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# Very Large Telescope

## Paranal Science Operations

## Gravity User Manual

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# Contents

# 1 Introduction

Gravity is a four-telescope beam combiner for the VLT-I operating in the K-band. It is equipped with various subsystems in order to precisely correct and control the incoming wavefront from the astronomical source via the telescopes to the Gravity beam combiner. These Gravity sub-systems include a fringe tracker, an IR wavefront sensor (with UTs only), a polarization control system, a pupil-guide and field-guide system. These systems interact and work in harmony with the VLT-I.

Gravity forms spectrally dispersed interference fringes of either a single astronomical source (single-field) or of two sources simultaneously (dual-field). In the latter case, the two sources are required to have a separation less than 2 arcsec when observing with the UTs, or less than 4 arcsec with the ATs. Fringes are produced in two separate channels, the fringe-track (FT) channel and the science (SC) channel. The science channel records the entire K-band at each of the three implemented spectral resolutions of R $\sim$ 22, 500 and 4000. The FT spectrometer always operates at low spectral resolution (R $\sim$ 22).

When observing in dual-field, one of the two sources is injected into the FT channel and its fringe pattern analyzed at a frequency of approximately a kHz. The FT fringe position is used in real-time to correct for the atmospheric and instrumental piston (i.e. a residual optical path difference between beams) by modulating piezo mounted mirrors within the instrument. The FT star thus allows longer detector integration times in the science channel (up to 60 seconds) without compromising the fringe pattern's contrast. Gravity science observations are always assisted by FT observations, unlike other VLT-I instruments like AMBER and PIONIER. In single-field the FT channel and SC channel receive light from the same star. In future calls, Gravity will be offered on the UTs in combination with the CIAO AO module for off-axis IR wavefront sensing.

Gravity provides access to interferometric quantities like absolute and differential visibility, spectral differential phase and closure phase, as well as the differential phase in dual-field between the two sources. These quantities allow reconstructing images at a spatial resolution that can reach 2 mas (depending on VLT-I baseline), as well as time-resolved differential astrometry per spectral bin at the exquisite accuracy of a few tens of $\mu$as.

## 1.1 Scope

The document is intended for science users of Gravity following the call for proposals by ESO. It gives an overview of the instrument and the way it can be used in persuing certain astrophysical programs, especially those that require milli-arcsecond spatial resolution.

## 1.2 Gravity news section

Gravity arrived on Paranal in July/August 2015 and first on-sky commissioning of the instrument took place in December 2015, a process that will continue in 2016 in order to integrate all systems properly into Gravity at VLT-I operations. Gravity science verification (SV) is planned for June and September 2016. The call for SV in P97 will be issued on March 1st with a deadline on March 25th. Before starting a Gravity proposal, the user is kindly advised to consult the ESO Gravity web pages for any late information that could not be included in this manual.

## 1.3 Contents of the manual

Sect. 2 puts Gravity within the ESO context and addresses the theme what Gravity as an astronomical instrument can deliver to science projects. To give background to users with little experience in optical interferometry, the section also presents a brief overview of its principles. Sect. 3 provides a technical but basic description of the instrument. The user is advised to read this section carefully in order to obtain a good idea of the instrument's capacities. A reference to instrument specifics to be kept in mind while planning a program for P98 is provided in Sect. 4. ESO guidelines for a Gravity proposal preparation is presented in Sect. 5. Sect. 6 provides the basic and ESO general information needed to prepare an observing program. Finally, Sect.7 presents the current calibration plan for Gravity observations.

### 1.4 Contact Information

This is a document that evolves continually per ESO period, especially as the instrument is undergoing its period of commissioning. The manual is updated according to changes in Paranal operations of Gravity or on request by the Gravity user community. Questions and suggestions should be channeled through the ESO User Support Department (email:usd-help@eso.org and home page). Further information can be found on the Gravity homepage. Any Gravity user should visit the instrument's home page on a regular basis in order to be informed about the current instrument status and updated developments.

## 2 Context

This section provides the context of the instrument from a science and ESO instrument suite point of view. It expands on the observables delivered by the instrument and how these could fit your science goals.

### 2.1 Is Gravity the right instrument for your science program?

The Gravity instrument is designed to deliver high angular resolution information (on milli-arcsecond scale) on celestial sources by coherently combining the light from four telescopes. The spatial resolution is reached owing to the telescopic baselines of the VLT-I. The user is referred to the VLT-I user manual for the offered telescope configurations, their baseline lengths and position angles. In P98, Gravity is offered in conjunction with Auxiliary Telescopes only and not with the Unit Telescopes.

Gravity has three spectral settings. For each setting it delivers interferometric quantities over exactly the same wavelength range that covers the near-IR K-band. For new VLT-I users, it is good to realize that interferometric instruments like Gravity do not return a mirror image of a luminous source on the sky. Instead, such instruments combine pair-wise the light coming from individual telescopes which creates fringes between each telescope pair (see Figure 1 for an example of the fringes produced by Gravity). Each fringe system per baseline is characterized by fringe contrast and phase. These two quantities are directly related to the brightness distribution of the celestial object according to the Van Cittert-Zernike theorem.

**Gravity can probably bring your science program valuable information which any other ESO instrument cannot if:**

- **your target has a characteristic size in the range 2-30 milli-arcsecond, and**
- **it is brighter than $K = 6.5^m$, or**
- **it is brighter than $K = 9.5^m$ and is accompanied within 4" by a reference star that is at most 3 magnitudes brighter than the science object.**

The Gravity public webpages detail the atmospheric conditions for the limiting magnitudes mentioned here.

