



EUROPEAN SOUTHERN OBSERVATORY

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Very Large Telescope

Paranal Science Operations

AMBER User Manual

Doc. No. VLT-MAN-ESO-15830-3522

Issue 93, Date 30/08/2013

Prepared W.J. de Wit 30/08/2013

Date Signature

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Released A. Kaufer

Date Signature

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Change Record

Issue/Rev.	Date	Section/Parag. affected	Remarks
83.0	2008-09-03	Various sections 1	FINITO use Limiting Magnitudes
83.1	2008-09-12	1	Limiting Magnitudes
84.0	2009-02-07	most of the doc 2.6	removed all VLT specific parts performance table
85.0	2009-08-26	8	a separate section for Calibration plan 'cold' darks
86.0	2010-02-27	7.2 2.6 6.1	1 simple OB is now 25 minutes in LR updated performances in HR-K CAL-SCI-CAL sequence is default
87.0	2010-08-29	8	FINITO tracking info. now recorded
89.0	2011-08-29	7.2 8	OB duration modified (LR:20min,MR/HR:25min) Amber self-coherencing described Minor improvements to the document
90.0	2012-02-24	1	Simple update - No new features
91.0	2012-08-26	8.4	FINITO-RMNREC keywords explained
92.0	2013-02-25	Various sections	Streamlining and upating.
92.1	2013-03-12	8.5	Background on RMNREC data
93.0	2013-08-30	7.2 6.1.3 6.1.3	LR/MR/HR: 20 minute OB duration long calibration sequence specifics cal-sci for HR

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1 INTRODUCTION

AMBER (**A**stronomical **M**ulti-**B**Eam combine**R**) combines interferometrically the near-IR light coming from two or three telescopes of the VLT-I. It measures simultaneously a variety of interferometric quantities: the fringe visibility, differential (with respect to wavelength) visibility, differential phase, closure phase and differential closure phase. These observables measure spatial details of a celestial source at a very high angular resolution, the highest available from any ESO instruments. AMBER can reach an angular resolution of the order of 1 milli-arcsecond ($1\text{mas}=0.001''$) and a spectral resolution of $R\approx 35$ in H and K band (simultaneously), $R\approx 1500$ in H or K (independently), or $R\approx 12000$ in K-band.

1.1 Scope

This document summarizes the modes, possibilities and limitations of AMBER as offered to the ESO community for P93, running from Oct 1st 2013 to March 31st 2014. Only the modes for P93 that are supported by ESO are discussed in this document. Bold-face font is used to emphasize any important issue regarding AMBER in P93 and they should be considered carefully by the reader. This instrument manual should be used in conjunction with the P93 VLT-I user manual available from the [manual webpages](#).

1.2 AMBER news section

At the start of this issue, we would like to highlight the following items:

- For P93, AMBER can be used in a container of cal-sci-cal-sci-cal, which will take 100 minutes of total execution time. It can be used in low spectral resolution and for seeing $< 1.2''$ and thin cloud coverage condition. A waiver needs to be requested. Regular rules regarding successful execution of containers with long execution times apply, i.e. the grading will be based on the first cal-sci-cal sequence only.
- Owing to the AMBER intervention of Jan. 2013, the AMBER limiting magnitudes have been adjusted to somewhat fainter magnitude. Please, consult [the limiting magnitude table](#).
- Since P88, the generated data files contain in addition to the AMBER data also the FINITO fringe-track data, indeed when FINITO is used to stabilize the AMBER fringes. These data allow *a posteriori* calibration and frame selection (see Sect. 8). The corresponding header and data keywords are described in Sect. 8.4.
- Since P91, AMBER employs group-delay tracking (i.e. “self-coherencing”) in both visitor *and* service mode when FINITO is not used (Sect. 2.6.2).
- **The on-sky sequence of observations delivering a calibrated measurement is required to be of the type ‘calibrator-science-calibrator’ (CAL-SCI-CAL) because of the intrinsic instability of the AMBER transfer function.** Programs interested in differential measurements only will be allowed to execute a ‘CAL-SCI’ sequence.

Before initiating an AMBER proposal, the user is kindly advised to consult the AMBER web pages for any late information not included in this manual. The AMBER pages can be found at this URL: <http://www.eso.org/sci/facilities/paranal/instruments/amber/>.

1.3 Contents of the manual

Sect. 2 presents a quick overview of interferometry and details on what AMBER can deliver. Sect. 3 provides a technical description of the instrument, discussing the instrument layout. A reference

to instrument specifics to be kept in mind while planning the observations or when reducing the data can be found in Sect. 4. In Sect. 5, additional information pertinent to observing with AMBER in P93 are presented. Sect. 6 and 7 provide the basic information needed to prepare an observing program. Finally, Sect. 8 presents the current calibration plan for AMBER data and a description of FINITO fringe-track data.

1.4 Contact Information

This document is evolving continually and is updated according to changes in Paranal operations of AMBER or on request by the AMBER user community. All questions and suggestions should be channeled through the ESO User Support Department (email: usd-help@eso.org and home page: <http://www.eso.org/sci/observing/phase2/USD.MIDI.html>). The AMBER home page is located at the following URL: <http://www.eso.org/sci/facilities/paranal/instruments/amber/inst/>.

Any AMBER user should visit the instrument home page on a regular basis in order to be informed about the current instrument status and any late development.

2 Context

2.1 Is AMBER the right instrument for your program?

AMBER is designed to deliver very high angular resolution information on celestial sources. The instrument provides in a decoupling of the single telescopic diffraction limit from the angular resolution limit owing to the instrument's conjunction with the VLT-I telescope/delay-line architecture. It delivers a far higher angular resolution than any other ESO instrument. It also has some strong limitations, which one should be aware of, in order to make sure that AMBER is the right instrument for a given research program.

AMBER does not return a 'mirror image' of a luminous source on the sky. Instead, it combines the light coming from three telescopes (either the auxiliary or unit telescopes) which creates fringes between each telescope pair (see Fig. 1). Each of the three fringe system is characterized by its contrast (also called visibility) and phase. These quantities are related to the brightness distribution of the celestial object. In addition, AMBER disperses the combined light and thus delivers spectrally dispersed data at very high angular resolution (i.e. spectro-interferometry). **If your target has a characteristic size in the range 2-30 milli-arcsecond and it is brighter than K=9, then AMBER can probably bring you information any other ESO instrument cannot.**

2.2 AMBER and other ESO instruments

AMBER yields information at angular resolution scales between λ/B and λ/D , B being the telescopes separations (ranging from 16m to 130m) and D the diameters of the telescopes (8m for the UTs and 1.8m for the ATs). A single-mode instrument like AMBER has no direct access to structures larger than λ/D . One might need in certain cases information at small spatial frequencies (i.e. larger scales) in order to complete the data collected with AMBER. The best-suited ESO instruments that can give access to these data are NAOS/CONICA and SINFONI, which measure diffraction-limited images in the same wavelength domain as AMBER. With NAOS/CONICA it is possible to do both imaging and spectroscopy and SINFONI is unique in that it does full field spectroscopy in a 3" by 3" field. Further information on these instruments can be found at: <https://www.eso.org/sci/facilities/paranal/instruments/naco/> and <http://www.eso.org/sci/facilities/paranal/instruments/sinfoni/>.

