AMBER, the Near-Infrared Instrument of the VLTI

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The AMBER instrument, installed at the Very Large Telescope (VLT), combines three light beams from as many telescopes to produce spectrally dispersed fringes from milliarcsecond angular scale. Two years after installation, the first astrophysical results are flourishing.

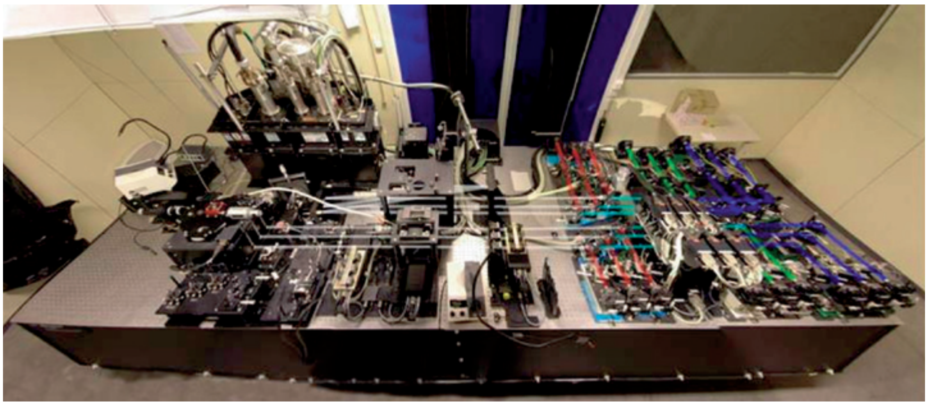

Figure 1: The VLTI instrument AMBER, which is the near-infrared instrument to combine and spectrally analyse the light caught by three of the telescope apertures (either UT's or AT's), is shown. The incoming beams have been superimposed on the photograph.

Progress in astronomy needs instrumental developments in several important directions: larger collecting area to observe fainter, more distant and therefore more ancient sources closer to the birth of the Universe; larger spectral coverage to probe different physical processes; and finally finer observations to investigate the physics in peculiar and extreme situations, such as the vicinity of putative black holes, or to find hidden details, such as extrasolar planets overwhelmed in the dazzle of their parent sun. Long baseline interferometry is the difficult but unique way to gain orders of magnitude in spatial resolution.

To achieve this goal down to the milliarcsecond scale, ESO has equipped its Very Large Telescope (VLT) with an interferometric mode (VLTI) combining giant telescopes spread over hundreds of metres in an exceptional site. At the focus of the VLTI, the near infrared Astronomical Multiple BEam Recombiner AMBER (Petrov et al. 2007), which coherently merges the light of three telescopes, has been installed; the instrument is shown in Figure 1. The resulting interference fringes in many spectral channels are analysed simultaneously, with low (35) and – for the first time – medium (1500) and high (12 000) spectral resolution. By merging three giant apertures into a single telescope, AMBER makes the VLTI the largest existing optical telescope both in collecting power and in angular resolution.

The consortium team[1] installed AMBER on the VLT in March 2004 and, although we are still in the test and commissioning process, we have obtained a wealth of original results about the close environment of a variety of stars. By using the amplitude and the phase information, and most of all their dependence with wavelength, we are able to constrain not only the size and geometry of these sources but also the relative morphology between the continuum and lines. In the following article, we describe the science results which have been obtained and which are published in a special issue of the journal *Astronomy & Astrophysics* (vol. 464, issue March II, 2007).

Science drivers and specifications

The specifications of AMBER have been defined as giving the highest priority to three key astrophysical programmes: young stellar objects; active galactic nuclei; and hot giant extrasolar planets. The first programme was considered as the minimum objective and the third one as an ambitious goal at the very edge of what could be achieved with the technology and VLTI infrastructure expected when AMBER was to be installed.

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We used the experience gained with IOTA, PTI, GI2T, and single-aperture speckle interferometry on high-angular-resolution instrumentation to define a certain number of strategic choices:
- operation in the near-infrared domain (1–2.5 μm)
- spectrally dispersed observations
- spatial filtering for high-accuracy absolute visibility
- very high-accuracy differential visibility and phase
- imaging information from closure phase
- high flux sensitivity

Table 1 lists the intersection between these strategic choices (columns) and the needs set by the scientific objectives (lines), as described in Petrov et al. (2007). Specifications in blue correspond to the most demanding ones.