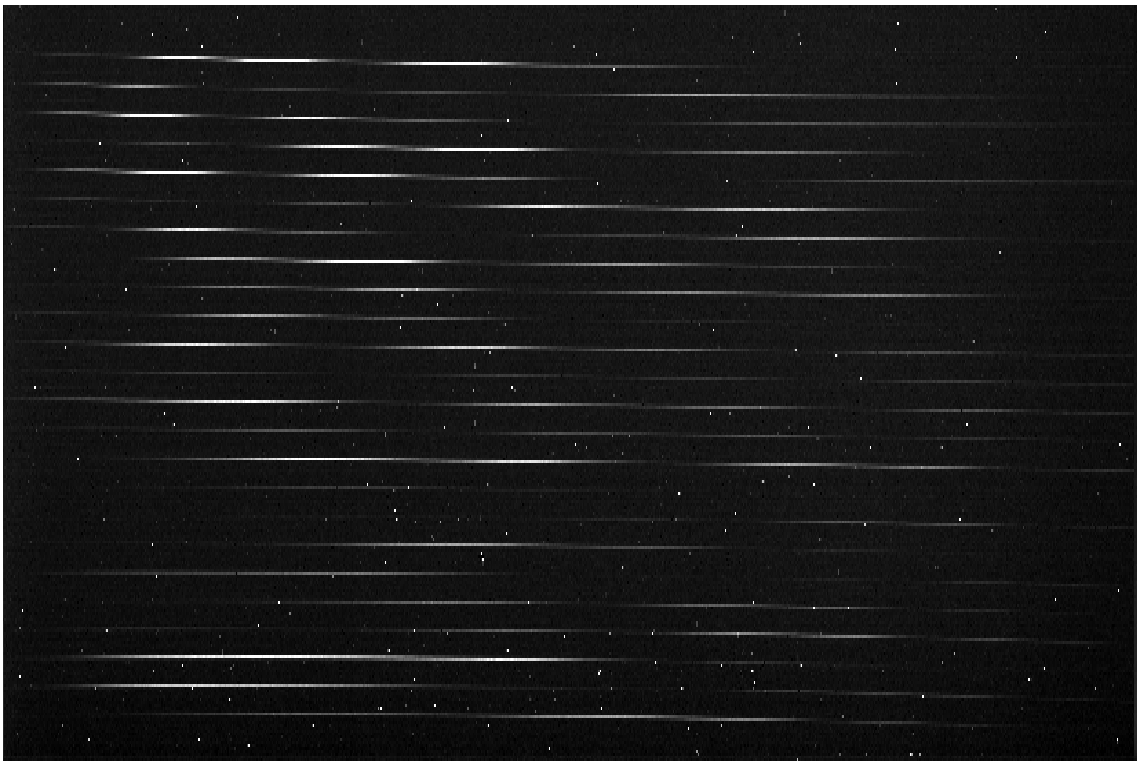

Figure 1: One raw Gravity frame on the science channel. Wavelength runs horizontally. In contrast to other beam combiners, Gravity does not record entire fringe packets but only four points on the central fringe (i.e. the so-called ABCD method of fringe detection). For each polarization, each pair of telescopes yields thus 4 spectra. The fringe can be seen by comparing spectra pertaining to the same pair of telescopes. The total number of spectra is thus 24: 6 pairs of telescopes, 4 points (*viz.* A,B,C,D) per pair.

## 2.2 Gravity and other ESO instruments

Gravity yields information at an angular scale of $\lambda$/B, B being the separation between a telescope pair. An interferometric instrument like Gravity is sensitive to luminous structures with a size-scale corresponding to the spatial frequency $\lambda$/B of the (projected) telescopic baseline. A range of baselines lengths and position angles are required to probe the geometry at different size scales. The largest size-scale that can be proved is given by the shortest baseline which is limited by the smallest separation of two telescopes. Complementary spatial information at larger spatial scales by means of single dish UT observations can be obtained with other ESO facilities, like NAOS/CONICA and SINFONI. These instruments deliver AO assisted diffraction-limited images in the same wavelength domain as Gravity. SINFONI performs integral field spectroscopy with a 0.8" x 0.8" or 8" x 8" field of view at the same spectral resolution as Gravity.

In addition to Gravity, the VLT-I offers two other interferometric instruments, *viz.* AMBER, which is three telescope beam combiner, and PIONIER that combines four beams. AMBER's unique capacity is the much higher spectral resolution of R=12,000 in K-band. AMBER observations can thus complement those of Gravity by providing velocity resolved interferometric observations of many astronomical sources. PIONIER operates in the H-band at low spectral resolution. It provides a 30% higher spatial resolution for continuum observations at shorter wavelengths. Gravity, AMBER, and PIONIER are fed by the same VLT-I infrastructure. Consequently, many aspects of the observation preparation and scheduling procedures are similar. Please, visit the instrument pages that detail the capacities of the ESO suite of instruments.

### 2.3 Optical interferometry basics

For the users who have little background in optical interferometry and would like to use Gravity, a brief and basic summary is provided here of what optical interferometry does and can. For a didactive description of the basics of this technic we refer to the proceedings of the various ESO VLT-I schools, for example the EuroSummer School "Observations and Data Reduction with the VLT Interferometer", New Astronomy Reviews, 2007, Volume 51, Issue 8-9.

The contrast and phase of monochromatic fringes obtained on a celestial source with a telescope baseline $B$ and light wavelength $\lambda$ 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 in the $(u, v)$ plane (so called after the usual variables for the spatial frequencies) then an inverse Fourier transform yields a model independent reconstruction of the source brightness distribution at the wavelength $\lambda$ and an angular resolution $\lambda/B_{\mathrm{max}}$. There are three 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 sextuplets 2) rely of the natural "super synthesis" by earth rotation and 3) the fact that Gravity records data simultaneously in many spectral channels.