The VLT-I offers a second interferometric instrument: MIDI. This instrument operates in the N-band (10 μ m) and combines and disperses the mid-infrared light coming from two telescopes (again either

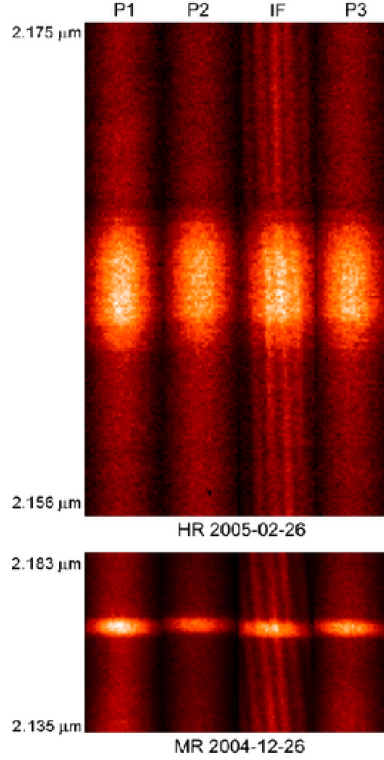


Figure 1: Image of the fringes recorded by AMBER in high (top) and medium (bottom) spectral resolution around the Br γ emission line of Eta Car. The P1-2-3 channels are the photometric channels, IF stands for interferometric channel (Weigelt et al. 2007, A&A 464, 87).

ATs or UTs). Both AMBER and MIDI use the same VLT-I infrastructure, and many aspects regarding observation preparation and scheduling are similar. More information on MIDI can be found at the following web address: <http://www.eso.org/sci/facilities/paranal/instruments/midi/>.

2.3 Optical interferometry basics

The contrast and phase of monochromatic fringes obtained on a celestial source with a telescope baseline B and light wavelength λ yield the amplitude and phase of a Fourier transform component of the source brightness distribution at the spatial frequency $f = B/\lambda$. If the full Fourier transform is sufficiently sampled, i.e. the spatial power spectrum of the source's brightness distribution is sampled at many different spatial frequencies, then an inverse Fourier transform yields a model independent reconstruction of the source brightness distribution at the wavelength λ and an angular resolution $\lambda/B_{\max}$. There are two ways to collect and sample the Fourier transform of spatial information in order to assess the geometry of the source: 1) obtain data on different baselines triplets 2) rely of the natural “super synthesis” by earth rotation and 3) the fact that AMBER records data simultaneously in many spectral channels.

Currently, most AMBER observations do not aim for image reconstruction, since it requires a very large quantity of data (hence a great amount of observing time). Not all science programs have goals which need imaging, because the information provided by one AMBER single observation is already rich. There are different observables, which can be grouped as follow:

- the visibility amplitude is related to the object's projected size along the projected baseline vector. The morphology of the object can therefore be retrieved through a modelling of the brightness distribution. Visibility will not be sensitive to non centro-symmetric brightness

distributions.

- The phase is not directly measurable by AMBER. However, differential phase and closure phase (the phase of the so called bispectrum) are measurable. **The closure phase and the differential phase are powerful tools to investigate asymmetry in the source geometry.**

It is important to note that the wavelength dispersion gives spatial information of two different kinds. On the one hand, there is the *spectral information* which allows to study the characteristic size of emission line regions, absorption line regions, e.g. with respect to the continuum emission. On the other hand, the wavelength plays a role because different wavelengths have different spatial resolutions: B/λ . In other words, the spectral dispersion helps to fill up the spatial frequency space (called also (u, v) plane, after the usual variables for the spatial frequencies). **One should constantly keep in mind these two complementary roles of the wavelength dispersion.**

2.4 AMBER observables

We introduce here the observables which can be extracted from AMBER data. The instrument delivers the following quantities for spectral resolutions of 35, 1500 and 12000 and a spectral coverage involving the K, H and J bands (see web pages):

- the **absolute visibility** in each spectral channel.
- the **differential visibility**, i.e. the ratio between the visibility in each spectral channel and the visibility in a reference spectral channel (average of several other channels for example).
- the **differential phase**, i.e. the difference between the phase in each spectral channel and the phase in a reference channel.
- the **closure phase** is the phase of the bispectrum computed in each spectral channel. The bispectrum is the complex product of three visibilities along a closed triangle. The closure phase is therefore theoretically equal to the sum of the three phases along the three baselines. This quantity is, to a great extent, independent from atmospheric perturbations.

2.4.1 Absolute visibility $V(f, \lambda)$

One visibility measurement for a single baseline can constrain the equivalent size of the source for an assumed morphology. Visibility measurements for several spatial frequencies (obtained through Earth rotation, different wavelengths, different telescopes combinations) constrain severely the models. The visibility should be carefully calibrated (see Sect. 8).

2.4.2 Differential visibility $V(f, \lambda)/V(f, \lambda_0)$

In some cases, one is interested in variations of size of a target as function of the wavelength. This is the case when observing a structure which is present in a spectral line, whereas the continuum corresponds to an unresolved structure. One can then calibrate the measurement in the line by those in the continuum and the knowledge of the absolute visibility is not required, just the ratio between the visibility at a given wavelength and a reference channel.

Another possible application of the differential visibility is the study of objects with angular characteristic of the order of $\lambda^2/B\Delta\lambda$ ($\Delta\lambda$ is the wavelength range): the visibility will vary inside the recorded band due to the super-synthesis effect. This is, for example, a powerful tool to detect and characterize binary with separation $a \sim \lambda^2/B\Delta\lambda$.

2.4.3 Differential phase

Because the instrument delivers spectrally dispersed fringe information, one can measure variations of the phase with the wavelength. The principle is exactly the same as in astrometry, except that the reference is the source itself at a given wavelength. The most remarkable aspect of this phase variation is that it yields angular information on objects which can be much smaller than the interferometer resolution limit. These features come from the possibility to measure phase variations much smaller than 2π (i.e. 1λ). When the object is non resolved, the phase variation $\Phi(f, \lambda) - \Phi(f, \lambda_0)$ yields the variation with wavelength of the object photocenter $\epsilon(\lambda) - \epsilon(\lambda_0)$. This photocenter variation is a powerful tool to constrain the morphology and the kinematics of objects where spectral features result from large scale (relatively to the scale of the source) spatial features. Note that if this is attempted over large wavelength ranges the atmospheric effects have to be corrected in the data interpretation.

