe detection (5s ,V=1)	K=11 H=11	K=12.2 H=11.6 J=10.5
Limiting magnitude with off-set reference star		K=19.4 H=20.0 J=18.7
Instrument contrast	0.8	0.9
Optical throughput (optics, fibers, spectro,detector)	K: 2% H: 1% J: 1%	
Instrument contrast stability	10^{-2} over 5 mn	10^{-3} over 5 mn
Differential phase stability	10^{-3} rad over 1 mn	10^{-4} rad over 1 mn

the data to calibrated measurements. However, all data will be recorded to allow more sophisticated post processing.

3 Summary of Amber top level specifications

Table 1 summarizes the top level specifications of AMBER after the various trade-offs made during the design phases. The expected performances have been reevaluated after the test of the actual components and subsystems which have already been delivered. They will be reevaluated again at the end of the laboratory test phase which is starting soon and after the Paranal commissioning which should be concluded by the summer 2003.

The goals given for the limiting magnitudes, in lines 11 and 12 of table 1, are actually our estimate of what will be the performances of AMBER given the optical throughput and instrument contrast estimated from the actual implementation of AMBER in the integration phase. The computation assumed the use of a single polarization and a Strehl ratio in K for an on axis reference source = 0.5 (when the science and reference sources are 1 arc minute away, the Strehl in K is divided by two). Without fringe tracking, the frame time was taken equal to 50 ms (high sensitivity mode). With off axis fringe tracking, the limiting magnitude was computed for a 10% visibility accuracy obtained after a 4 hour exposure divided in 144 frames of 100 s. The numbers are given for two UTs. With three ATs one could expect to lose about 3 magnitudes.

4 Overview of the Amber implementation

Figure 3 shows the global implementation of AMBER with the additional features needed by the actual operation of the instrument.
There are three spatial filters, one for each spectral band, because of the limited wavelength range over which a fiber can remain single mode. The three spatial filters inputs are separated by dichroic plates. For example the K band spatial filter (OPM-SFK) is fed by dichroic which reflect wavelengths higher than 2 μm and transmit the H and J bands. After the fiber outputs, a symmetric cascade of dichroics combines the different bands again, but the output pupil in each band has a shape proportional to the central wavelength of the band. Therefore the Airy disk and the fringes have the same size for all central wavelength. This allows to use the same spectrograph achromatic optics for all bands and to have the same sampling of all the central wavelengths.
Then the beams enter the cylindrical optics anamorphoser "OPM-ANS" before entering the spectrograph SPG through a periscope used to align the beam produced by the warm optics and the spectrograph. The spectrograph has an image plane cold stop, a wheel with cold pupil masks for 2 or 3 telescopes. The separation between the interferometric and photometric beams is performed in a pupil plane inside the spectrograph, after the image plane cold stop. After dispersion, the spectrograph chamber sends the dispersed image on the detector chip DET.
The Calibration and Alignment Unit (OPM-CAU), contains all calibration lamps and can emulate the VLTI in the integration, test and calibration phases. The matrix calibration system (OPM-MCS) is set of plane parallel plates which can be introduced in the beam sent by the OPM-CAU in order to introduce the $\lambda/4$ delays in one beam necessary to calibrate the matrix of the "pixel to visibility" linear relation.
Several components of the AMBER instrument, such as the dichroics, the fibers, the filters, the beam splitter, the cryostat window are optimized for only one polarization. Then, the other polarization will provide only a small gain in flux but can produce a substantial loss in contrast. To avoid this, one polarization can be eliminated by movable polarization cubes (OPM-POL).
The OPM-BCD is a tentative representation of the Bean Commuting Device. It is necessary to commute the beams without inverting the individual images, to avoid readjusting the atmospheric refraction corrector (OPM-ADC) at each beam