AMBER concept

The optical principle and the data reduction are described in much greater details in other papers in the special A&A issue (respectively Robbe-Dubois et al. 2007; Tatulli et al. 2007). In addition, a summary and a brief justification of the fundamental choices made in the design of AMBER and its data processing can be found in Petrov et al. (2007). The selection of the concept is the result of an iteration between scientific specifications, performance, and complexity estimates in the context of some preferences set by previous experience with interferometric instruments.

Scientific topic	Spectral coverage	Spectral resolution[a]	Minimum *K*-band magnitude	Maximum visibility error[b]	Imaging (closure phase)
Key programmes					
Young stellar objects	*J*, *H*, *K*, lines	medium	9	10^{-2}	yes
AGN dust tori	*K*	low	11	10^{-2}	yes
Extrasolar planets	*J* + *H* + *K*	low	5	10^{-4}	no[c]
General programmes					
Stellar structure	lines	high	2	10^{-4}	yes
Circumstellar envelopes	*J*, *H*, *K*	medium	4	10^{-2}	yes
Binary stars	*K*	low	9	10^{-3}	yes
QSO and AGN BLR	*J*, *H*, *K*, lines	medium	11	10^{-2}	no

Table 1: Summary of the initial scientific requirements and top level specifications for AMBER. From Petrov et al. (2007).

[a] At the time when it was specified, low spectral resolution meant about 35, medium resolution about 1000 and high resolution at least 10 000.
[b] Error on either visibility amplitude (in normalised visibility units) or differential phase (in radians).

[c] It was found that after the initial specification, closure phase is likely to be more critical for exoplanets than simultaneous *J*+*H*+*K* observations.

AMBER was designed following the concept of multi-axial beam combination, namely an optical configuration similar to the Young's slits experiment, which overlaps images of the sources from different telescopes. A set of collimated and mutually parallel beams are focused by a common optical element in a common Airy pattern that contains fringes. The output baselines are in a non-redundant set-up, i.e. the spacing between the beams is selected in order that the Fourier transform of the fringe pattern shows separated fringe peaks at all wavelengths. The Airy disk needs to be sampled by many pixels in the baseline direction (an average of four pixels in the narrowest fringe, i.e. at least 12 pixels in the output baseline direction), while in the other direction a single pixel is sufficient. To minimise detector noise, each spectral channel is concentrated in a single column of pixels by cylindrical optics. This multi-axial beam combiner has been selected because it allows an easy and modular evolution from two to three telescopes and because it simplifies the design of the interface to the spectrograph and of the spectrograph itself.

Figure 2 summarises the key elements of the AMBER concept. First, each beam is spatially filtered by a single-mode optical fibre. After each fibre, the beams are collimated so that the spacing between the output pupils is non redundant. The multi-axial recombination consists of common optics that merges the three output beams in a common Airy disc containing Young's fringes. Thanks to a cylindrical optics anamorphoser, this fringed Airy disc is fed into the input slit of a spectrograph. In the focal plane of the spectrograph, each column (in the figure, but in reality each line) of the detector contains a monochromatic image of the slit with three photometric (P1, P2, P3) zones and one interferogram (IF). In this figure, the detector image contains a view, rotated by 90°, of the AMBER real-time display showing three telescope fringes, in medium resolution between 2 090 and 2 200 nm, on the bright Be star α Arae. The three superimposed fringe patterns form a clear Moiré figure because, in that particular case, the three optical path differences were substantially different from zero during the recording. Note the vertical brighter line indicating the Brγ emission line.

Figure 3 displays the raw detector image from AMBER obtained in the three-telescope low-resolution mode on the star τ Bootis in April 2006. The stellar signal is spectrally dispersed in the vertical direction and each (pair of) detector lines contains a spectral channel. The rows of *K*-band and *H*-band occupy respectively the upper and the lower half of the screen. From left to right, the first, second, and fourth columns represent the photometric beams for each one of the three telescopes, while the third column contains the interferometric signal, with the three superimposed fringe systems.