An interferometry program would not necessarily aim for image reconstruction. It should be well argued in the phase I proposal when a program's science critically depends on the reconstruction of a high resolution image. The observables produced by e.g. Gravity already allow very detailed analysis of a physical phenomenon near a astronomical source, without the need to fill up the (u,v) plane to a high degree. There are different observables, which can be grouped as follows:

- 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 modelling of the brightness distribution.
- The absolute phase is directly measurable by Gravity only in dual-field mode, i.e. when simultaneosuly fringe tracking on a source which is not the science target. On the other hand, spectro-differential phase (phase difference between spectral channels) and closure phase (the phase of the so called bispectrum) are always measurable. The closure phase and the differential phase are powerful tools to investigate asymmetry in the source geometry. The absolute phase accessible in dual-field mode constitutes a very accurate measurement of the differential astrometry between the FT and SC targets.

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: $B/\lambda$. In other words, the spectral dispersion helps to fill up the $(u, v)$ plane. One should keep in mind these two complementary roles of the wavelength dispersion.

### 2.4 Gravity observables

The Gravity instrument delivers the following interferometry observables for each of the three spectral resolutions provided by the instrument, *viz.* 22, 500 and 4000 and for the full instrument wavelength range (1.99 to 2.45 $\mu$m):

- The absolute visibility in each spectral channel;
- The spectral 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);

- In dual-field mode, the absolute phase (in each spectral channel) using the FT source as reference. This quantity contains the astrometry of the SC source (relative to the FT reference) and encompasses the information contained in the closure phases and the differential phases below;
- The spectral differential phase, i.e. the difference between the phase in a certain spectral channel and the phase in a reference channel;
- The closure phase, being the phase of the bispectrum computed in each spectral channel. The bispectrum is the product of three complex visibilities along a closed telescope triangle. The closure phase is therefore theoretically equal to the sum of the three phases along the three baselines. This quantity is independent from atmospheric perturbations.

### 2.4.1 Absolute visibility $V(\mathbf{f}, \lambda)$

A single visibility measurement on a single baseline can constrain the equivalent size of a partially resolved source for an assumed morphology, e.g. a uniform disk or a ring. Visibility measurements at several spatial frequencies (obtained either through Earth rotation, at different wavelengths or by different telescope combinations) constrain strongly the equivalent size and can provide information on the geometry of the emitting structure. Visibility measurements should be carefully calibrated by means of calibrator stars (see Sect. 7).

### 2.4.2 Differential visibility $V(\mathbf{f}, \lambda)/V(\mathbf{f}, \lambda_0)$

Certain science programs have an interest in variations of a source size as function of wavelength. For example, a structure which emits strongly in a certain spectral transition (a stellar wind) relative to the continuum emission of an altogether different physical structure (a star). The measurement in the spectral line can be calibrated by those of 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 application of the differential visibility is the study of objects with a characteristic angular size of the order $\lambda^2/B\Delta\lambda$ ($\Delta\lambda$ is the wavelength range): the visibility will vary inside the recorded band due to the super-synthesis effect. This is, for example, an appropriate tool to detect and characterize binaries with separation $a \sim \lambda^2/B\Delta\lambda$.

### 2.4.3 Astrometric phase $\Phi_{SC}(\mathbf{f}, \lambda) - \Phi_{FT}(\mathbf{f}, \lambda)$

In dual-field mode, i.e. when the FT reference star is distinct from the SC target, Gravity provides a direct measurement of the science target's phase by using the FT source as a phase reference. Clearly, the nature of the FT source needs to be known. This quantity constitutes a direct measurement of the differential astrometry between the photocenters of the two targets. For this quantity to be meaningful one or several binary calibrators must be observed immediately before or after the science observations and the Gravity metrology must run continuously between the calibration and science observations. Alternatively, if the two targets are bright enough for fringe-tracking, the two fields should be exchanged during the science observation in order to calibrate the metrology directly on the science pair. Assuming that the FT reference is point-like, then $\Phi_{FT}(\mathbf{f}, \lambda)$ is 0. Beware that if the FT reference contains asymmetric structure, then $\Phi_{FT}(\mathbf{f}, \lambda)$ is not necessarily 0 nor even constant.

### 2.4.4 Differential phase $\Phi(\mathbf{f}, \lambda) - \Phi(\mathbf{f}, \lambda)$

Because the instrument delivers spectrally dispersed fringe information, one can measure variations of the phase with wavelength. The principle is exactly the same as in astrometry, except that the reference is the source itself. 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. This results from the capacity to measure phase changes much smaller than $2\pi$ (i.e. $1\lambda$). When the object is unresolved, the phase variation $\Phi(f,\lambda)-\Phi(f,\lambda_0)$ yields the variation with wavelength of the object photocenter. 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 t his is attempted over large wavelength ranges the atmospheric effects have to be corrected in the data interpretation.

#### 2.4.5 Closure phase $\Phi_{ijk}(\mathbf{f},\lambda)$

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. In addition, with 4 telescopes, there are a total of six phases and four closure phases (per spectral channel). Closure phase contains therefore a fraction of the total phase information.

### 2.5 Image reconstruction

By obtaining a dense $(u,v)$ filling of an astronomical source, one can consider to invert the measured Fourier components in order to create an approximation of the object brightness distribution on the sky. In order to get a meaningful image it is important to maximize the number of spatial frequencies in the $(u,v)$ plane. Several software packages have been specifically developed for optical interferometry to reconstruct or invert the image coping with a sparse $(u,v)$ coverage and incomplete phase information. For now, it is the user's initiative to pursue image reconstruction of extensive Gravity datasets.

### 2.6 Gravity characteristics

The main characteristics of Gravity are summarized in Table 1. For details on the offered modes see Sect. 4 and the Gravity web pages for latest information.

### 2.7 Gravity performances

Gravity's typical performance reaches a precision in the visibilities of 5%. A number that has been determined from the first on sky observations during the commissioning of the instrument. In closure phase the instrument reaches about $1^o$ precision. The minimum visibility for which the instrument can still track is about 5%. The science channel will reach saturation at the minimum offered DIT at $K = -2^m$.

Gravity is offered to observe at zenith distance not over $50^o$ for data quality reasons. This limit is the same as the one implemented for FINITO.