2.4.4 Closure phase

The closure phase, the sum of the phases of the 3 baselines inside a triangle, is independent from any atmospheric and instrumental phase offsets. It is therefore a very robust quantity in terms of calibration stability.

2.4.5 Image reconstruction

Image reconstruction consists in computing an approximation of the object brightness distribution out of the Fourier components measured by the interferometer. In order to get a meaningful image it is important to measure the maximum number of spatial frequencies in the (u, v) plane. This iterative procedure can be carried with several software tools that have been specifically developed for optical interferometry and take into account, among other things, the sparsity of the coverage and the lack of phase information. However the superiority of image reconstruction to model fitting can only appear with a significant paving of the (u, v) plane

In this manual we do not address the question of model fitting or image reconstruction. We focus on the description of AMBER operation and its interferometric observables extraction.

2.5 AMBER characteristics

The main characteristics of AMBER are summarized in Table 1. For offered modes see the [AMBER web pages](#).

2.6 AMBER performances

2.6.1 AMBER accuracies

The following table shows the typical observables accuracies in good conditions (seeing of $0.8''$ with the UTs, $0.6''$ with the ATs, coherence time of 4ms or better), for targets at least 1 magnitude brighter than the limiting magnitudes and with a standard number of frames taken. Better performances can be obtained in better conditions or by stacking more frames (should be specifically asked), see foot notes ^{1,2,3,4} for exceptions. “NG” means not guaranteed.

Table 1: AMBER characteristics

Description	Specification
Number of beams	Three
Spectral coverage	JHK (1 – 2.5 μm)
Spectral resolution in K	$\mathcal{R} \sim 35$ $\mathcal{R} \sim 1500$ $\mathcal{R} \sim 12000$
Spectral resolution in J & H	<i>same as in K</i>
Instrument contrast	0.8
Optical throughput	2% in K 1% in J and H
Detector size	1024 $\times$ 1024 detector array
Detector read-out noise	11.37 e^-
Detector quantum efficiency	0.8
Observables:	
Visibilities	$V(f, \lambda)$
Differential visibilities	$V(f, \lambda)/V(f, \lambda_0)$
Differential phase	$\Phi(f, \lambda) - \Phi(f, \lambda_0)$
Closure phase	$\Phi_{123}(\lambda)$

mode	FINITO	calibrated V	diff. ϕ	CP
low HK	not used	10%	NG	5 ^{o1}
	coherencing	5%	NG	3 ^{o1}
	cophasing ⁴	7%	NG	3 ^{o1}
medium K	coherencing	5%	2 ^o	4 ^o
	cophasing	5%	1 ^o	2 ^o
medium H	any mode ³	5%	2 ^{o2}	4 ^{o2}
high K	cophasing	5%	1 ^o	2 ^o

¹ The closure phase error in low resolution is dominated by systematics, namely a strong dependency of the closure phase with the piston (fringes' phase shift, or OPD shift). We believe it is not possible to reach a better precision, even by stacking frames.

² The medium H band phase products suffer from systematics not understood at the moment.

³ Usually, the use of the fringe tracker biases the calibrated visibility. The main source of bias when using the fringe tracker is when a jump of one fringe does not correspond to a jump of one fringe in the science channel. FINITO operates in the H band, hence AMBER H band data collected using FINITO in cophasing are much less biased than medium K data.

⁴ The precision and accuracy of visibilities can be significantly increased by using *a posteriori* visibility calibration using FINITO recorded data. Technical tests in low spectral resolution mode with an excellent fringe tracking performance (cophasing) have shown that precisions as good as $\approx 1\%$ on squared visibilities could be reached on bright targets. See 8 for a more detailed explanation.

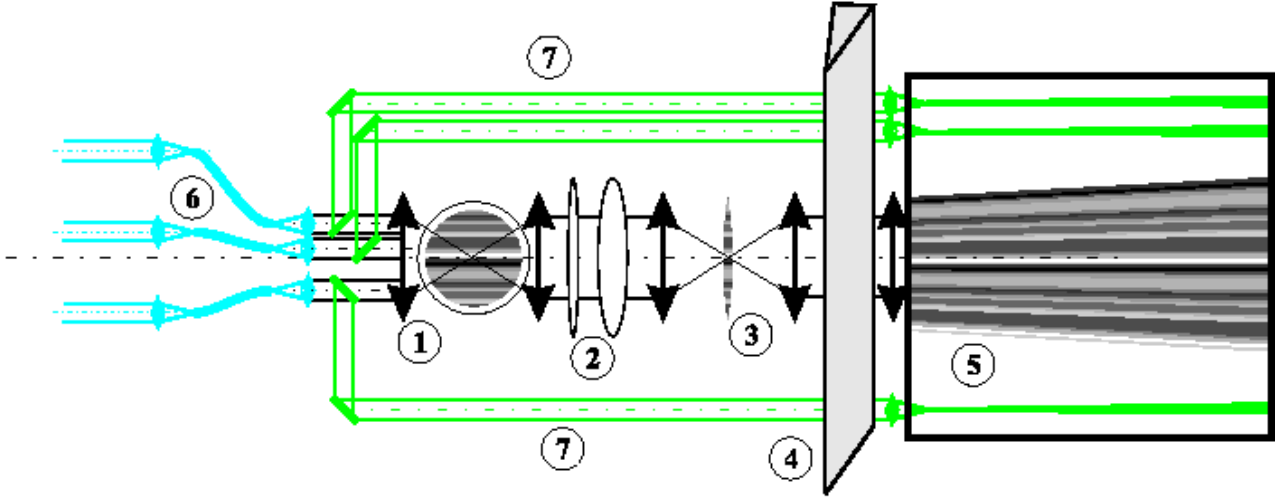


Figure 2: Basic concept of AMBER: (1) multi axial beam combiner; (2) cylindrical optics; (3) anamorphosed focal image with fringes; (4) "long slit spectrograph"; (5) dispersed fringes on 2D detector; (6) spatial filter with single-mode optical fibers; (7) photometric beams.

2.6.2 Self-coherencing

AMBER employs the ability to track the fringes in order to maintain induced optical path fluctuations ("piston") well within the coherence length. This was offered in visitor mode since P89 and in both visitor mode and service mode since P91. Self-coherencing (also known as "group-delay tracking") is always employed when FINITO is not used. At each frame acquisition a quick-look software extracts the main observables from the data: the fringes amplitude, signal to noise and piston. The determined optical path correction is sent as an offset to the delay lines. Since the AMBER observables depend on the *self-coherencing* performances, technical validations show a significant improvement of the data quality. While these numbers are to be taken with caution (good conditions, relatively bright sources), the instrumental transfer function level may increase by several 10% and its stability improved with the largest effect in the low spectral resolution mode. Closure phase accuracy is also significantly increased. This operating mode can be deactivated upon request in the README.

Proposals requiring performances better than these should state how they are going to be obtained (special calibration, large data set, etc).

