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Very Large Telescope
Paranal Science Operations
VLTI User Manual

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102.0	25/02/2018	AMBER and FINITO are decommissioned, clarification of the off-axis coude guiding distances	Release for P102 Phase-1
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List of Abbreviations

AGB	Asymptotic Giant Branch
AGN	Active Galaxy Nucleus
AMBER	Astronomical Multi-BEam Recombiner
AT	Auxiliary Telescope
CIAO	Coudé Infrared Adaptive Optics
ESO	European Southern Observatory
FINITO	FrInge-tracker (designed by) NIce and TOrino observatories
FOV	Field Of View
GRAVITY	General Relativity Analysis via VLT InTerferometrY
IRIS	Infra-Red Image Sensor
LST	Local Sidereal Time
MACAO	Multi-Application Curvature sensing Adaptive Optics
MATISSE	Multi-AperTure mid-Infrared SpectroScopic Experiment
MIDI	MID-infrared Interferometric instrument
NAOMI	New Adaptive Optics Module for Interferometry
OB	Observation Block
OPC	Observation Program Committee
OPD	Optical Path Difference
PIONIER	Precision Integrated-Optics Near-infrared Imaging ExpeRiment
PRIMA	Phase-Referencing Imaging and Micro-arcsecond Astrometry
SM	Service Mode
SNR	Signal-to-Noise Ratio
SR	Strehl Ratio
STRAP	System for Tip-tit Removal with Avalanche Photodiodes
STS	Start Separator
TCCD	Technical Charge-Coupled Device
USD	User Support Department
UT	Unit Telescope
VCM	Variable Curvature Mirror
VLT	Very Large Telescope
VLTI	Very Large Telescope Interferometer
VM	Visitor Mode
YSO	Young Stellar Object

1 INTRODUCTION

1.1 Scope

This document summarizes the characteristics and performances of the Very Large Telescope Interferometer (VLTI), as it will be offered to astronomers for the six-month ESO observation period P103 (running from 1 April 2019 to 30 September 2019). This document is a mandatory complement to the user manuals of the VLTI instruments, since it contains very important information to prepare the proposals for PIONIER, GRAVITY. and MATISSE In particular, the requirements by the VLTI sub-systems for the feasibility of an observation are listed at the end of this manual.

The **bold** font is used in the paragraphs of this document to put emphasis on the important facts regarding VLTI in P103.

This version is released for Phase I of P103 and contains a clarification on the separation between the science and the guide star when performing off-axis guiding. **The major change in P103 is the introduction of MATISSE.** Minor corrections were also done over the document.

1.2 Contacts

The authors hope that this manual will help the users to get acquainted with the VLTI before writing proposals for interferometric observations. This manual is continually evolving and needs to be improved according to the needs of observers. If you have any question or suggestion, please contact the ESO User Support Department (email:`usd-help@eso.org`).

2 A FEW WORDS ON INTERFEROMETRY

2.1 Introduction

This section gives a short summary and a reminder of the principles of interferometry. Astronomers interested in using the VLTI, but who are not familiar with interferometry yet, can get tutorials from the following links:

- `http://olbin.jpl.nasa.gov/intro/index.html` (Optical Long Baseline Interferometry News tutorials).
- `http://www.eso.org/sci/facilities/paranal/telescopes/vlti/index.html` (VLTI general description and tutorials).
- `http://www.mariotti.fr/obsvlti/obsvlti-book.html` (proceedings of EuroWinter school "Observing with the VLTI").
- `http://www.vlti.org` (List of other available schools and tutorials.)

2.2 Interest of interferometry

Long-baseline interferometry is a high-angular resolution technique in astronomy. It is useful to obtain information about details at the milli-arcssecond (mas) level, such as:

- Diameters of stars, intensity profiles across stellar disks, morphology of circumstellar environments and stellar surface features.
- Diameters and chemical composition of dusty shells and disks around YSOs and AGB stars.
- Inner structures of AGNi.
- Parameters of the orbits of close binary stars.

2.3 How an interferometer works

An optical interferometer samples the wave-fronts of the light emitted by a remote target. Sampling is performed at two or more separate locations. The interferometer recombines the sampled wave-fronts to produce interference fringes.

Two telescopes are separated on the ground by a "baseline" vector. The wave-fronts add constructively or destructively, depending on the path difference between the wave-fronts, and produce a fringe pattern that appears as bright and dark bands, with the bright bands being brighter than the sum of intensities in the two separate wave-fronts. A path-length change in one arm of the interferometer by a fraction of a wavelength causes the fringes to move. If the beams from the telescopes are combined at a (small) angle, the fringes consist of a spatially modulated pattern on the detector.

The angular resolution that the interferometer can achieve depends on the wavelength of observation, and on the length of the projected baseline (the projected baseline vector is the projection of the on-ground baseline vector onto a plane perpendicular to the line-of-sight. The

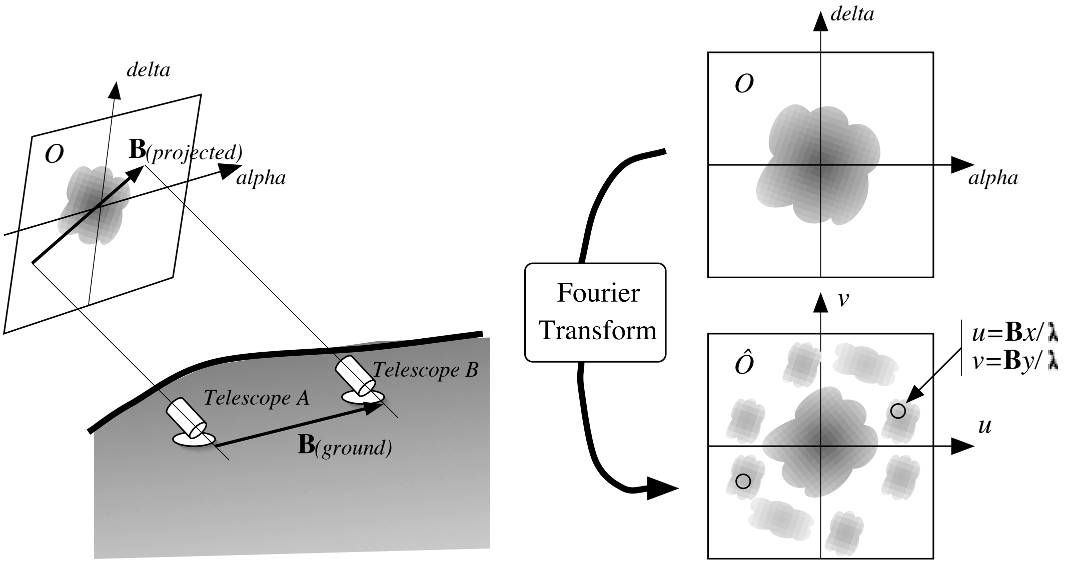

Figure 1: Basic principle of ground-based long-baseline optical interferometry. The sample of $\hat{O}$ for the given projected baseline and wavelength is given by the small circle (the graphical representation of $\hat{O}$ is fictive).

projected baseline changes over the night because of Earth rotation). The smallest angular scale that can be resolved is of the order of λ/B, where λ is the wavelength of the observation and B is the projected baseline of the interferometer. This is equivalent to the expression for diffraction-limited spatial resolution in single telescope observations, where B would be the telescope diameter. In the case of optical interferometry, the actual resolution depends on the accuracy at which the fringes' contrast is measured. Hence, the smallest angular scale can actually be smaller than λ/B.