Gravity will operate in conjunction with the telescope tip-tilt sensor STRAP on the ATs. STRAP 's limiting magnitude in V=11.0. Details on STRAP can be found in the VLTI user manual.

Gravity is not foreseen to operate with 3 telescopes and indeed is not adapted to handle this.

The above performances are estimates and more knowledge of the instrument will allow to make these estimates of these quantities more precise following more operational experience.

Table 1: Gravity characteristics

| Description | Specification |
|---|---|
| Number of beams | Four |
| Spectral coverage | K-band (1.99 – 2.45 $\mu$m) |
| Spectral resolutions | $\mathcal{R}$ ∼22 |
| | $\mathcal{R}$ ∼500 |
| | $\mathcal{R}$ ∼4000 |
| Instrument contrast | 5% |
| Instrument throughput[1] | ∼20% |
| Observables: | |
| Visibility | $V(f, \lambda)$ |
| Differential visibility | $V(f, \lambda)/V(f, \lambda_0)$ |
| Phase (dual-field mode only) | $\Phi_{SC}(\mathbf{f}, \lambda) - \Phi_{FT}(\mathbf{f}, \lambda)$ |
| Differential phase | $\Phi(f, \lambda) - \Phi(f, \lambda_0)$ |
| Closure phase | $\Phi_{ijk}(\lambda)$ |

[1] Derived in first commissioning and corrected for VLT-I transmission

# 3 Gravity working principles

The goal of the Gravity design is to provide a largely self-contained instrument for precise narrow angle astrometry and phase referenced imaging of faint targets in K-band. The following figures and block diagram illustrate the Gravity concept for the example of Galactic Center observations with the UTs (see Fig. 2). We choose this particular example because it covers most of the operational modes of the instrument. For clarity, only two of four telescopes, i.e. one out of six baselines are shown.

The working principle of Gravity with the UTs is as follows. A bright wave front reference star (IRS7, 5.57" separation, K = 6.5) outside the 2" FoV of the VLTI is picked up by the UT Coudé star separator (STS) and imaged onto the Gravity IR **wavefront sensors** (called CIAO) located in each of the UT Coudé rooms. This bright reference star thus serves as an off-axis AO reference star. The wavefront correction is applied using the MACAO deformable mirrors. Gravity can also be used with the generic MACAO optical wavefront sensors on the UTs. Note that when observing with the ATs tip-tilt guiding at the telescope is performed by STRAP as usual.

The 2" telescopic FoV of the VLTI (UT case; 4" on the ATs) contains both the science target (Sgr A*) and the phase reference star (IRS16C, 1.23" separation, K = 9.7). Both objects are re-imaged via the main VLT-I delay lines onto the Gravity Beam Combiner Instrument. Note that Gravity can operate in single-field and dual-field mode. In the former case, the SC target also serves as FT reference star and the light is 50%-50% split between the two channels.

**Laser guiding beams** are launched at the star separator and telescope spiders to trace tip-tilt and pupil motion, respectively, within the VLTI beam relay. The Gravity beam combiner instrument has internal sensors and actuators to analyze these beams and to apply the corresponding corrections. Longer-term drifts of the object are compensated with the help of the internal **acquisition camera** (working at H-band). This camera also analyses the signal from the pupil-guiding laser beams launched at the telescope spider.

In dual-field mode, the **fiber coupler** then splits the VLTI field containing the two stars and they are injected in separate mono-mode fibres of the science and fringe-track channel respectively. A

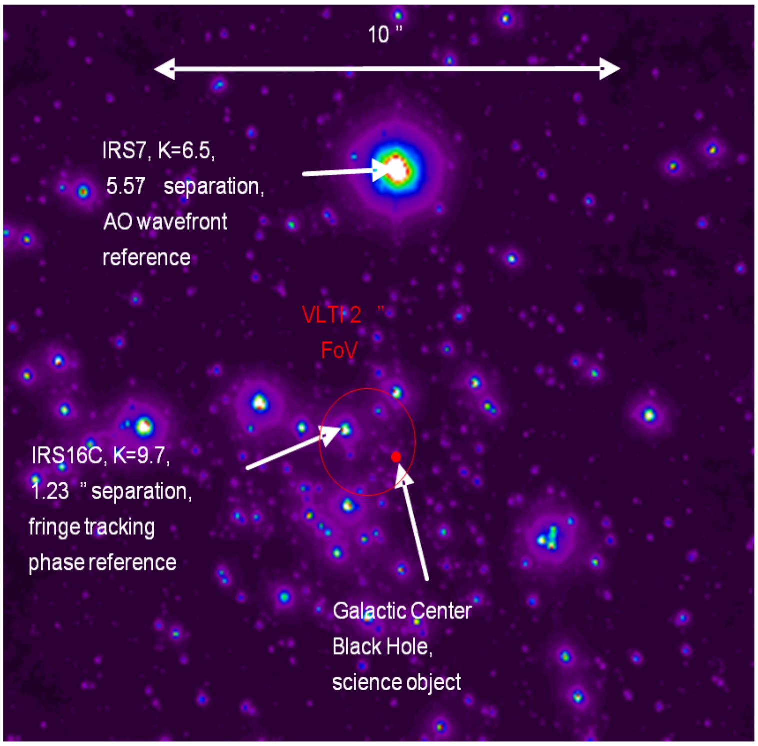


Figure 2: View of the Galactic Center illustrating the required celestial configuration for Gravity AO assisted observations.

rotatable half-wave plate is used to control the linear polarization of the light. In single-field mode, a beam splitter is used instead to inject half of the light from the same source into each mono-mode fiber. A **fiber control unit** including rotators and stretchers align the polarization for maximum contrast, and compensate the differential OPD between the phase reference star and science object caused by the angular separation on sky. The beam combiner itself is implemented in an **integrated optics** chip with instantaneous fringe sampling (following the so-called ABCD method). The bright FT reference star (IRS16C, 1.23" separation, K = 9.7) feeds the **fringe tracker**, which measures the phase and group delay from five spectral channels across the K-band. The OPD correction is applied to a small internal piezo-driven mirror that stabilizes the fringes of both the reference star and the faint science object (Sgr A*) at high frequency.