2.6.3 Performances issues prior to P86

Note that previous to P85, AMBER showed spurious fringing in HR-K, which was difficult to calibrate and led to degraded performances in this mode. A solution has been implemented to fix the problem: the performance of this mode are now similar to performances in MR-K.

3 AMBER overview

3.1 AMBER principle

Fig. 2 summarizes the key elements of AMBER's conceptual design. A set of collimated and parallel beams are focused by a common optical element in a common Airy pattern which contains the fringes (-1- in Fig. 2). The spacing between the beams is selected for the Fourier transform of the fringe pattern to show separated fringe peaks (non-homothetic mapping). The Airy disk needs to be

sampled by many 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. Each spectral channel is thus concentrated in a single column of pixels (-3- in Fig. 2) by cylindrical optics (-2- in Fig. 2). The fringes are dispersed by a standard "long slit" spectrograph (-4- in Fig. 2) on a two dimensional detector (-5- in Fig. 2). 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, it is simply cooled down to liquid nitrogen temperature.

High accuracy measurements require spatially filtered optical beams. The single way to achieve such filtering with decent light transmission is to use single mode optical fibers (-6-in Fig. 2). 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 and sent directly to the detector (-7- in Fig. 2). Before entering the fibers, the beams should be cleaned from the differential atmospheric refraction in the H and J bands or, in some cases, from one polarization.

3.2 AMBER layout

Fig. 3 shows the global implementation of AMBER with the additional features needed by the actual operation of the instrument. The user can find more detailed information in Robbe-Dubois et al. 2007, A&A 2007, 464, 13 and Petrov et al. 2007, A&A, 464, 1.

3.2.1 Warm optics

The three spatial filter inputs (one for each spectral band) are separated by dichroic plates. For example the K band spatial filter (OPM-SFK) is fed by dichroic which reflect wavelengths higher than $2\text{ }\mu\text{m}$ 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 the same spectrograph achromatic optics to be used for all bands and the same sampling of all the central wavelengths to be operated.

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.

3.2.2 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.

3.2.3 Detector

After dispersion, the spectrograph chamber sends the dispersed image on the detector chip (DET).

3.2.4 Calibration unit

The Calibration and Alignment Unit (OPM-CAU) emulates the VLT-I for test and calibration purposes. 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 instrument.

To increase the instrument contrast, one polarization is eliminated by a polarization filter (OPM-POL) located after the dichroics.

3.3 From images to visibilities

The raw data produced by AMBER are images of the coherent overlap of the 3 beams dispersed by a prism (LR) or grisms (MR and HR). One get in addition 3 photometric outputs corresponding to each beam. An image of the detector is displayed in Fig. 1.

The fringes are processed for each wavelength individually. The first action consists in separating the 3 fringes pattern apart. During the calibration, the fringes corresponding to each baseline is recorded. The interference term of the base ij is for the pixel k :

$$m_{ij}(k) = 2\sqrt{P_i P_j} (c_{ij}(k)V_{ij} \cos(\Phi_{ij}(k)) + d_{ij}(k)V_{ij} \sin(\Phi_{ij}(k))) \quad (1)$$

The quantities $c_{ij}(k)$ and $d_{ij}(k)$ are called the carrying waves and are displayed in Fig. 5. The interferogram (subtracted from photometry) can write: $i_{\text{corr}}(k)$ as:

$$i_{\text{corr}}(k) = \sum_{j>i} m_{ij}(k) \quad (2)$$

$$= M(k) \times C \quad (3)$$

where C is a vector of the values (R_{ij}, I_{ij}) corresponding respectively to the real- and imaginary-part of the correlated flux $2\sqrt{P_i P_j} V_{ij}$ for all baselines and $M(k)$ is a matrix with the values of the carrying waves $c_{ij}(k)$ and $d_{ij}(k)$. The matrix $M(k)$ is the so-called pixel-to-visibility matrix (P2VM). The AMBER internal calibration process consists into measuring this P2VM.

The P2VM calibration procedure occurs every time the instrumental setup is changed. The P2VM is automatically included in the standard templates and thus requires no input or configuration by the observer.

4 Instrument limitations and problems

The following caveats and limitations should be taken into consideration:

- Mechanical vibrations. When using UTs, the VLT-I makes use of system that actively reduces the effect of the mechanical vibrations of the telescopes . This system, called Manhattan2, helps to reduce the optical path variations of the beams, but its use makes sense only when the FINITO is used. The reason is that the piston introduced by telescope vibrations is much smaller than that introduced by atmospheric turbulence. Residual vibrations may still exist however, and it prevents a stable transfer function. Absolute data calibration is therefore much better when using the ATs.
- Spectral range. When FINITO is used, for any given spectral mode the full spectral range can be read out on the detector. When FINITO cannot be used, and the DIT is required to be short, then the spectral range which can be read-out from the detector is limited. Detailed information on the wavelength ranges can be found in [this table](#).
- The closure phase error in low resolution is dominated by some not understood systematics. We believe it is not possible to reach a better precision even by stacking frames.
- Medium resolution H band data suffer from systematics in the phases, not understood at the moment.

Fast optical path difference fluctuations due to vibrations and atmosphere lead to:

- a decreased instrument contrast;
- a degraded instrumental contrast stability and therefore a degraded final precision and accuracy of calibrated visibility;

For that purpose, when FINITO is used as a fringe tracker, the fringe tracking data is now recorded to allow post-processing of AMBER visibilities (see Sect. 8.4).

5 AMBER in P93

In P93, the modes offered are the High Resolution K band (HR-K), Medium Resolution K band (MR-K) and H band (MR-H), and the low resolution K and H bands (LR-HK), with a spectral resolution $\lambda/\Delta\lambda$ of approximately 12000, 1500 and 35, respectively.

In LR-HK mode, the K band will be acquired simultaneously with the H band. The laboratory field stabilizing instrument 'IRIS' is always used during an observation and it uses 25% of the K-band flux. Additionally, FINITO uses 70% of the H band flux.

Since P84, FINITO is part of the standard mode in HR-K, MR-K and MR-H (see [here](#)). **Any proposal asking not to use FINITO in these modes should properly explain the reason why and require a waiver.** FINITO fringe tracking information will be recorded with AMBER data (see Sect. 8).

As of P91, AMBER self-coherencing is operational in visitor and service mode. AMBER has the capability to send a correction to the delay line in order to better maintain the fringes within coherence length, by measuring the optical path difference from its fringes. This will result in an increased and more stable instrumental contrast, and a less dispersed closure phase.

See the AMBER instrument webpage: <http://www.eso.org/instruments/amber/inst/> for the most recent information on the exact wavelength ranges and section 6.2.1 for the configuration options for the spectrograph.

5.1 Service and Visitor Modes

For P93, AMBER is offered in service mode and in visitor mode (see Sect. 10 for the definition of these modes). During an observing period, the unique contact point at ESO for the user will be the User Support Department (email: usd-help@eso.org and homepage: <http://www.eso.org/sci/observing/phase2/USD.MIDI.html>).