AMBER observables

During the observation, we record exposures of several frames, each exposed during the detector integration time. Typically a calibrated point is made of five exposures of 1000 frames of 20 to 100 ms. For each baseline and in each spectral channel, we obtain a measure of the intensity and of the visibility amplitude and phase used to derive the various AMBER observables.

Spectrum of the source

Each one of the photometric beams yields a spectrum of the source within the chosen spectral window. The spectrum is a crucial element of AMBER model fitting. Simultaneous observations of high-resolution infrared spectra, for example with the ISAAC instrument, have often been found to be very useful.

Absolute visibility per spectral channel

The absolute visibility[2] in each spectral channel is the direct result of the data processing. The absolute visibility mainly depends on the equivalent size of the source in the direction of the baseline. Visibility alone does not allow axisymmetric and non-axisymmetric solutions to be disentangled (except with a very good u-v coverage), and will be of little use if the structure of the object is completely unknown.

Differential visibility

The differential (or relative) visibility is the source visibility in a spectral channel, often called work channel, calibrated by

[2] The measured absolute visibility is affected by the piston jitter within one frame. This jitter should be frozen by VLTI fringe tracking or measured when the flux per frame is high enough. Currently this correction is impossible because the vibrations in the Unit Telescopes produce a piston variation between consecutive frames that is almost always larger than the wavelength.

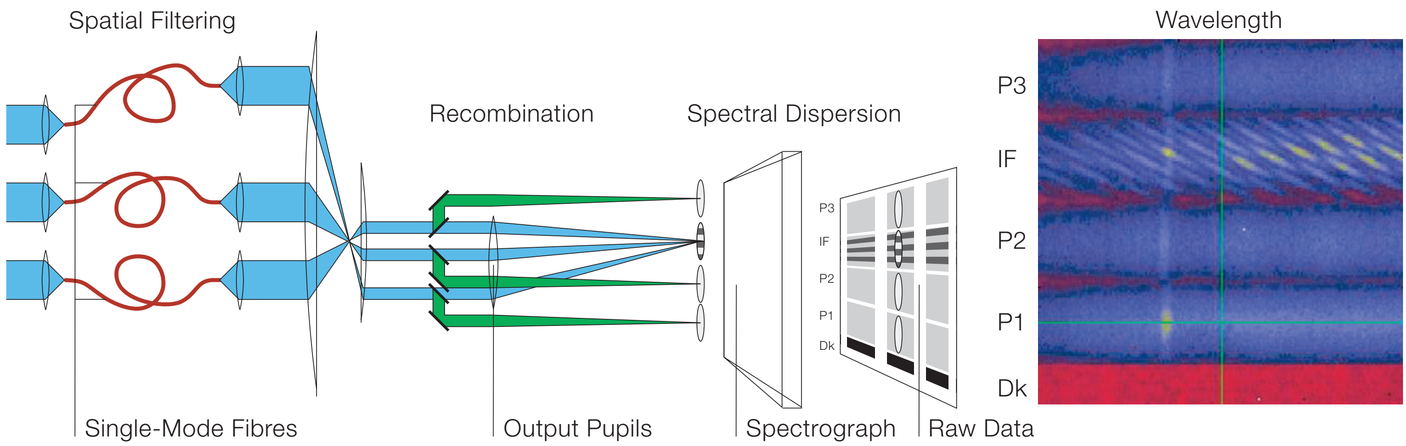

Figure 2 (above): The basic concept of AMBER (see text for details).