The **science spectrometer** is optimized for longer, background limited integration times of faint objects, and offers a variety of operation modes, including broad band (ten spectral pixel) observations and low (R 500) and moderate (R 4000) resolution spectroscopy. Both fringe tracker and science spectrometer can be used with a Wollaston prism to split and simultaneously measure two linear polarization states. The differential OPD between the science and reference beam is measured with a **laser metrology system**. The laser light is back-propagated from the Gravity Beam Combiners covering the full beam up to above the telescope primary mirror. The metrology signal is encoded via phase-shifting interferometry and measured by photodiodes mounted to the telescope spider arms. Gravity provides simultaneously for each spectral channel the visibility of the reference and science object, and the phase difference between reference and science object.

The **calibration unit** simulates the light from two stars and four telescopes, and provides all functions to test and calibrate the beam combiner instrument All functions of the beam combiner instrument with the exception of the calibration unit, the metrology receivers, and the guiding lasers are implemented in a cryostat for optimum stability, cleanliness, and thermal background suppression. The cryostat is installed in the VLTI interferometric laboratory. Figure 5 shows an overview of the

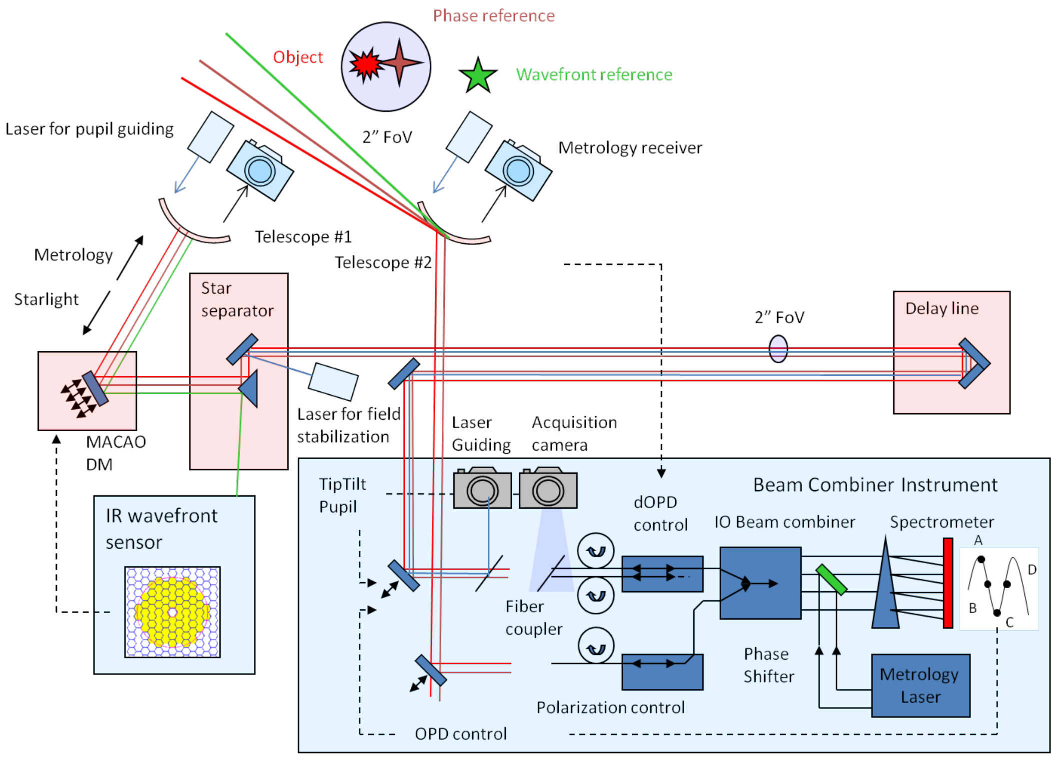


Figure 3: Working principle of Gravity with UTs.

beam combiner instrument cryostat and inside subsystems.

# 4 Gravity in P98

P98 is the first period for which Gravity is offered to the ESO community in open time. Gravity is offered in imaging mode only with auxiliary telescopes for two spectral settings (medium and high).

## 4.1 Offered modes

For this first period of Gravity observations the instrument will be offered in the so-called *imaging mode*, which is different from the *astrometric mode* of the instrument. The latter mode will be commissioned during the forthcoming cycles. In imaging mode, Gravity will acquire interferometric fringes from which visibilities, differential phase and closure phase can be extracted, as explained before. Note that Gravity always observes with four telescopes (ATs only in P98) and with fringe stabilisation by means of the Gravity fringetracker. The interferometry quantities can be obtained from the data by means of the ESO Gravity pipeline. More details on calibrations and calibrator stars can be found in Sect. 5.1.3.

In P98 the user has the liberty in choosing the set-up of the instrument according to their science requirements. In particular the user has to choose the setting of the following instrument functions:

- Polarization: both settings for the wollaston prism are offered, i.e. the so-called split and combined. In combined mode, both polarizations are recorded separately. So far, it has not been possible to detect any significant differences in visibility accuracy between the two settings. The split setting would be appropriate for bright objects for which high accuracy visibilities are requested. The combined setting is appropriate for fainter objects in order to not lose