The visitor mode is more likely to be offered for proposals requiring non-standard observation procedures. The OPC will decide whether a proposal should be observed in SM or VM. As for any other instrument, ESO reserves the right to transfer visitor programs to service and vice-versa.

6 Preparing the observations

Proposals should be submitted through the ESOFORM. Carefully read the following information before submitting a proposal, as well as the ESOFORM user manual. The ESOFORM package can be downloaded from: <http://www.eso.org/observing/proposals/> Considering a target which has a scientific interest, the first thing to do is to determine whether this target can be observed with AMBER or not.

Please note that the limiting magnitudes for AMBER observations depend on the seeing and sky transparency, and that appropriate weather conditions have to be requested in the Phase 1 proposal. The details of the current magnitude limits can be found at the AMBER instrument webpage: <http://www.eso.org/instruments/amber/inst/>.

6.1 Proposal guidelines

For general information about the VLT-I facility, please refer to the [VLT-I User Manual](#)

6.1.1 Guaranteed time observation objects

Check any scientific target against the list of guaranteed time observation (GTO) objects. This guaranteed time period covers the full P93. Make sure the target has not been reserved already. The list of GTO objects can be downloaded from: <http://www.eso.org/sci/observing/teles-alloc/gto.html>.

6.1.2 Time critical, combination of triplets

For successful observations in either service or visitor mode, it is very important that special scheduling constraints such as the combination of different triplets within a certain time range or other time-critical aspects are entered in Box 13 'Scheduling Requirements'. The proposal should also be marked as time critical (see the ESOFORM package for details).

6.1.3 Calibrator Stars

The user should use appropriate calibrator stars in terms of target proximity, magnitude and apparent diameter. It should be provided by the user with the submission of the Phase2 material. To help the user to select a calibrator, a tool called "CalVin" is provided by ESO, see here: <http://www.eso.org/observing/etc/>. Three calibration sequences are offered in service mode:

- SCI-CAL (first science then calibrator) is reserved to program only requesting differential quantities. **This is the default mode for the HR setting, as the HR setting does not allow any reliable absolute visibility calibration.**
- CAL-SCI-CAL (science bracketed by calibration) is mandatory for any program requesting absolute calibration and **therefore is the default mode.**
- As of P93 a long calibration sequence of CAL-SCI-CAL-SCI-CAL is offered. Restrictions apply: only LR, seeing $< 1.2''$ and THN conditions. Regular rules regarding successful execution of containers with long execution times apply, i.e. the grading will be based on the first cal-sci-cal sequence only ([see here](#)). A waiver is mandatory.

Further details can be found in Section 8.

6.1.4 Field of View

AMBER is a single-mode instrument and therefore the field of view (FoV) is limited to the Airy disk of each individual aperture, i.e. 250 mas for the ATs in K and 60 mas for the UTs in K. For most observations this will not have consequences but can be limiting to observations of objects that consists of several components *e.g* binaries, stars with disk and/or winds, etc that have a spatial extension equal or superior than the interferometric FoV. While such observations are not impossible the observer will have to take into account this incoherent flux contribution in his data analysis.

6.1.5 Complex fields

When observing complex fields within a few arcseconds, it is necessary that MACAO/STRAP behaves very well in order to disentangle the desired object from others (see VLT-I Users Manual for seeing and limiting magnitude of STRAP/MACAO). However, for fields with several objects within 1 to 3

arcseconds it is not guaranteed that MACAO will perform properly. It is therefore recommended to use a guide star in this situation.

For fields with objects with separations less than an arcsecond MACAO will resolve the objects down to ~ 0.1 - 0.15 arcsec. For separations smaller than ~ 0.3 arcsec, it cannot be guaranteed that the proper target has been injected into the fiber. These acquisitions have to follow a non-standard extensive procedure and require the presence of the PI in Visitor Mode.

6.1.6 Bright objects

In Low Resolution observations (LR) of very bright objects ($K_{\text{mag}} < 0$), the detector can saturate even when using Neutral density filters during excellent weather conditions. The user should consult the webpages for the latest information on the magnitude limits. If possible the user should try to use the MR spectral configuration if the scientific goals still can be achieved in this mode.

6.2 Choice of the AMBER configuration

6.2.1 Instrument set-up

The instrument set-up is defined by the spectral configuration of the instrument and the 3T configuration.

Any change of the spectral configuration requires an internal calibration, i.e. spectral calibration and P2VM calibration. This is automatically taken care of by the internal calibration plan and no action or setups are needed from the user. Note that only one spectral configuration is allowed in one OB. Any change of the neutral densities, the ADC, the position of the fiber heads, i.e. all elements located before the spatial filters does not require internal calibrations. They can be used or not depending on the source characteristics.

6.2.2 Observing modes

Without FINITO, only fixed DITs of 25, 50, or 100 ms (ATs only) are offered. With FINITO longer DITs are available. In MR-K and HR-K, the choice of short DIT restrict the width of the central band. The details on the exact wavelength ranges, DITs, and central wavelengths available can be found on the AMBER Instrument webpage <http://www.eso.org/instruments/amber/index.html>.

7 Introducing Observation Blocks (OBs)

For general VLT instruments, an **Observation Block (OB)** is a logical unit specifying the telescope, instrument and detector parameters and actions needed to obtain a **single** observation. It is the smallest schedulable entity which means that the execution of an OB is normally not interrupted as soon as the target has been acquired. An OB is executed only once; when identical observation sequences are required (*e.g.* repeated observations using the same instrument setting, but different targets or at different times), a series of OBs must be constructed.

Because an OB can contain only one target, science and associated calibration stars (cf. Sect. 8) should be provided as two different OBs. Thus each science object OB should be accompanied by a calibrator OB. These OBs should be identical in instrument setup, having only different target coordinates.

Moreover with single-telescope instruments, any OB can be performed during the night. In the case of interferometric instrument, the instant of observation define the location of the observation in the (u, v) plan.

7.1 Standard observation (OBS_Std)

A standard observation with AMBER in P93 can be split in the several sub tasks (see Fig. 6):

1. Configuration: Setup of the desired spectral resolution, wavelength range and DIT.
2. Internal calibration of the chosen instrument configuration (P2VM) see sec. 3.2.4.
3. Acquisition: Slew telescopes to target position on sky, and slew the delay-lines to the expected zero-OPD position.
4. As stated in VLT-I User Manual, the user has the possibility to use a guide star for the Coude systems, different from the target. Refer to this manual for the limitations of this option.
5. Fringe Search: Search the optical path length (OPL) offset of the tracking delay-lines yielding fringes on AMBER (actual zero-OPD), by OPD scans at different offsets. When fringes are found the atmospheric piston is calculated and the OPL offsets corresponding to zero-OPD are applied.
6. If FINITO is used the above step is performed by FINITO and not by AMBER.
7. Observations: Start to record data of interest with suitable DIT. In P93 it is foreseen to only use DITs of 25 ms or 50 ms for standard absolute phase observations, and DITs of 100 ms for differential phase observations. The longer DIT allows a larger wavelength range in MR-K, MR-H or HR-K observations.
8. If FINITO is used longer DITs are available.