2.4 Interferometric observables

An interferometer measures the coherence between the interfering light beams. The primary observable, at a given wavelength λ, is the complex visibility $\Gamma = \mathrm{V}\exp(i\phi) = \hat{O}(u,v)$. In this expression, $\hat{O}(u,v)$ is the Fourier transform of the object brightness angular distribution $O(x,y)$. The sampled point in the Fourier plane is $(u = B_x/\lambda, v = B_y/\lambda)$. (B_x, B_y) are the coordinates of the projected baseline (see Fig. 1).

A two-telescope interferometer cannot allow to retrieve ϕ because of the atmospheric turbulence and the lack of absolute reference. Only the squared amplitude, or visibility (V^2) and differential (as function of wavelength) visibility and phase, are accessible. With more than two telescopes, e.g. with PIONIER, summing the phases that are measured in all the baselines leads to a quantity called "closure phase" which is free of atmospheric corruption.

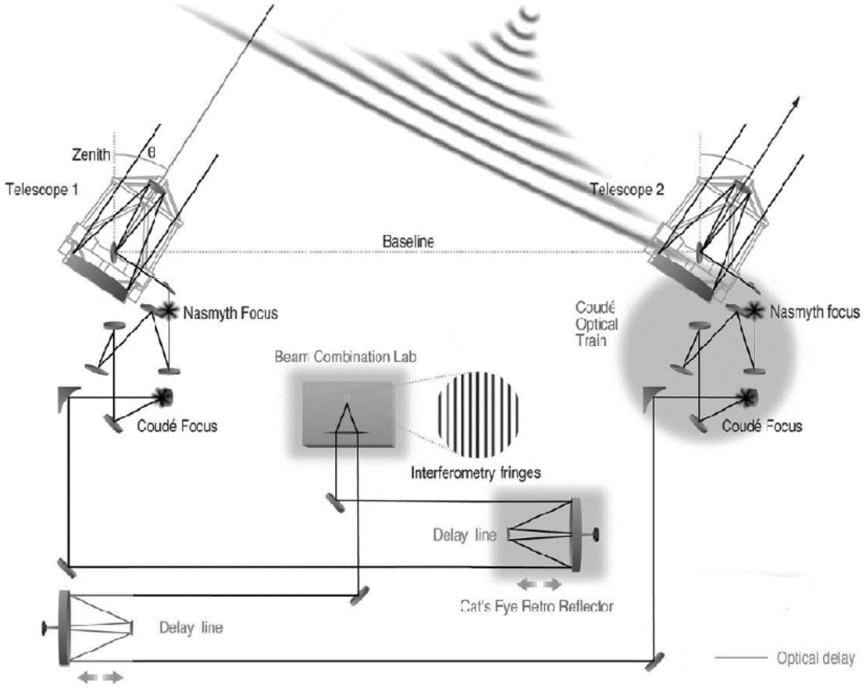

Figure 2: The optical path in the VLTI (when two telescopes are used).

3 OVERVIEW OF THE VLTI

The VLTI is located on the top of Cerro Paranal (latitude: 24°40′ S ; longitude: 70°25′ W.). There are two main operation modes for the VLTI: the mode using the 8-m unit telescopes (UTs) of the VLT (which are mostly used in stand-alone for non-interferometric observations with instruments attached to their Cassegrain and Nasmyth foci), and the mode using the 1.8-m auxiliary telscopes (ATs) forming the VLT Interferometer Small Array (VISA). These telescopes are not used for stand-alone operation. In both modes, the interferometric instruments which can be used are the same. The difference are in terms of sensitivity and (u, v) regions that can be "explored". The involved VLTI-specific sub-systems are also the same in both modes:

- An optical system of mirrors to transport the beams.
- A system of delay-lines.
- A set of stabilization devices (IRIS, pupil imager...).

These systems are detailed in this manual.

The optical train of the VLTI is illustrated in Fig. 2: the beam from each telescope is transferred by optical reflections through a first tunnel called "light-duct" and then through the delay-line tunnel (perpendicular to the light-ducts, see Fig. 6), up to the VLTI laboratory.

4 THE TELESCOPES FOR THE VLTI

The available telescopes for the VLTI observations in P103 are the fixed 8-m Unit Telescopes —UTs— of the VLT and the movable 1.8-m Auxiliary Telescopes —ATs— (for all VLTI instruments).

4.1 The Unit Telescopes

4.1.1 Description

The VLTI can be attached to the Coudé foci of each UT (located underneath the azimuth platform of the telescope)to bring the stellar light from the Nasmyth focus to the entrance of a VLTI "light-duct". The optical layout of the UT Coudé train is presented in Fig. 3. As for VLT observations, the telescope is tracking in "field-stabilization" mode: the Nasmyth guide probe camera tracks on a selected guide star (observable within the $\approx$ 30 arcmin FOV of the Nasmyth focus which is centered on the target observed by the VLTI) by applying tip-tilt correction to the M2 mirror of the telescope.

4.1.2 Star Separators (STS)

Since 2016, all 4 UTs are equipped with Star-Separators in the Coudé rooms below the UTs. The goal of the UT-STS is to create two fields:

- one for the VLTI instrument (GRAVITY or PIONIER), and
- one for the CIAO infrared wavefront sensors.

The use of the UT-STS is completely transparent to PIONIER and GRAVITY+MACAO users.

4.1.3 MACAO

Each UT Coudé is equipped with an adaptive optics system called MACAO. It consists of a Roddier wavefront curvature sensor which has an array of 60 avalanche photo-diodes. This analyzer applies a correction to the shape the deformable mirror (DM) of the UT Coudé. The DM is mounted on a tip-tilt correction stage onto which the tip-tilt measured by MACAO is offloaded when the DM is at the limit. When the tip-tilt mount is at the limit, it is offloaded by offsetting the Nasmyth guide probe position, and therefore by offsetting the M2.