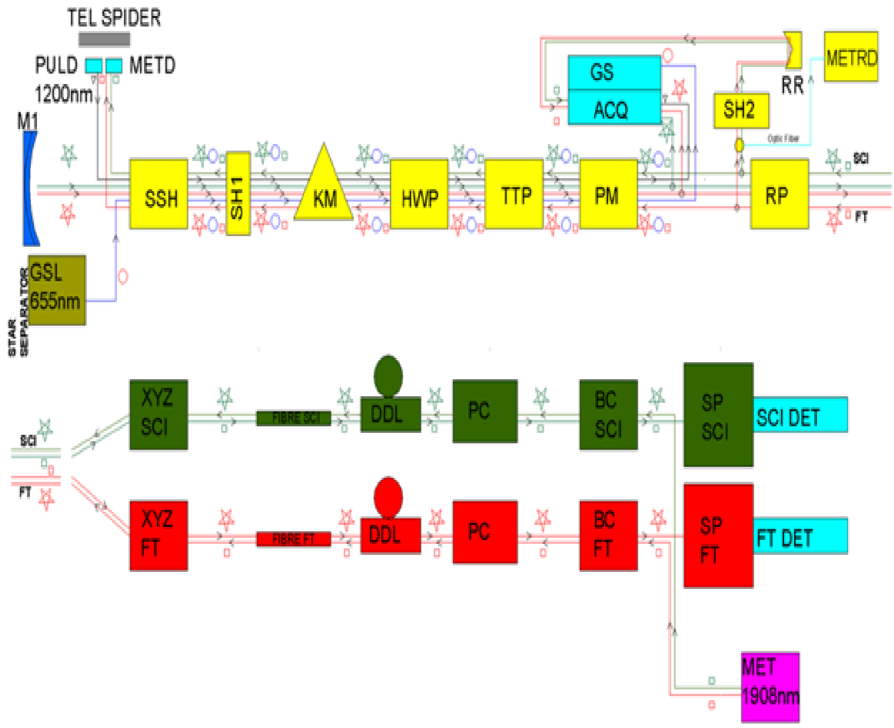


Figure 4: Block Diagram of the Gravity beam combiner instrument. GSL: guiding system laser, SSH: safety shutter, SH1: entrance shutter, KM: K-mirror, HWP: half wave plate, TTP: tip tilt piston mirror, PM: pupil actuator mirror, GS: guiding system sensor, ACQ: acquisition camera, RR: retro-reflector, SH2: shutter for retro-reflector, METRD: fiber coupler diode, RP: roof prism, XYZ SCI: x,y,z stage of science fiber, XYZ FT: x,y,z stage of fringe tracker fiber, FIBRE SCI: science fiber, FIBRE FT: fringe tracking fiber, DDL: differential delay line, PC: polarization controller, BC SCI: science beam combiner, BC FT: fringe tracking beam combiner,SP SCI: science spectrometer, SP FT: fringe tracking spectrometer, SCI DET: science detector, FT DET: fringe tracking detector, METD: metrology diode, PULD: pupil laser diode, MET: metrology laser diode.

half of the precious light. If one can afford to go in split (i.e. enough SNR) then request the split mode. **Important note:** The two polarization settings are implemented in Gravity for contrast reasons and not to measure the intrinsic polarization of the source.

- Field: both settings are offered, i.e. single-field and dual-field. In single field, the science source is also the FT source. The K-band light is split 50% between the two channels. For limiting magnitudes and magnitude difference between the two source we refer to the Gravity public webpages.

- Spectroscopic settings: Gravity is offered in medium (500) and high (4000) spectral resolution. Low-resolution data from the fringe tracker is always delivered together with the science data. tracker. This allows to go fainter, sacrificing the spectral resolution. Unlike the situation with the FINITO data, the fringes of the Gravity fringe tracker are reduced by the data reduction pipeline.

## 4.2 Service and Visitor Modes

For P98, Gravity is offered in service mode except for GTO. During the observing period, the unique contact point at ESO for the user will be the User Support Department (email: `usd-help@eso.org`

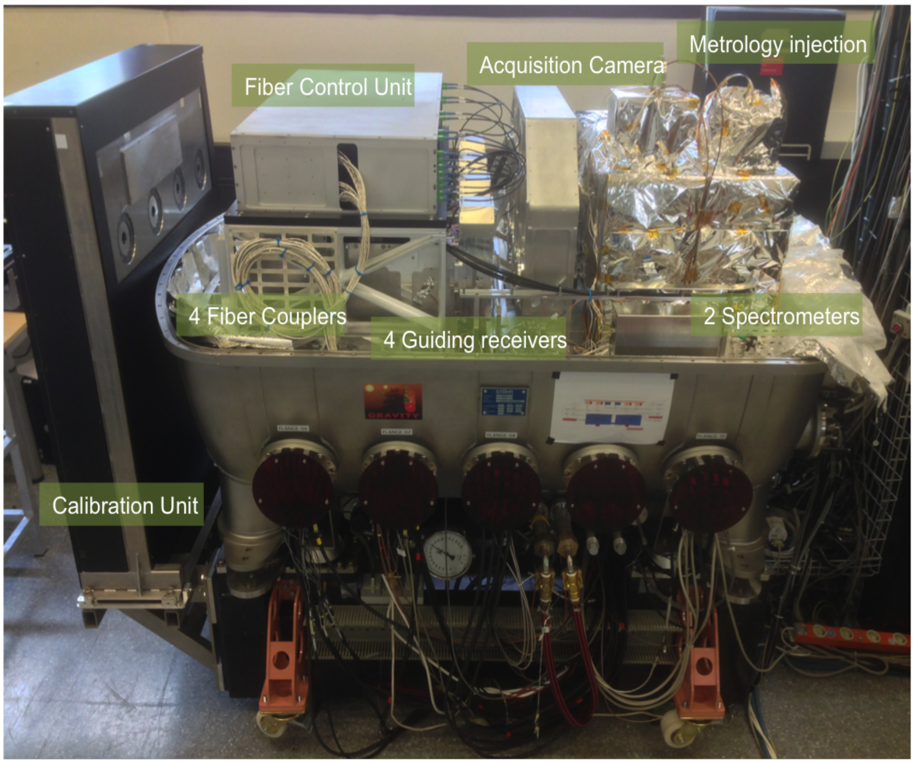


Figure 5: Overview of the beam combiner instrument cryostat and its subsystems in it.

and homepage).
Note, that for this first period of Gravity operation, it was decided to not accept large programs and monitoring programs. These types of program will most likely be available in forthcoming calls.