7.2 Computing time overheads for added bands

NEWS: As of P93, the execution time of MR and HR OBs is reduced from 25 to 20 minutes. This implies that the execution of an OB is 20 minutes in each of the three spectral settings. Hence, the default CAL-SCI-CAL sequence requires 60min (3 OBs) regardless of spectral setting.

Users interested in several spectral positions should add 15 minutes for each additional spectral band per OB. Similarly, users interested in repeating the same spectral band to obtain more frames should add 15 min per OB. A maximum of 2 additional bands per observation (*i.e.* per OB) is allowed.

8 Calibration Plan

8.1 Data products

The observatory shall provide the following calibrations to science (SCI) or calibrator stars (CAL) data:

1. daily: darks obtained with the same DITs as the data. Two different types of darks are provided (see Sect. 8.2).
2. daily: sky obtained with the same DITs as data, taken right after the "on target" data.
3. daily: "Pixel to Visibility matrix" (P2VM) for all observations. All pairs SCI-CAL or triplet CAL-SCI-CAL should be taken with the same P2VM, taken prior to the sequence. The validity of the P2VM is 6 hours.
4. at period change or any instrument intervention: "bad-pixel" and "flat-field" maps.

8.2 Dark frames

We provide two different types of dark frames: 'cold' and 'warm' darks. Cold darks are taken by closing the spectrograph with a cold metallic patch, so the detector sees an element at the temperature of the cryostat. Conversely warm darks are taken by closing shutters outside of the cryostat, hence there will be a residual of thermal emission (especially at longest wavelengths).

Warm darks are taken right before the observations, whereas cold darks are taken the following morning. The reason why the cold darks cannot be taken simultaneously is because the cold patch is on the same wheel as the spectrograph slit. Hence, taking cold darks for every observations is not possible without moving the grism wheel every time. This is why cold darks are taken in the morning.

It is recommended to use 'cold darks' and 'sky' for the actual data reduction. 'Warm darks' are currently kept for consistency with the previous observation procedure.

8.3 Calibrator stars

Calibrator stars are stars with known angular diameters, yielding to the highest possible visibility, knowing that:

- fringes' SNR should be comparable between SCI and CAL.
- CAL should be as close as possible to SCI (ideally $\leq 25\text{deg}$ and similar airmass).
- CAL should be observable one hour before AND one hour after the SCI target. This is to ensure that it can be observed after or before the SCI if the later has been observed at the limit of its LST constraint. In the case of bracketed observations (i.e CAL-SCI-CAL) and impossibility to find a calibrator observable before and after a second calibrator should be used.

Considering that the choice of calibrator can be tailored to the actual specificities of the scientific goal, the users are responsible for the choice of their calibrators, and the creation of the subsequent OBs. ESO offers the CalVin tool¹ to chose the calibrator stars.

The observation of calibrator stars are used to measure the transfer function of the instrument, namely:

- visibility transfer function: $V_{\text{inst}}^2 = (V_{\text{measured}}^2 / V_{\text{expected}}^2)_{\text{CAL}}$ the calibrated visibility is estimated by: $V^2 = (V_{\text{measured}}^2)_{\text{SCI}} / V_{\text{inst}}^2$.
- phase closure transfer function: $CP_{\text{inst}} = (CP_{\text{measured}} - CP_{\text{expected}})_{\text{CAL}}$ the calibrated phase closure is estimated by: $CP = (CP_{\text{measured}}) - CP_{\text{inst}}$.

Other quantities can be calibrated, for example the chromatic phase dispersion. The chromatic phase dispersion is a function of the air path between each pair of telescopes. With many CAL at different DL stroke, one can compute a polynomial fit to the differential phase and extrapolate the polynomials coefficients as a function of air path difference.

All calibrator stars observation (DPR.CATG='CAL') are made public by ESO, so users can retrieve all calibrators taken in a given night in order to refine their estimation of the transfer function.

Sequence CAL-SCI-CAL should be used if absolute products will be used: this is the most common case. Some particular programs only require differential interpretation: users should use the SCI-CAL sequence for this special programs.

¹<http://www.eso.org/observing/etc/>

8.4 FINITO fringe tracking information

8.4.1 Principle

Even during the shortest AMBER integration times (25 ms) and with FINITO operating correctly the random optical path fluctuations (jitter) have sufficient amplitude to lead to 1) a contrast decrease (therefore a bias) and 2) an unstability of the visibility transfer function. Both linked phenomenon contribute to a significant decrease of AMBER performances.

During one AMBER frame acquisition residual fringe motion reduces the fringe contrast by a factor $\exp(-\sigma_\phi^2)$ where σ_ϕ is the fringe phase standard deviation over the frame acquisition time. Therefore, since the jitter varies with time, this attenuation factor is unfortunately not stable and there is a high probability that data taken several minutes later on the calibrator, will not allow to cancel the term and will result in final biased visibilities.

Since FINITO measures fringe phase several times during one AMBER frame acquisition (typical integration time is of the order of 1ms) it provides a way to compute a contemporaneous estimation of the attenuation factor. Therefore an *a posteriori* frame to frame correction is possible.

8.4.2 Application

The commissioning of the VLT-I Reflective Memory Network Recorder (RMNrec) in February 2008 has made possible to store the real-time FINITO, OPDC (Optical Path Difference Controller Machine) and Delay Lines data into proper FITS files. Preliminary results published by Lebouquin et al. (SPIE 2008,7013, p33, Schöller et al. eds.) have shown encouraging perspectives for AMBER data post-processing using FINITO data. These results have been confirmed by technical tests which have shown the possibility for a very significant increase in visibility precision and have motivated the decision to include FINITO data within AMBER data. However the reader should be warned that performant corrections can only be reached if FINITO performs well (cophasing) i.e if the source is bright and not too resolved. Also it is important to note that the latest version of the amdlib pipeline (3.0) does not include the post-processing. This correction is therefore left to the observer. Further testing will be carried in the future to better constrain the observational specifications requested to obtain good results.

8.5 AMBER/FINITO: RMNREC data description

8.5.1 General

When the FINITO fringe tracker [6] is used with AMBER [7], real time data are recorded along the raw AMBER frames. These additional data can be used to refine the data reduction of AMBER [8,9]. They are generated by continuously recording the content of the Reflective Memory Network (RMN) [5] and can be found as binary extension in the AMBER FITS files: **'FNT1'**, **'FNT2'**, **'OPDC1'** and **'OPDC2'**. FNT extensions refer to the raw FINITO data, whereas the OPDC tables contain data regarding the active control of the optical path delay, as the name suggests: OPDC stands for Optical Path Delay Controller.