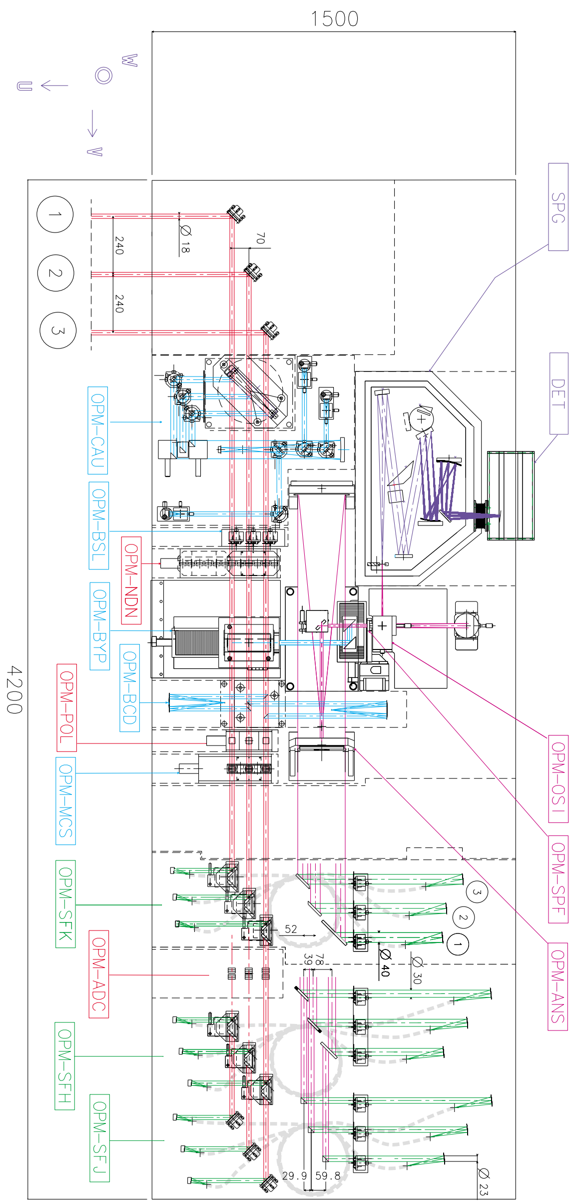

Fig. 3. Amber global implementation

inversion.
A free space before the first spatial filter is reserved for a potential future extension of AMBER. It was originally intended to be used for a multi mode unit allowing to

work with some field in the slit direction. It can also be used to install a red light spatial filter or more generally to feed an extension of AMBER to another spectral domain. For the time being these extensions are not planned nor budgeted.

4.1 The Amber Consortium

The Institutes and Laboratories in charge of the study, construction, commissioning and hand over to ESO of AMBER are the first five in the authors affiliation list of this paper. The warm optics, from the interface with the VLTI to the interface with the cooled spectrograph, the static and remotely controlled mechanics, the electronics hardware and the instrument control software are built in Nice. The cooled spectrograph with its optics, static and remotely controlled mechanics is produced in Florence. The Detector, its electronics, the data acquisition chain and the real time processing are provided by Bonn. The software to prepare, manage and reduce the observations is carried out in Grenoble, where the global integration and laboratory tests in Europe are performed. Individual participants from the other Institutes in the affiliation list provide expertise in optical interferometry as well as on the astrophysical objectives of AMBER.

5 Conclusion

We are now integrating the subsystems (Spectrograph, Detector, OPM) of AMBER. The global integration will start in the first weeks of september and will be followed by one semester of laboratory tests in Grenoble. The commissioning at Paranal with the siderostats should take place in the spring and summer of 2003, for first observation with two larger telescopes (ATs or UTs with OA) early in Autumn as soon as they are available for near infrared interferometry. The three telescopes operations is foreseen about one semester later.

The first Science Demonstration, Guaranteed Time and Open Time observations could start in October 2003, on a shared risk basis, because the instrument will be only partially commissioned during this semester. The first full operation semester will be the April-September 2004 one. The Consortium has to establish its GTO program by the end of the year and provide a copy to ESO to enter in negotiation with non consortium member willing to use the SDT with some protections of the consortium priorities.

The expected performances of AMBER, as well as its highly automated operation and data reduction almost guarantee a large harvest of ground breaking results. The "easy" subjects, which do not require approaching the accuracy or magnitude limits include the study of disks, jets, binarity in Young Stellar objects, the study of envelopes, extended atmospheres and stellar structure in evolved stars as well as the study of hot star envelopes sometimes in connection with the activity of the central star. A basic program, which has not been sufficiently developed yet will be about fundamental parameters (diameters, rotation, masses, distances) of fairly standard stars. This will be a by product of the important program which will be necessary to qualify the calibrators for AMBER: given the magnitudes and