MACAO's performances for $V = 15$ are $\sim$ 20% of Strehl ratio at $\lambda = 2.2\,\mu$m. In good conditions, MACAO can be used with a star as faint as $V = 16$. Figure 5 presents expected Strelh ratio as a function of the target V-magnitude.

If the target is fainter than $V = 16$ it is possible to perform "off-target Coudé guiding" if a guide star can be found within a radius of 57.5 arcseconds whose center is -10 arcseconds in RA w.r.t the science star (see Fig.4 below).

The guide star must be brighter than $V = 16$ but if it is fainter than V >14 there is still a risk that Coudé guiding could fail depending on the off-axis distance and sky conditions (seeing, τ_0).

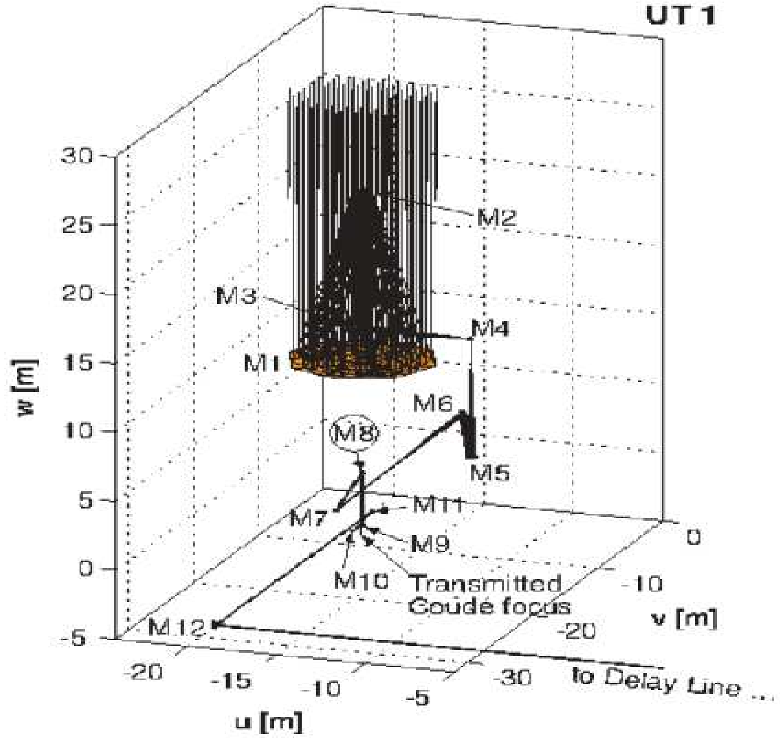

Figure 3: The optical layout of the lower part of the Coudé train and the relay optics

We guarantee that the MACAO loop is closed, under the following conditions:

- Seeing (500nm) less than 1.5 arcsec.
- Coherence time (500 nm) τ_0 larger than 2.0ms.
- Airmass less than 2.0.
- Distance from the optical axis less than 57.5 arcsec, see Fig. 4.

MACAO can be used only if the sky conditions are better than THICK. Rapid changes of flux due to thick clouds passing would degrade the performances of the MACAO and even endanger the APDs.

MACAO isoplanatism When a guide-star other than the scientific target is used, the quality of the correction of the image of the target depends on the angular distance θ between both objects. The isoplanatic angle is defined as the angular distance over which the variance

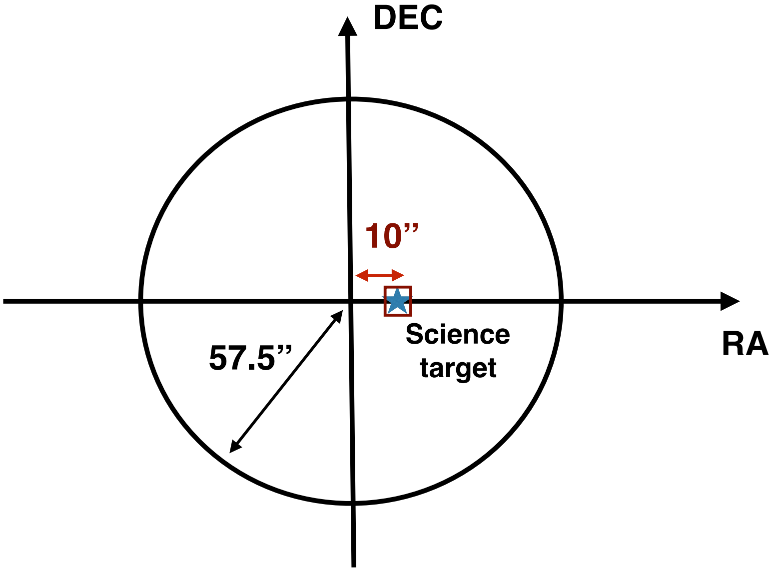

Figure 4: The circle above represents the area where a star can be chosen for an off-target Coudé guiding. The current use of the STSs imposes that the science object should be located +10 arcseconds in RA (to the East) away from the optical axis. This constrains the guide star distance for the off-target Coudé guiding. This means in particular that no Coudé-guiding will be possible if the guide star is more than +47.5 arcseconds away (in pure RA) from the science target.

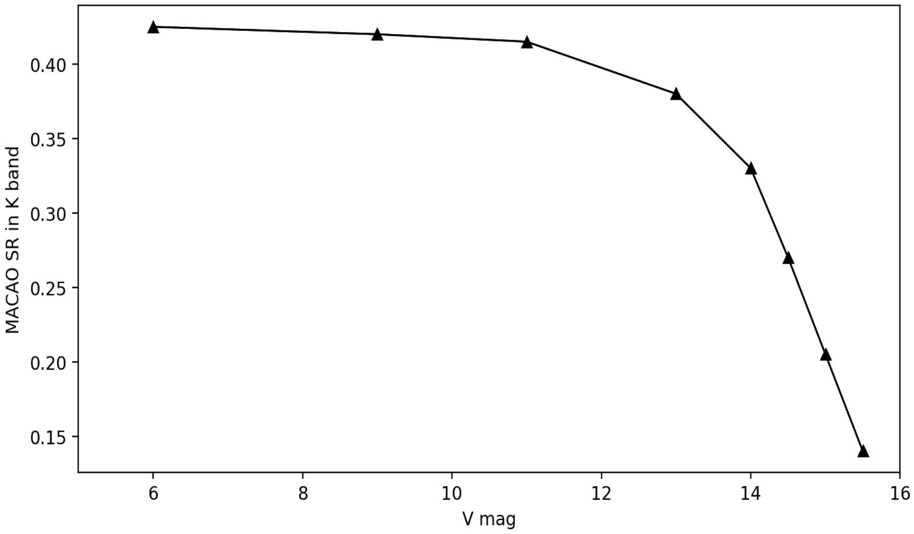

Figure 5: MACAO Strehl ratio (SR) in K-band as a function of V magnitude. From Haguenauer et al., 2016, SPIE Proceedings, 9909, 99092Y.