# 5 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 Gravity or not. Please note that the limiting magnitudes for Gravity observations depend on the seeing and sky transparency, and that appropriate weather conditions have to be requested in the Phase 1 proposal. The current magnitude limits for observations with Gravity can be found on the Gravity instrument webpage.

## 5.1 Proposal guidelines

For general information about the VLT-I facility, please refer to the VLT-I User Manual

### 5.1.1 Guaranteed time observation objects

Check any scientific target against the list of guaranteed time observation (GTO) objects. This guaranteed time period covers the full P98. 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`.

### 5.1.2 Time critical

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).

### 5.1.3 Calibration sequence and total time requested

The user should use appropriate calibrator stars in terms of target proximity, magnitude and apparent diameter. *Ideally*, the calibrator is within $10^o$ on sky and within $0.5^m$ of the science object, yet during commissioning the transfer function has shown to be stable for calibrators with a difference of $1.0^m$. These numbers may become less stringent with an increased understanding of the instrument. Clearly, the calibrator is required to be as small as possible, again, ideally unresolved. The calibrator stars should be provided by the user with the submission of the Phase 2 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/.
Two calibration sequences can be requested (for each spectral setting):

- SCI-CAL (first science then calibrator), which is the standard calibration sequence.
- CAL-SCI-CAL (science bracketed by calibration), which requires a waiver because its execution exceeds 1 hour.

Gravity is offered in fixed slots, up to one hour. The standard mode will be the SCI-CAL sequence, with each OB taking 30 minutes. A second calibrator can be requested through a waiver for a total CAL-SCI-CAL length of 90 minutes. The user is required to provide a clear justification for deviating from the standard calibration sequence. Both single and dual field will use the same length of the OB. While the dual field mode requires a longer acquisition, it is more sensitive. Details on instrument calibration can be found in Section 7.

### 5.1.4 Field of View

Gravity is a dual-field instrument, that's to say that the acquired field with the target source will be split inside the instrument to follow two different beams (FT and SC). The separation between the SC and FT fibres is limited by the VLT-I field of view in the interferometric laboratory: 2" on the UTs, 4" on the ATs. The field of view (FoV) seen by each fibre 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-band. For most observations this will not have consequences but can be limiting the 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. **For SV and P98, Gravity is offered only in conjunction with the ATs, not with the UTs**.

### 5.1.5 Complex fields

When observing complex fields within a few arcseconds, it is necessary that the field contains a dominant, significantly brighter object for the AO or tip-tilt correction (see VLT-I User Manual for seeing and limiting magnitude of STRAP/MACAO). In this case a finding chart must always be provided with the OBs.

### 5.1.6 Bright objects

The user should consult the webpages for the latest information on the magnitude limits.

## 5.2 Choice of the Gravity configuration

### 5.2.1 Quadruplet

Gravity is offered in P98 only in conjunction with the VLT-I auxiliary telescopes. For details on the VLT-I AT configurations, baseline lengths and position angles we refer to the VLT-I user manual. Three AT quadruplets (small, medium and large) are offered. They allow probing three ranges of spatial frequencies. Model-fitting programs should study carefully which quadruplet is the most suitable. For complex or imaging programs it may be necessary to use all three AT configurations. Note however that AT reconfigurations are executed only once every few weeks. The user has to assess whether this is an issue for fast evolving objets.

### 5.2.2 Wavefront sensor configuration

Gravity is used in P98 with the generic optical wavefront sensor on the ATs, STRAP. In forthcoming calls Gravity can be used in conjunction with the UTs and the dedicated Gravity wave front sensing system CIAO.

### 5.2.3 Observing modes: dual-field vs. single-field

The most important choice for the user, which defines the observing mode, is the dual-field vs. single-field choice. Most sources can only be observed in single-field mode, in which case a beam splitter is used to send half of the light to the FT arm and the other half to the science channel. When a bright enough source is available in the VLTI FoV and has a angular distance of maximum 4" and at minimum 1.5", it is possible to fringe-track on this source. This allows observing fainter science targets. For information on the limiting magnitudes see the ESO public web-pages on Gravity.

### 5.2.4 Optical setup: spectral resolution, split or combined polarization

The optical set-up is defined by the spectral and polarimetric configuration of the instrument. The calibrator and science targets should be observed with the very same set-up and only one set-up can be used in a given OB.

For sensitivity reasons, the Gravity spectrometer concentrates all the flux of a single spectral line in less than 2 pixels ($\sim$ 1.5 pixels FWHM at high resolution, 1.82 pixels FWHM at medium resolution). In other words, Gravity is not Nyquist-sampled. This sampling is still sufficient to retrieve the position of a single isolated line to arbitrary precision, limited only by signal-to-noise and systematic effects. However, for more complex spectral energy distributions (e.g. velocity gradients in spectrally unresolved emission lines), the radial velocity accuracy of Gravity should be expected to be limited to one spectral channel (0.24 nm at high spectral resolution, 2.2 nm at medium spectral resolution). In some cases, analysing Gravity data together with integral field or long-slit spectroscopic data at higher resolution will help.

Gravity can operate in two polarimetric modes, *viz.* the split and combined mode. Polarizing effects in the VLT-I give rise to a differential phase between the two polarization states. This is compensated for in combined mode. In split mode, the fringes of the two polarization states are recorded independently. Note, that this optical set-up does not allow a measurement of the source's intrinsic polarization.