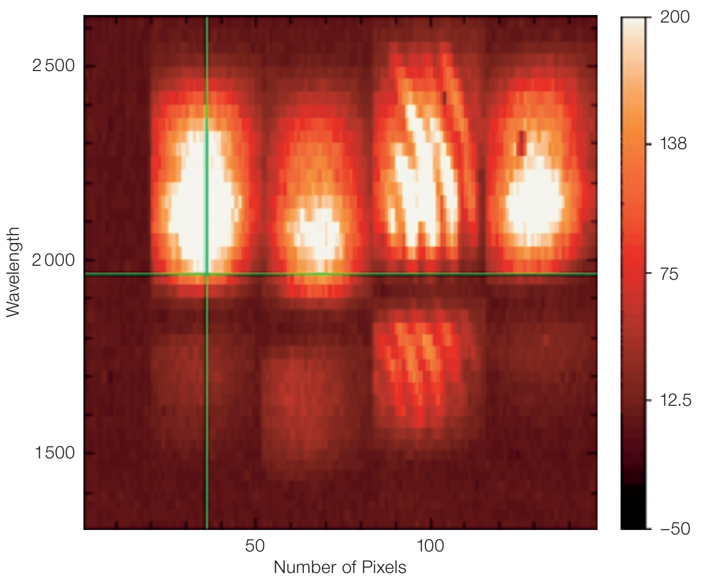

Figure 3: Raw detector image from AMBER obtained in the three-telescope low-resolution mode on the star τ Bootis in April 2006.

the average visibility of a reference channel. The differential visibility is independent of most of the systematic effects affecting the absolute visibility, and it does not need the use of a calibrator star. The relative visibility basically yields the same physical information as the spectrally-resolved absolute visibility, but it is much better calibrated, at the cost of losing information on the reference channel.

Differential phase

In optical, as well as in radio astronomy, source phase information refers to the phase of its complex visibility. In a single-mode interferogram, the phase is related to the position of the fringes, and in the absence of nanometer accuracy metrology, the measured phase is affected by an unknown instrumental term linked to the VLTI+AMBER differential piston and to the instantaneous atmospheric piston between the beams of the baseline. A remarkable feature of the differential phase is that, for non resolved sources, it is proportional to the variation of the photocentre of the source. Given sufficient signal-to-noise ratio, the photocentre variation with wavelength can be measured on very unresolved sources with many very rich astrophysical applications.

Closure phase

The closure phase between baselines is the phase of the average 'bispectral product' of the coherent fluxes. It is independent of any terms affecting individual beams including the achromatic piston and the chromatic optical path difference. For any triplet of baselines, the closure phase is zero for an axisymmetric object. For non-axisymmetric candidates, the closure phase varies with the third power of the object angular size when it becomes unresolved. Then, a non-zero closure phase is a strong indication of a source with an interferometrically resolved non-axisymmetric feature.

AMBER operation

AMBER is working within the standard Science Operations framework in use for the VLT instruments. The VLTI Science Operations is described in Rantakyrö et al. (2004). The AMBER general user can concentrate on the scientific objectives of the run rather than on details of the telescopes, VLTI, and AMBER operations. In this framework, the user's main, if not single, concern is to make certain that the proper calibration procedures are used.

The main calibration required is the interferometric calibration of the instrument which is specific to the observing mode. This calibration can be modified by any change in the spectrograph set-up, and the operating procedure will force the observer to measure a new calibration for any new set-up, prior to science observations. The observer must choose between a standard-accuracy calibration, to be within the specifications of AMBER, and a high-accuracy one, to try to approach the goals of highest accuracy.

All interferometric observables, including the differential and the closure phases, are affected by systematic effects that can be removed or reduced using a calibrator star with known complex visibility. An important task for the observer is to choose good calibrators. Ideally a calibrator is a point source; however, finding strictly non-resolved and bright-enough stars is a real problem. A good calibrator is then a single, non-variable star, which can be considered as a uniform disk with a known diameter.

Observing is performed through the VLT control system using the standard tool P2PP (Phase 2 Preparation Package) to create observation blocks. These blocks contain several templates, to set up the instrument, to point the interferometer, optimise the beam injection into AMBER, search for fringes, and acquire observation data. The observation block is executed through BOB (Breaker of Observing Blocks). Some of the templates are executed in parallel, such as the injection of light into the AMBER fibres for each telescope.

AMBER performance

The knowledge of the full VLTI environment (including vibrations, adaptive optics correction, fringe tracker, tunnel turbulence, etc.; see review by Bonnet et al. 2006) is still too preliminary to enable us to predict what would be the ultimate performance of AMBER on the VLTI. Therefore the reader should be guided by the performance given here, which has been secured for the various calls for proposals, but follow the improvements either in *The Messenger* or in the calls for proposals.