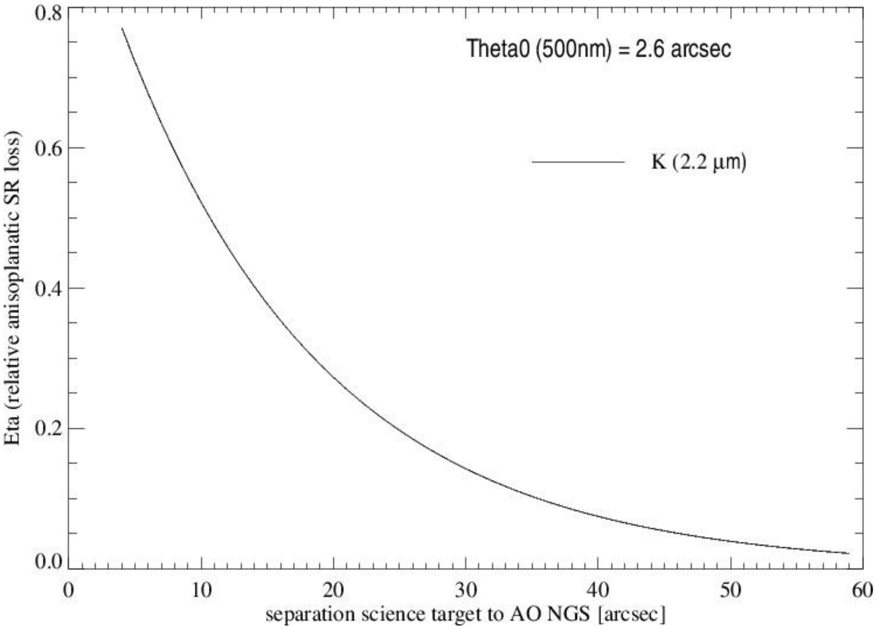

Figure 6: SR loss due to anisoplanatism as a function of the separation between the natural guide star (NGS) and the center of the VLTI field of view. An anisoplanetic angle of Theta0 (500nm) = 2.6 arcsec was assumed here as an average value for Paranal.

of the phase is 1 radian squared. It depends on the Fried parameter r_0, the mean altitude of the turbulence layer $< h >$ and the zenith angle z as follows:

$$\theta_0 = 0.31 \times \frac{r_0}{< h >},$$

The mean wavefront error is given by:

$$< \phi^2 >= (\theta/\theta_0)^2$$

Because of a limited number of observations in the past with off-axis guiding, it is difficult to give figures based on actual measurements, but we definitively recommend to observe with a seeing better than 0.8 arcsec. When the seeing is 0.8 arcsec, the isoplanatic is in general such that an attenuation of 1 K-magnitude per 15 arcsec of separation between the target and the guide-star is expected. The theoretical SR loss due to anisoplanetism is presented in Fig. 6.

4.1.4 CIAO off-axis

From P101, CIAO (Coudé Infrared Adaptive Optics) infrared wavefront sensors are offered in the off-axis mode for GRAVITY. Primarily designed to observe the red sources of the Galactic Center, they analyse the wavefront in the infrared (H and K bands) and command the M8s deformable mirrors to increase fiber coupling and sensitivity of VLTI instruments. In the off-axis mode, they use the second field of the STS, getting 100% of the infrared light. The 4 CIAOs are composed of 9x9 Shack-Hartmann wavefront sensors equipped with SAPHIRA detectors recording frames at 100-500Hz. We guarantee the CIAO loops to be closed for the following conditions:

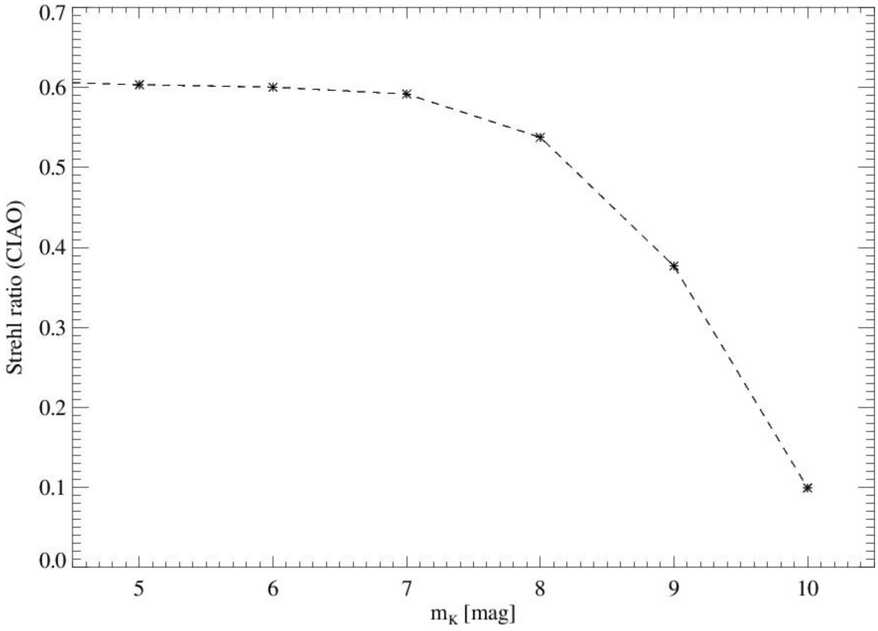

Figure 7: CIAO Strehl ratio in K-band as a function of the m_K apparent magnitude. This off-axis SR measured has been corrected for the Eta factor.

- Separation between AO source (NGS) and scientific target must be higher than 4 arcseconds and smaller than 60 arcseconds. Strehl ratio performances decrease with separation as shown on Fig. 6.
- Point source with K<= 10 mag
- Seeing (500nm) <= 1.1 arcsec
- Coherence time (500nm) > 1.5 ms
- Airmass <= 2.0

Typical performances during commissioning are reported on Fig. 7.

4.1.5 MACAO or CIAO off-axis?

The CIAO H+K band wavefront sensor offers the opportunity to find Natural Guide Stars (NGS) in deeply embedded or extincted regions, where it was previously not possible to do adaptive optics (due to the lack of visual NGS). In general, the use of CIAO systems is therefore recommended for red AO reference sources with m_V-$m_K \geq 5$ mag and when no on-axis target are available.