# 6 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. 7) 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.

## 6.1 Standard observation (`OBS_Std`)

A standard observation with Gravity can be split in the several sub tasks:

1. Configuration: Setup of the desired spectral resolution and polarization mode;
2. VLTI acquisition: Slew telescopes to target position on sky, slew the delay-lines to the expected zero-OPD position, use the STS to send the field to Gravity;
3. Acquire the MACAO, CIAO or STRAP guide star. As stated in VLT-I User Manual, the user has the possibility to use a guide star for the Coud systems, different from the target. Refer to this manual for the limitations of this option.
4. Depending on the separation between the FT reference and the SC target, set-up the Gravity fiber coupler sub-system: rotate the field, position the beam or field splitter, move the fibers on the two sources;
5. The operator may then check that the acquisition is correct using a finding chart;
6. Optimize flux injection in the FT fiber and optionally in the SC fiber;
7. Search for fringes and close the FT loop;
8. Start recording data according to DIT, NDIT and NEXP.
9. Optionally, move the SC fiber to a sky position (i.e. with no astrophysical source) and record flux to estimate the sky level.

## 6.2 OB continuation

It is possible to repeat the science template in the OB. In dual-field mode, this allows for exchanging the role of the FT and SC targets (e.g. to study both members of a binary), or to move the SC fibre toanother target using the same FT reference (e.g. to study two or more members of a star cluster). As explained in Sect. 8.3, calibration templates can also appear in the science OB.

# 7 Calibration Plan

## 7.1 Summary

Table 3 summarizes the calibration data used by the pipeline to fully calibrate the SC data. The observatory will automatically provide the data in green, but the user is responsible for requesting the data in blue and providing the relevant OB. The user needs only to provide the OB for the mode that is used: either single-field or dual-field.

| Calibration | Template | Frequency | Duration | Pipeline Output |
|---|---|---|---|---|
| Dark | GRAV_gen_cal_dark | Daily | 1min | DARK_SC/FT |
| Flat | GRAV_gen_cal_calunitflat | Daily* | 4min | GAIN_SC/FT<br>BAD_SC/FT<br>PROFILE_SC/FT |
| Wavelength | GRAV_gen_cal_wave | Daily* | 15min | WAVE_SC/FT |
| P2VM | GRAV_gen_cal_p2vm | Daily | 20min | GAIN_SC/FT<br>DARK_SC/FT<br>PROFILE_SC/FT<br>BAD_SC/FT<br>WAVE_SC/FT<br>P2VM_SC/FT |
| Dual-field | GRAV_dual_obs_calibrator | -Required after each metrology loss<br>-Required for visibility calibration<br>-At will of user | 30min | VIS_SC_DUAL_CAL<br>VIS_FT_DUAL_CAL<br>VIS_DUAL_CAL |
| Single-field | GRAV_single_obs_calibrator | -Required for visibility calibration<br>-At will of user | 20min | VIS_SC_SING_CAL<br>VIS_FT_SING_CAL<br>VIS_SING_CAL |
| Dispersion | GRAV_gen_cal_disp | Monthly | 4h | DISP_CAL |

(*) = This calibration is also included in the P2VM calibration template. It is not required if the P2VM template is used.
Blue = user responsible / Nighttime
Green = Science operations / Daytime

## 7.2 Calibrator Stars

The calibrators will be used to estimate both visibilities and phases. The phase referencing can be difficult since we must know the level of asymmetry of the chosen calibrator. Binary or multiple objects, or asymmetric stellar envelopes could create difficulties. The Gravity calibrators have been chosen as close as possible to the single, symmetric, small star paradigm, in order to have a clean reference in particular for the phase. The observation of two calibrators instead of one may be useful in order to check how well the paradigm is fulfilled. The single and symmetric conditions are required in order to have a phase reference with a well-defined behavior. The average phase of the fringes obtained on a binary or asymmetric star changes with the orientation and length of the projected baseline, and can also change with time, e.g. due to orbital motion. A symmetric and single star will have a minimal (ideally zero) and stable intrinsic phase. Moreover, a small angular size of the reference object will improve the robustness of its phase to an intrinsic asymmetry (the smaller angularly, the smaller the phase for a given asymmetry level). A small angular size also is desirable to reduce the effect of the angular extension of the calibrator on the error bars of the visibilities. For instance, lets consider the particular case of a calibrator with the same angular size as the scientific target. Its size is known a priori, as an example from surface brightness considerations, to an accuracy of 2%. Using this calibrator alone, it will be impossible to obtain the angular size of the scientific target with an accuracy better than 2%, due to the systematic nature of the a priori error on the calibrator size. Therefore, the smaller the calibrator, the smaller is the systematic calibration error.

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 $\leq$ 25deg 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 tool[1] to chose the calibrator stars.

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

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

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[2] *The Very Large Telescope Interferometer - Challenges for the Future*, Astrophysics and Space Science vol 286, editors: Paulo J.V. Garcia, Andreas Glindemann, Thomas Henning, Fabien Malbet; November 2003, ISBN 1-4020-1518-6.

[3] *Observing with the VLT Interferometer*, Wittkowski et al., March 2005, The Messenger 119, p14-17

[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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[7] *Gravity: Observing the Universe in Motion.* F. Eisenhauer et al., 2011, The Messenger, Vol. 143, pp. 16-24

# 9 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.

**Dual-Field Mode**: Gravity mode of operation when the FT reference and the SC target are distinct from each other. In this mode, the SC target may be fainter than the FT limiting magnitude, and astrometric phase information can be retrieved. The maximum separation between the two targets is 2 on UTs and 4 on ATs.

**Fringe tracker (FT)**: One sub-system central to the design of Gravity is its fringe-tracker, which analyses the fringes of a reference target in real time to estimate and correct for atmospheric and instrumental piston. This allows integrating longer (up to 1 minute) on the science channel to obtain high signal-to-noise spectra at high resolution. The FT also provides for a natural phase reference in dual-field mode to detect fringes on a faint nearby object and to obtain differential astrometry between the FT and SC channels.

**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.

# 10 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 |
| GTO: | Guaranteed time observations |
| IR: | Infra Red |
| 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 |
| SC: | Science Channel |
| 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 |

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