In main header:

The main header contains a lot of information, and allows in particular to reconstruct the configuration of the VLTI at the time of the observations:

- telescope's stations configuration is retrieved: `HIERARCH ESO ISS CONF STATIONi`, for *i* in [1,2,3]
- AMBER configuration (its three beams) corresponds to VLTI input channels: `HIERARCH ESO ISS CONF INPUTi` for *i* in [1,2,3]

- `HIERARCH ESO DEL FT SENSOR` is set to 'FINITO' if FINITO was used, 'NONE' otherwise.

FINITO beams are denoted 0,1,2. The correspondance can be quite confusing bu the following table gives the standard configuration:

Input channel	AMBER	FINITO
1	1	2
3	2	0
5	3	1

Other FINITO important parameters can be found with keywords starting with `HIERARCH ESO ISS FNT`

Timing issue:

Each AMBER frame has a time stamp in MJD (column `TIME`). RMNREC data use microseconds since the date `HIERARCH ESO PCR ACQ START` in the main header. The two are not synchronized perfectly, because:

- Unlike FINITO, AMBER is not on the reflective memory network (RMN) of the VLTI: it means fine time alignment is required in post processing to aligne FINITO data on the AMBER data.
- AMBER frames are tagged in MJD with a time accuracy of $1e-8$ days, or 0.87 milliseconds. This is an ESO standard and cannot be changed easily.

While converting UT times to MJD, It is a good idea to check the UT date to MJD formula using the Header the values of "MJD-OBS" and "DATE-OBS".

8.5.2 OPDC1, OPDC2

These two tables are for the channel 1 and 2 of FINITO, which corresponds to the optical combination of FNT0-FNT1 and FNT0-FNT2 respectively, that is AMBER beam2-beam3 and AMBER beam1-beam2.

- `TIME`: in micro seconds since "HIERARCH ESO PCR ACQ START"
- `rtOffset`: real time offset, pure accumulated tracking of FINITO, in meters
- `fringeFlag`: obsolete
- `offValid`: obsolete
- `opdcState`: state machine controller

state
0 idle
1 fringe search
2 on hold
3 group delay jump
4 group delay tracking
5 on hold
6 phase jump
7 phase tracking

- **unwrapPhase**: unwrapped phase. **This is actually in radians, not meters: files before April 2013 were wrongly labeled.**
- **fullOffset**: offset between the zero OPD prediction and actual position, including instrument offset, refraction and so on. This is in meters.

During the states 2 and 5, no fringe tracking commands are sent as the controller waits for the signal-to-noise ratio to rise above a given level (known as the “close” level). In states 3 and 6, the controller decided that the offset between the target and current position is too large and needs to be corrected via a jump.

8.5.3 FNT1, FNT2

As for the OPDC tables, these two tables are for the channel 1 and 2 of FINITO, which corresponds to the optical combination of FNT0-FNT1 and FNT0-FNT2 respectively, that is AMBER beam2-beam3 and AMBER beam1-beam2.

- **TIME**: in micro seconds since “HIERARCH ESO PCR ACQ START”
- **Coher**: group delay, **in radians, not meters: files before April 2013 were wrongly labeled**
- **CoherFlag**: Obsolete
- **Phase**: fringes’ phase as measured by FINITO, **in radians, not meters: files before April 2013 were wrongly labeled**
- **PhaseFlag**: Obsolete
- **SNR**: Signal-to-noise ratio of the fringes.
- **MOD**: modulation **in radians, not meters: files before April 2013 were wrongly labeled**
- **FNTX1** (resp. 2 for FNT2), **FNTX0**: photometric channels for 1 (2) and 0 (raw data, in ADU)
- **FNTX1A** (resp. 2 for FNT2), **FNTX1B** (resp. 2 for FNT2): interferometric channels (raw data, ADU)

9 Bibliography

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- [4] reference documents (templates, calibration plan, maintenance manual, science/technical operation plan), especially **VLT-MAN-ESO-15000-4552**, the VLT-I User Manual.
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10 Glossary

Constraint Set (CS): List of requirements for the conditions of the observation that is given inside an OB. OBs are only executed under this set of minimum conditions.

Observation Block (OB): An Observation Block is the smallest schedulable entity for the VLT. It consists of a sequence of Templates. Usually, one Observation Block include one target acquisition and one or several templates for exposures.

Observation Description (OD): A sequence of templates used to specify the observing sequences within one or more OBs.

Proposal Preparation and Submission (Phase-I): The Phase-I begins right after the Call-for-Proposal (CfP) and ends at the deadline for CfP. During this period the potential users are invited to prepare and submit scientific proposals. For more information,

<http://www.eso.org/observing/proposals.index.html>

Phase-II Proposal Preparation (P2PP): Once proposals have been approved by the ESO Observation Program Committee (OPC), users are notified and the Phase-II begins. In this phase, users are requested to prepare their accepted proposals in the form of OBs, and to submit them by Internet (in case of Service-mode). The software tool used to build OBs is called the P2PP tool. It is distributed by ESO, and can be installed on the personal computer of the user.

See <http://www.eso.org/observing/p2pp/>

Service Mode (SM): In Service Mode (opposite of the Visitor-Mode), the observations are carried out by the ESO Paranal Science-Operation staff (PSO) alone. Observations can be done at any time during the period, depending on the CS given by the user. OBs are put into a queue schedule in OT which later send OBs to the instrument.

Template: A template is a sequence of operations to be executed by the instrument. The observation software of an instrument dispatches commands written in templates not only to instrument modules that control its motors and the detector, but also to the telescopes and VLT-I sub-systems.

Template signature file (TSF): File which contains template input parameters.

Visitor Mode (VM): The classic observation mode. The user is on-site to supervise his/her program execution.

11 Acronyms and Abbreviations

AD:	Applicable document
AMBER:	Astronomical Multi-BEam Recombiner
AO:	Adaptive optics
AT:	Auxiliary telescope (1.8m)
CfP:	Call for proposals
CP:	Closure Phase
CS:	Constrain set
DI:	Differential Interferometry
DIT:	Detector Integration Time
DDL:	Differential Delay line
DL:	Delay line
DRS:	Data Reduction Software
ESO:	European Southern Observatory
ETC:	Exposure Time Calculator
FINITO:	VLT-I fringe tracker
FT:	Fringe tracker
IRIS:	InfraRed Image Stabiliser
LR:	Low Resolution
LST:	Local Sideral Time
MACAO:	Multiple Application Curvature Adaptive Optics
MR:	Medium Resolution
MIDI:	MID-infrared Interferometric instrument
MIR:	Mid-InfraRed [5-20 microns]
NDIT:	Number of individual Detector Integration
NIR:	Near-InfraRed [1-5 microns]
OD:	Observation Description
OB:	Observation Block
OT:	Observation Toolkit
OPC:	Observation Program Committee
OPD:	Optical path difference
OPL:	Optical path length
Phase-I:	Proposal Preparation and Submission
P2PP:	Phase-II Proposal Preparation
QC:	Quality Control
REF:	Reference documents
SM:	Service Mode
SNR:	Signal-to-noise ratio
STRAP:	System for Tip-tilt Removal with Avalanche Photo-diodes
TBC:	To be confirmed
TBD:	To be defined
TSF:	Template Signature File
UT:	Unit telescope (8m)
VIMA:	VLT-I Main Array (array of 4 UTs)
VINCI:	VLT INterferometric Commissioning Instrument
VISA:	VLT-I Sub Array (array of ATs)
VLT:	Very Large Telescope
VLT-I:	Very Large Telescope Interferometer
VM:	Visitor mode