the resolutions (in particular in differential mode) it will be quite uneasy to find stars that can be considered strictly unresolved.
Three directions are more challenging for different reasons.
We feared that the extragalactic program will be very limited because a very few extragalactic sources seemed bright enough to allow the operation of the interferometer. The most recent number about the fringe tracking performance (limit H ≥ 13) is reassuring. We will be able to study the inner structure of a few dozens objects often down to the BLR.
The extra solar planet program seems also extremely challenging because we need such a high accuracy. I am now convinced that we have a fair chance of success with two UTs and that the combination of phase closure with 3 UTs together with the beam commutation methods developed specifically for AMBER give us a very good chance to obtain the masses, and more important, the spectra of at least two dozens of hot Jupiters.
A third type of observations will be quite challenging because it will require very long observations. Its about the reconstruction of multiwavelength images of very complex objects such as some circumstellar envelopes or inner parts of Galaxies. We will be able to perform only a small number of such observations and a careful preparation, based on simpler preliminary observations and on the maximum use of the spectral observation would be wise.
Finally I hope that at least some of the exotic proposals we have received will evolve in major applications and that many non foreseen ideas will be proposed by the community.

References

Cassaing F., et al. 2001, Optical path difference sensor, C.R. Acad. Science, Paris, T. 2, Serie IV, p. 67-96

Chelli A. 2002, Introduction to data reduction, Euro Winter School *Observing with the VLTI*, Perrin, G. and Malbet, F. editors, Les Houches, France, 4-8 February 2002 (these proceedings).

Chelli A. and Petrov R.G. 1995, Model fitting and error analysis for differential interferometry I - General formalism, Astron. & Astrophys. Suppl. Series 109, 1995, pp 389-399.

Coudé du Foresto, V., Perrin, G., Ruilier, C., Mennesson, B., Traub, W., Lacasse, M. 1998, *Proc. SPIE*, 3350, 856.

Glindemann A. 2002, Presentation of the VLTI and its subsystems, Euro Winter School *Observing with the VLTI*, Perrin, G. and Malbet, F. editors, Les Houches, France, 4-8 February 2002 (these proceedings).

Haniff Ch., Introduction to optical interferometry, Euro Winter School *Observing with the VLTI*, Perrin, G. and Malbet, F. editors, Les Houches, France, 4-8 February 2002 (these proceedings).

Lane B.F., Colavita M.M., Boden P.R. and Lawson P.R., Palomar Testbed Interferometer: update, SPIE proceedings 4006, Munich, March 2000, pp 452-458.

Mege P., Malbet F., and Chelli A. 2000, Spatial filtering in AMBER, SPIE proceedings 4006, Munich, March 2000, pp 310-307.

Mouillet D. et al. 2000, AMBER data structure, processing and calibration, SPIE proceedings 4006, Munich, March 2000, pp 261-268.

Mourard D., et al. 2001, GI2T/REGAIN interferometer, C.R. Acad. Science, Paris, T. 2, Serie IV, p. 35-44

Perrin G. 2002, MIDI, the thermal infrared instrument, Euro Winter School *Observing with the VLTI*, Perrin, G. and Malbet, F. editors, Les Houches, France, 4-8 February 2002 (these proceedings).

Perrin G., Coudé du Foresto V., Ridgway S.T., *et al.* 1997, High accuracy optical visibilities on long baselines: first results and prospects, Infrared Space Interferometry Workshop *Astrophysics & the study of Earth-like planets*, Eiroa, C. editor, Toledo, Spain, February 1996, p. 233

Petrov R. G., Vannier M., Lopez B., Bresson Y., Lagarde S., Bensammar S. 2002, Observation de planètes extra-solaires géantes chaudes par interférométrie et astrométrie différentielle chromatique, SF2A colloquium, Paris, 24-28 June 2002.

Sgransan D., et al. 2000, How AMBER will contribute to the search of brown dwarfs and extra solar planet, SPIE proceedings 4006, Munich, March 2000, pp 269-276.

Stee P. 2002, Differential interferometry, Euro Winter School *Observing with the VLTI*, Perrin, G. and Malbet, F. editors, Les Houches, France, 4-8 February 2002 (these proceedings).

Stee Ph. et al. 1995, A&A, 367, 532

Vannier M., Petrov R. G., Robbe-Dubois S., Lopez B., Bresson Y., Lagarde S. 2001, Optimizing a differential interferometric instrument, in Proceedings of workshop *Scientific Drivers for ESO Future VLT/VLTI Instrumentation*, Garching, June 2001

Vannier M., Petrov R. G., Robbe-Dubois S., Lopez B. 2001, Differential interferometry detection and spectrocopy of extra-solar planets with VLTI, SF2A colloquium, Lyon, 28 May-1 June 2001.