To decide between MACAO and CIAO adaptive optics systems, and identify the best NGS, do the following:

- For each potential NGS within 60 arcsec of the science target, derive the on-axis Strehl ratio SR_{MACAO} and the off-axis SR_{CIAO} from Fig. 5 and 7 .
- Estimate the attenuation of the Strehl ratio, Eta, due to anisoplanatism, presented in Fig. 6.

- Multiply both numbers (i.e. Eta * SR_{MACAO} and Eta* SR_{CIAO}) to get the Strehl ratio on the science target, and select the combination of NGS and AO system, which provides the highest SR on the science target.

4.2 The Auxiliary Telescopes

The VLTI features four auxiliary telescopes (ATs) that are now used simultaneously for scientific observations. Their locations on the VLTI platform (hence the baselines they define) are defined in the Paranal schedule which is released before the observation period starts. They are usually used several days in a row on the same locations. Relocation of the AT to a new station can only be done during the day. A maximum of 2 ATs can be moved in a single day. Any relocation of ATs is followed by a relocation night that will be used by Science Operations to verify the system before starting normal operations (VM or SM). **Following a vast intervention of mirror exchanges and recoating of the ATs' Coudé train that ended in July 2018, the AT transmission increased by about 65% in the near-infrared.**

Like the UTs, the light from the ATs use a Coudé train to bring the stellar light to the delay-line. A drawing of the Optical layout of the AT is presented in Fig. 8.

4.2.1 STRAP

During P102, after the release of the P103 VLTI manual, STRAP will be replaced by NAOMI (see next section). However before NAOMI is fully characterized on-sky, users should use the STRAP characteristics for the preparation of their observations.

The sensitivity of STRAP on the ATs is V =13.5. If the target is fainter than V =13.5, it is possible to perform "off-target Coudé guiding", provided a suitable guide-star exists. This guide-star must be brighter than V =13.5 and within a radius of 57.5 arcseconds whose center is +/- 10 arcseconds in RA w.r.t the science object: **by default the scientific star is put +10 arcsec in RA from the center of the field when the telescope is located at a North station (same as for the MACAO off-target Coudé Guiding, Fig.4) and -10 arcsec when the telescope is located at a South station. Users who wants to perform off-axis guiding with a mixed North/South configuration (e.g. medium or large configurations) should pay particular attention to the fact that the guiding star should be close enough to the center of the field for both North and South ATs (basically in a 47.5 arcsec radius from the science object, see Fig 18 at the end of the document.**

If V >12, there is a risk that Coudé guiding cannot be performed, depending on the off-axis distance and the on- sky conditions (seeing, τ_0). There are some restrictions on the ATs guiding with Strap due to the moon:

- If the FLI is ≥85%, and the guide star is **fainter** than 9th magnitude, guiding is not possible for distances to the moon closer than 20 degres.
- If the FLI is ≥85%, and the guide star is **brighter** than 9th magnitude, guiding is not possible for distances to the moon closer than 10 degres.

Note that, unlike the UTs, the ATs have no possibility of guiding if they cannot guide with the Coudé. Therefore, it is mandatory to use a suitable Coudé guide star (either the target itself or an off-axis guide star).

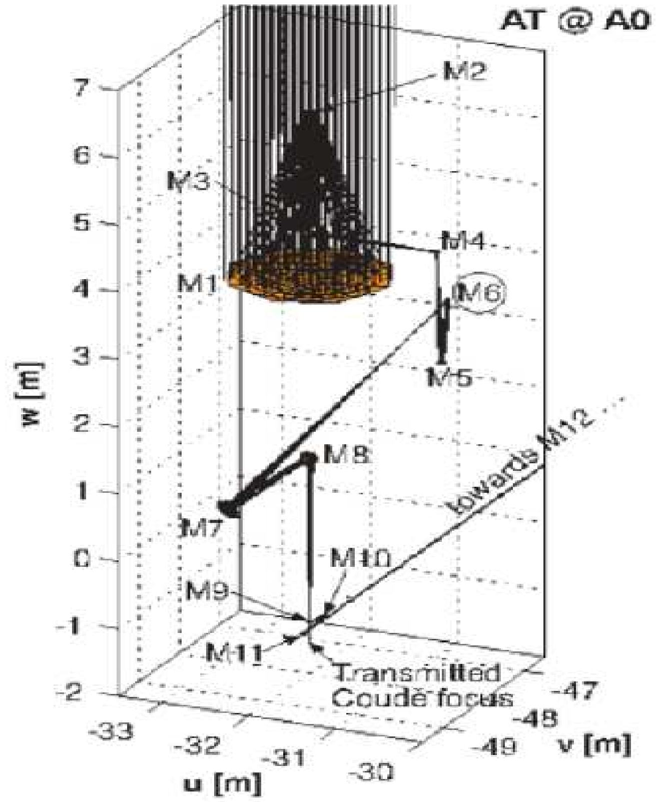

Figure 8: Optical layout of an AT with the telescope optic (M1..M3), Coudé train (M4..M8) and relay optic (M9..M11). Note that the lower part of the diagram is not valid since 2015, because the relay optics have been replaced by the Star Separators.

Figure 9: A unit telescope (left) and an auxiliary telescope (right).

4.2.2 NAOMI

Foreseen to be completed in by mid-November 2018, the installation of the New Adaptive Optics Module for Interferometry (NAOMI) will provide ATs with low-order Shack-Hartman systems operating in the visible. By delivering a higher and more stable Strehl ratio during turbulent conditions, the NAOMI systems will allow a more robust fiber coupling in the VLTI instruments which will translate into a higher sensitivity and precision in the data. NAOMI will also provide chopping up to 5 Hz to subtract the thermal background seen by MATISSE. Expected performances in terms of Strehl ratio versus the R-band guide star magnitude are presented in Fig. 10.