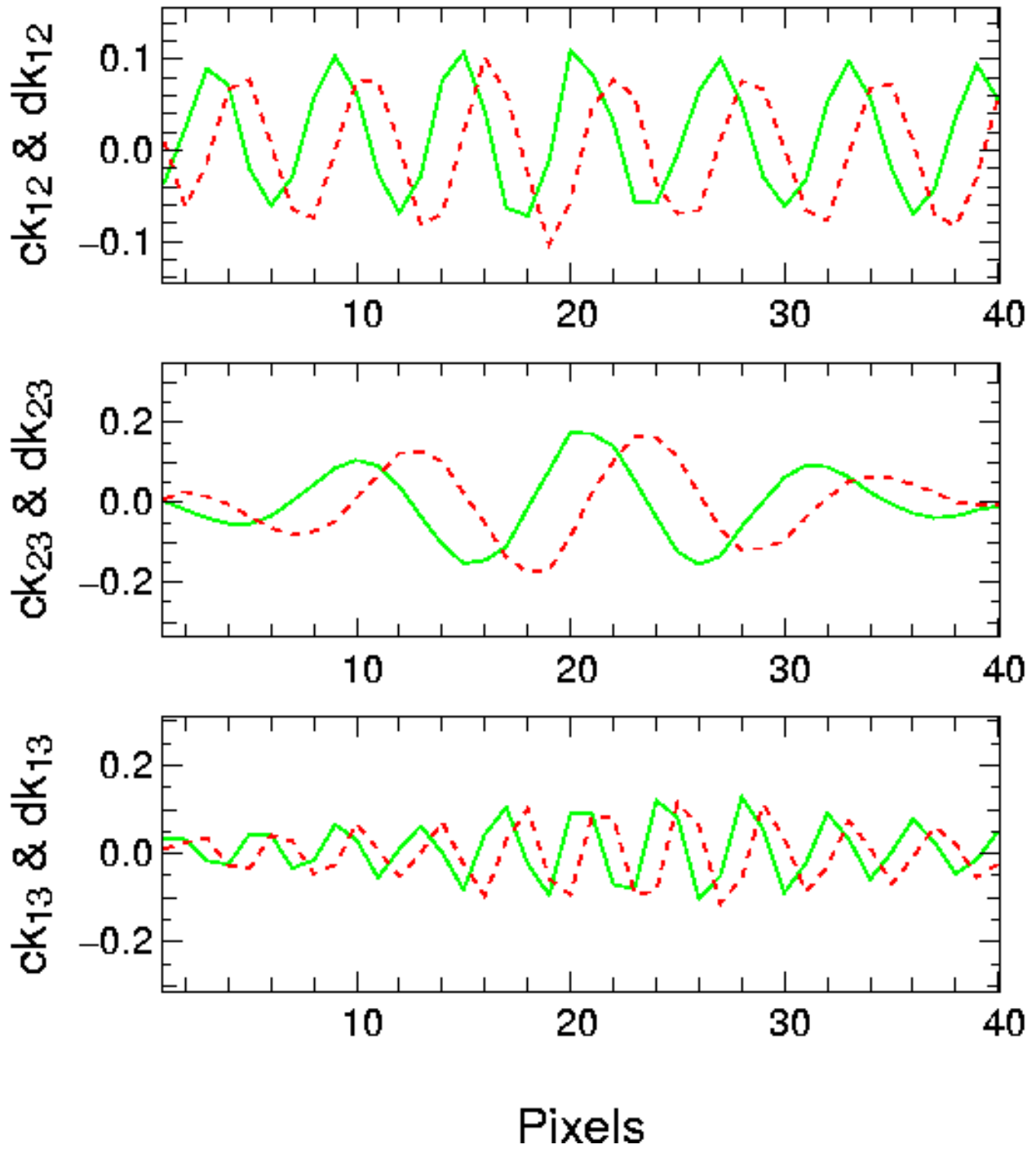


Figure 5: Example of carrying wave $c(k)$ (solid green line) and $d(k)$ (dashed red line).

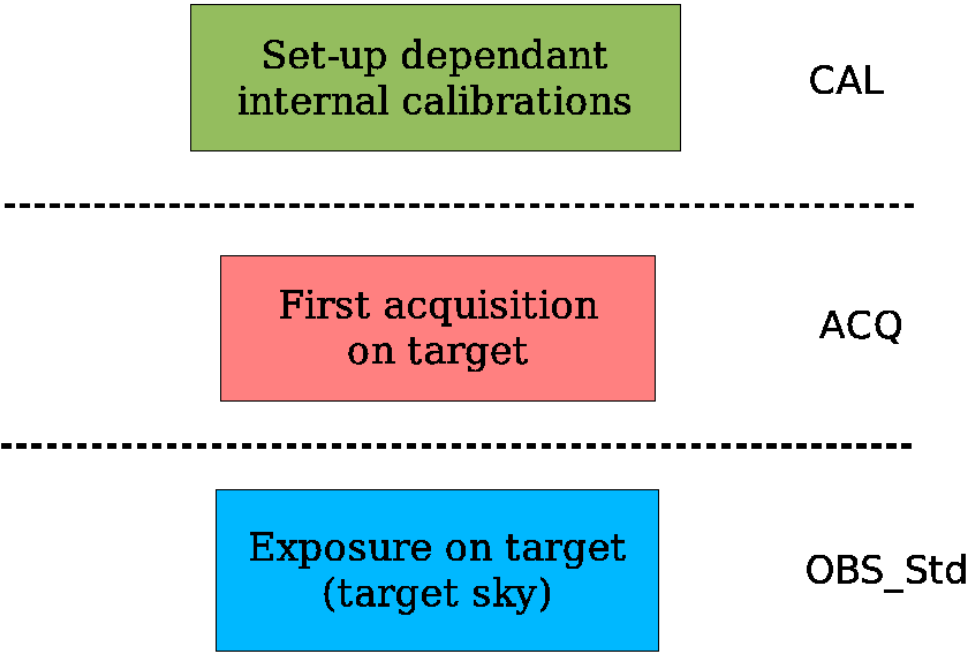


Figure 6: Standard observation mode (Std).