In the present state[3], the transmission measured on AMBER and the VLTI shows that the current coherent limiting magnitude on the UTs is K ~ 7 and K ~ 5 on the ATs. This limit can be pushed by up to a magnitude using non-standard DITs and allowing a lower selection of frames with SNR higher than two.

With the ATs, the VLTI+atmosphere fringe contrast already ranges from 0.5 to 0.9.

[3] With a VLTI and atmosphere fringe contrast of 0.12 without frame selection and before any improvement in the vibrations of the UTs.

In present conditions with AMBER taking the full advantage of the FINITO performance, all spectral resolution modes will be accessible on the AT for K ~ 3 in average conditions and K ~ 5 in the 20 % best conditions, with enormous possibilities in stellar physics.

With the UTs, without reducing too much the total throughput, the level of vibration can probably be brought down into the range 150 to 200 nm rms. The contrast, integrating all effects like the atmosphere and residuals from the VLTI, can then reach values higher than 0.6, a performance which is currently obtained on the ATs. Then AMBER on the UTs could reach a coherent limiting magnitude as high as K = 11 in the very best conditions, i.e. routinely K ~ 9 in the future.

References

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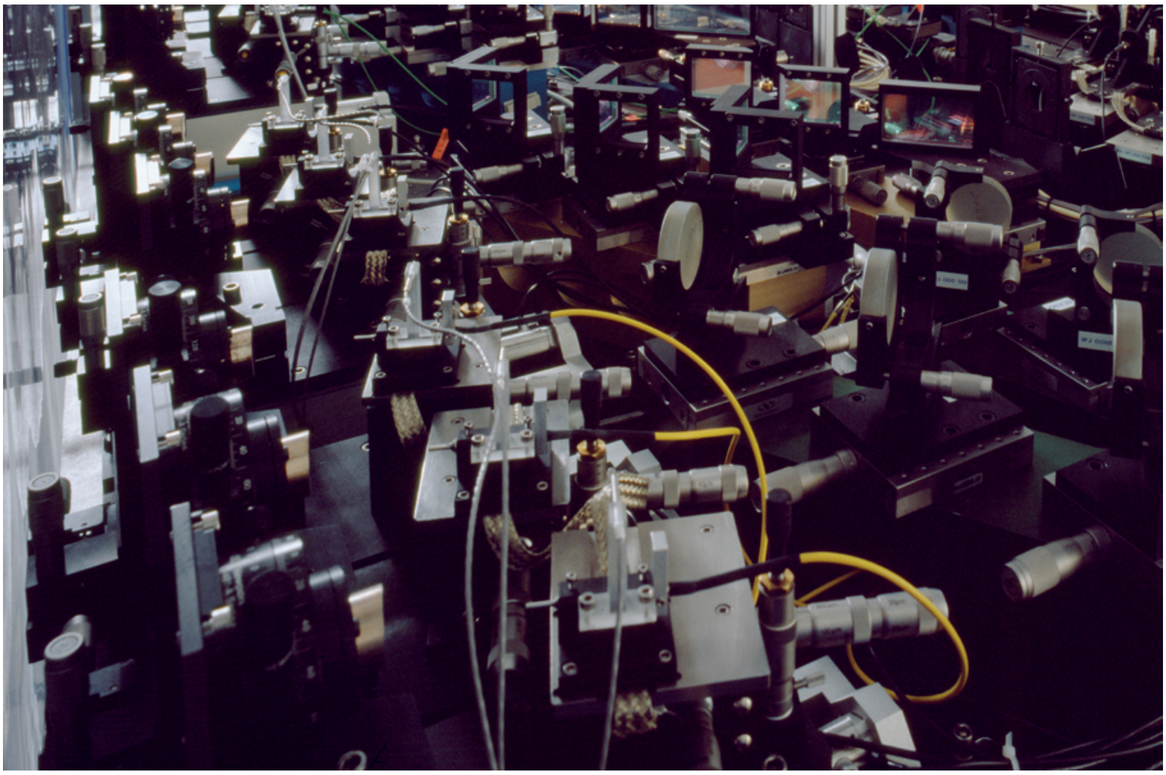
Photo: H. H. Heyer, ESO



The AMBER instrument in the VLTI laboratory at Paranal.