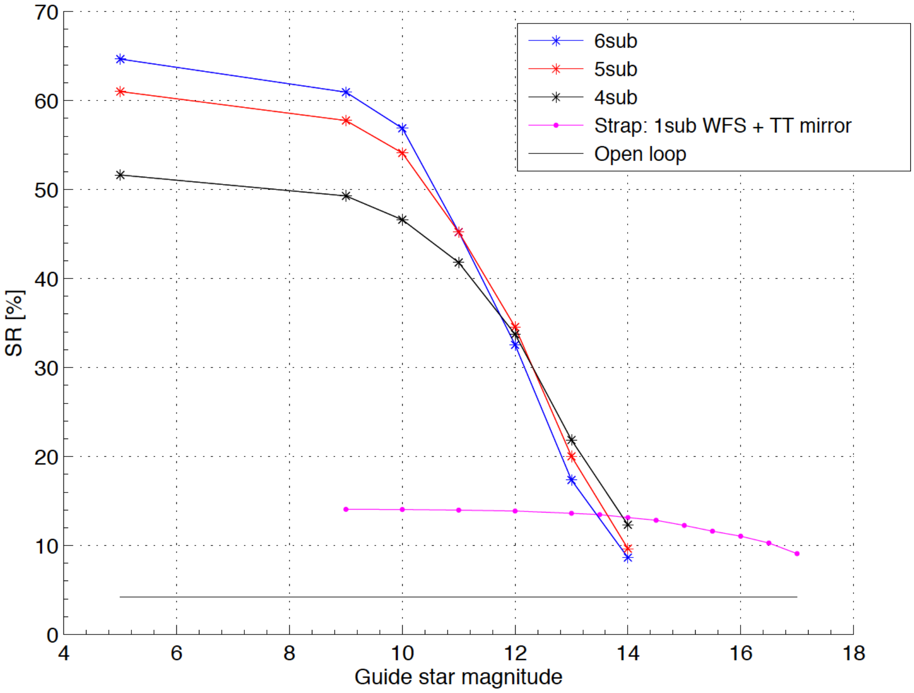

Figure 10: Expected Strehl ratio for NAOMI compared to the current STRAP system and the open loop case versus the R-band magnitude of the guide star. From Dorn et al. 2014, article in the ESO Messenger.

During September, October and November 2018, the 4 NAOMI modules will be installed, commissioned and used in operations. Their use is transparent to the user. More detailed can be found in Dorn et al. 2014 (ESO Messenger) and Gonté et al. 2016 (SPIE proceedings).

4.2.3 AT Star Separators (STS)

The Star separators (STS) were introduced originally for the PRIMA project in order to enable the VLTI to acquire simultaneously 2 stars. The STS have replaced the "single star" relay optics since 2015, directly below the telescope. VLTI-AT now uses the STS for the following reasons:

- The DL VCM pressure will always be below 2 bars, leading to more stable pupil relay.
- The larger field of view: ≥4" in diameter as opposed to ≤2" for single feed.

- Ability to stir and guide the pupil thanks the tip-tilt mounted VCM in the STS.

The STS have better optical properties, in particular the pupil relay and field of view. The old SF ROS suffered from poor pupil steering (M10) and poor longitudinal imaging because the delay Line VCM could not be operated at pressure above 2.5 bar, which was not sufficient for good pupil relay.

The STS have their own VCM which reduces the pressure of the DL VCM and properly re-images the pupil in the middle of the tunnel. The result is that we will now operate with DL-VCM pressure always below 2 bars. The STS also offer a much larger field of view ($\geq$4" in diameter as opposed to $\leq$2" for SF), which is mandatory for GRAVITY. **The uses of the AT-STS is completely transparent to GRAVITY, MATISSE and PIONIER users.**

For more informations, please see *"Star separator system for the dual-field capability (PRIMA) of the VLTI"* Delplancke et al. SPIE (2004).

5 THE BASELINES OF THE VLTI

5.1 Introduction

As explained in Sect. 2.3, a baseline is the geometrical arrangements of the two telescopes used during the VLTI observations. Four telescopes are used simultaneously with PIONIER, GRAVITY or MATISSE. To "explore" the regions of interest in the (u, v) plane of a scientific target, the user has to:

1. Select one or several multiplets (i.e., the set of telescopes): 4T for PIONIER, GRAVITY and MATISSE.
2. Define the local sidereal time (LST) ranges for the observation. The LST defines, from the selected baseline, the actual "projected" baseline that will define the (u, v) region.

To help with this preparation ESO has made available a tool called VisCal [1] to compute the visibility of targets as a function of the baseline. Alternatively, one can use the ASPRO tool[2], developed by the JMMC. This tool is community based and developed in closed collaboration with ESO.

All the baselines, at a given time, should use the same type of telescope: it is not possible to combine an AT and a UT in the same array configuration. The various offered baselines for the current period can be found online at:

http://www.eso.org/sci/facilities/paranal/telescopes/vlti/configuration/

Section 5.3 and 5.4 provide also this information.

5.2 The delay-lines

The delay-lines are used to compensate the OPD between the two telescopes, from the incoming stellar waveplane to the instrument entrance. Each telescope has a dedicated delay-line.

Each delay-line consists of a carriage that can move along rails to adjust the optical path length. The carriage contains retro-reflecting optics. One carriage is fixed, whereas the other

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[1] http://www.eso.org/observing/etc/

[2] http://www.jmmc.fr/aspro

3 continuously move in order to compensate the OPD for the apparent sidereal motion and slow drifts. The carriage optics is based on a cat's eye optical design. The central mirror of the system is located in an image plane and mounted on a piezo actuator for fine OPD adjustments. This mirror is the "variable curvature mirror" (VCM): its radius of curvature can be adjusted in real-time by a pneumatic device that applies a pressure on the back of the mirror. The aim of the VCM is to perform a pupil re-imaging (usually very close to the instrument in service) to a desired location, whatever the delay-line position. The advantages of transferring the pupil are:

- An optimized field of view (≥4" with the ATs). Fringes can be obtained from any target within the FOV.
- A reduction of the thermal background related to VLTI optics.

Although the use of the VCMs is not critical for the UT operations, the VCM are used as a rule when observing with them.

To compensate OPD drifts due to uncertainty of the array geometry, as well as atmospheric piston, position offsets can be applied at high rate to the moving delay-line by the OPD controller. The OPD controller receives commands from the science instrument itself (PIONIER, GRAVITY or MATISSE).

The optical delay provided by the delay-lines can be between 11 m and 111 m. Depending on the baseline, there are limitations of the sky accessibility (i.e., alt-az position of the target to be observed) due to the limitation of the delay-line range. When three baselines are used, the sky accessibility is not simply the superposition of the accessibility of the three baselines separately, but a more restricted (alt-az) range due to the inter-dependencies of the delays of the three baselines.

5.3 UT Baselines

For P103, **all the four unit telescopes are available for VLTI observations**. The following table gives the characteristics of the possible ground baselines (E is the component over the East direction and N over the North direction):

Name	E (m)	N (m)	On-ground baseline length (m)
UT1-UT2	24.8	50.8	56.5
UT1-UT3	54.8	86.5	102.4
UT1-UT4	113.2	64.3	130.2
UT2-UT3	30	35.7	46.6
UT2-UT4	88.3	13.5	89.3
UT3-UT4	58.3	-22.2	62.4

For the longest baseline (UT1-UT4 and UT1-UT3), there are limitation for the direction of pointing in the sky, related to the range of the delay-lines. The VisCalc tool (see Sect. 7.5) gives the possible limits. A quick look at the accessibility range (target declination and hour angle of the observation) can be found at the end of this document (section 8.2), as well as on the following page:

http://www.eso.org/sci/facilities/paranal/telescopes/vlti/configuration/

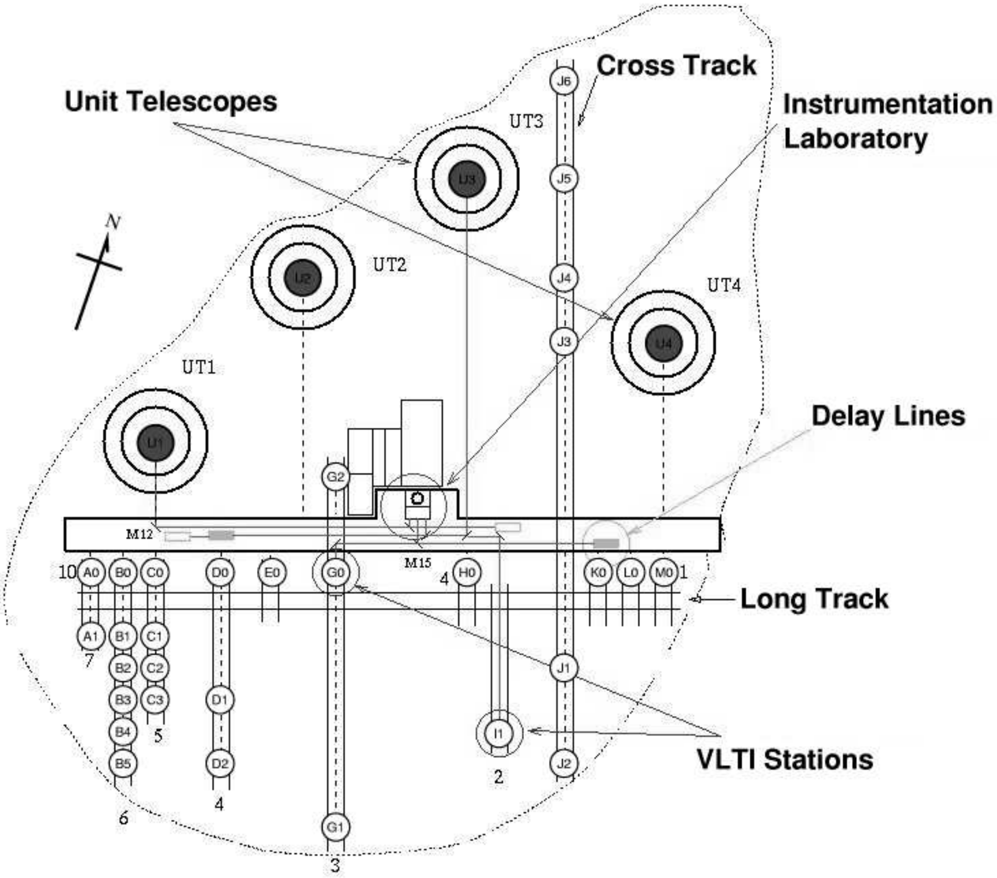

Figure 11: Layout of VLTI telescope locations.

5.4 AT baselines

Auxiliary Telescopes are offered as 4 telescopes configurations. Changing quadruplets require to physically move ATs. Only 2 ATs can be moved per day, so 2 days are required to change quadruplet.

From P101, the astrometric AT configuration (A0-G1-J2-K0) is explicitly scheduled dual-feed observations are only offered on the small and astrometric configurations. The astrometric configuration, A0-G1-J2-K0, is a variation of the standard large configuration A0-G1-J2-J3. The astrometric configuration has all its telescopes south of the delay line tunnel, which is mandatory for GRAVITY dual-feed observations. In order to optimize scheduling, some single-feed observing blocks of SM runs requesting the large configuration might be executed on the astrometric configuration instead since it offers similar baseline lengths and sky coverage.

The list of available quadruplets of telescopes offered for P103 is listed below:

AT Configurations	PIONIER, MATISSE GRAVITY single-feed	GRAVITY dual-feed
Small (A0-B2-C1-D0)	yes	yes
Medium (D0-G2-J3-K0)	yes	no
Large (A0-G1-J2-J3)	yes	no
Astrometric (A0-G1-J2-K0)	no	yes

At the time of Phase I, user are only requested to provide informations on which of the available quadruplets they wish to use for observations.

-

For a requested quadruplet or triplet, the pointing restrictions (depending on the target declination and on the hour angle of the observation), due to delay-line range and/or vignetting by the neighboring telescope enclosures, can be found at the end of this document (section 8.2), as well as on the following page:

http://www.eso.org/sci/facilities/paranal/telescopes/vlti/configuration/

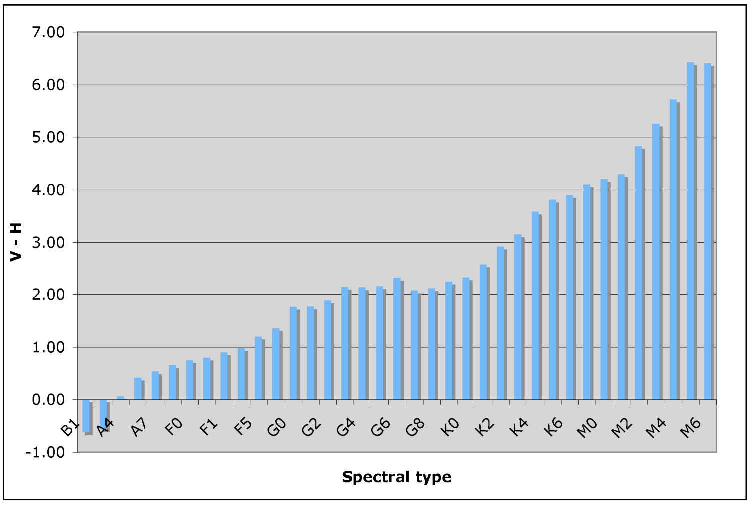

Figure 12: Difference of magnitude between V and H bands, depending on the spectral type.

6 VLTI STABILIZATION

6.1 Introduction

In this section, we describe the sub-systems of the VLTI that are used for "non-blind tracking": each of these sub-systems consists of a sensor retro-feeding one or several mechanical actuators. The aim of these systems is to provide stable beams to the instrument by correcting the effects of the atmospheric turbulence, or of the mechanical defects (vibrations, roll/pitch/yaw, etc...). As many of these sub-systems use the stellar light as input signals, it is important to know their performances to assess the feasibility of the observation proposals.

6.2 IRIS

IRIS is the infrared field-stabilizer of the VLTI. It consists of a fast infrared (K-band) camera onto which the images from each beam are projected (1 image per detector quadrant). The photocenters of each beam are measured in real-time. Its purpose is to perform field-stabilization on the telescopes by measuring the low-frequency tip-tilt from the VLTI laboratory. IRIS guarantees, therefore, the correct alignment of the beam during the observations.

Only the slow-guiding mode is used for PIONIER and MATISSE (no IRIS guiding for GRAVITY). In slow-guiding, the tip-tilt corrections are sent to XY-tables of the telescope to correct the pointing of the telescopes. The frequency of the correction is around 1 s.

Although the users are requested to give the H-magnitude in the instrument OBs, this value can be used as an approximation of the K-magnitude for IRIS, and allows IRIS to work at its best performances, thanks to an adaptive integration time algorithm. An approximation of the H-magnitude can be found from the V-magnitude and the spectral type of the target, using the plot on Fig. 12.

The limiting magnitudes in K-band for IRIS are (in slow-guiding):

- $K = 8.0$ with the ATs.
- $K = 11.5$ with the UTs.

6.3 Pupil alignment

Due to a random slight warp of the delay-line rails, the transverse location of the pupil for each beam in the VLTI laboratory may vary with the position of the delay-line carriage of the beam. A re-alignment of the tip-tilt of the M10 mirrors (located in an image plane) of the telescopes is needed to re-center the pupil of the beams. The pupil position is measured by IRIS in the VLTI laboratory and corrected.

The limiting magnitudes in the visible which allow the pupil alignment are:

- $K = 5.0$, with the ATs.
- $K = 8.5$, with the UTs.

For most of the calibrator stars, the pupil can be aligned. For scientific targets that are too faint in the visible to allow the pupil alignment, one has to rely on the quality of the delay-line rails: the experience shows that, if the pupil has been previously aligned for the calibrator, the delay-line carriages are usually not moved far away when observing the scientific target, so the pupil shift (measured when the target pupil can be seen) is often negligible. For this reason (but not only), the angular distance between both objects has to be taken into account when one is selecting a calibrator. Anyway, the pupil alignment will usually be performed on the scientific target whenever it is bright enough.

7 ORGANIZATION OF THE VLTI OBSERVATIONS

7.1 General

For P103, VLTI observations can be performed either in service mode or in visitor mode (for PIONIER, GRAVITY and MATISSE). For the phase-1 of a period, the unique contact point at ESO for the user is the User Support Department (see Sect. 1.2). For the phase-2, USD is still the contact point for service mode, and the Paranal Science Operation department is the contact point for visitor mode: see http://www.eso.org/sci/observing/phase2/VMGuidelines.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*.

7.2 Test of a new imaging scheme

In P103, ESO will continue to test a scheme to optimise operations for aperture synthesis with the VLTI. This scheme only applies to service mode proposals using ATs with PIONIER, GRAVITY and MATISSE. It requires that proposals aiming at imaging reconstruction with PIONIER, GRAVITY or MATISSE with the ATs include the sentence "This program aims at collecting VLTI data for reconstructing images." using the "SpecialRemarks" macro.

In addition, such proposals should request time corresponding to at least six concatenations (CAL-SCI for GRAVITY or MATISSE, or CAL-SCI-CAL-SCI-CAL for PIONIER) per object and per AT configuration, on at least two configurations. They should also specify the maximum period over which data can be collected, based on the expected evolution time scale of the target, with a minimum of ten days due to operational constraints. The observations will consist in a set of OBs with broad LST ranges (few hours) chosen by the PI. However, the targets may be observed outside the specified LST ranges and also use intermediate configurations, in order to optimize the uv coverage (on a best-effort basis).

7.3 Calibration

The raw visibility μ measured on a target by an interferometer is always lower than the theoretical expected visibility V. The transfer function of an interferometer is given by $T = \mu/V$. In order to determine T, the method is to observe a star with a stable and known angular diameter called a "calibrator" for which the expected visibility V_0 is known. Measuring its raw visibility μ_0 gives an estimate of T that can be used to calibrate the visibility on a scientific target.

For each scientific target observed, a calibrator has to be observed right after or before. It is up to the user to select the calibrator of the scientific target. The criterion to select a calibrator may include.

- Stable angular diameter known with a good precision, or unresolved ($V_0 \approx 1.0$) object for baseline and wavelength of the observation.
- Proximity in the sky to the scientific target.

- Magnitude comparable to the scientific target

Calibrators can be selected using the CalVin tool (see Sect. 7.6). Alternatively, the JMMC tool named SearchCal can be used.

7.4 Preparation of the VLTI observations

To assess the feasibility of an observation (mostly in term of limiting magnitudes in different spectral bands), the following tools need to be used:

- This manual.
- The instrument manual (PIONIER, GRAVITY or MATISSE).
- The "VisCalc" tool.
- The "CalVin" tool.

Other software packages exists. In particular, one can consult the Jean-Marie Mariotti Center Proposal Preparation page.

7.5 Baselines and LST constraints

The VisCalc webtool is available from:
http://www.eso.org/observing/etc/.
Giving as input the target parameters (theoretical geometry and declination), the instrument, the baseline configuration, and the observation time interval, VisCalc computes important information, like the observability range (considering the telescope pointing limits, the vignetting by the enclosures, the delay-line limits), and the expected visibility over the observation interval.

7.6 Calibrator selection

The CalVin webtool is available from:
http://www.eso.org/observing/etc/.
For a given target coordinates, instrument, and baseline configuration, CalVin returns a list of the possible calibrators. The list can be filtered by applying constraints to the possible calibrators like magnitude, angular distance from the target, spectral type, etc...

7.7 Moon constraints

Because the VLTI instruments work all in the infrared and have very small field of view, Moon constraints (angular distance to the target, Moon illumination) do not limit the interferometric observations themselves. However, if the Moon is too close to the target, the scattered moonlight may prevent MACAO (for the UTs) or STRAP/NAOMI (for the ATs) from working correctly. Please refere to section 4.2 for the limitations on Moon distance for the ATs. For the UTs, VLTI runs occur usually close to the full moon (FLI$\sim$1), hence we recommend that the guide star is more than 30 degrees away from the Moon.

The VLTI night astronomers make sure that the OBs in service mode are executed when the Moon is far enough from the targets. In visitor mode, users should carefully schedule their night-time using Moon ephemeris to avoid problems of scattered moonlight.

7.8 Instrument-specific constraints

Observations in SM can be performed with extra constraints (e.g. seeing) which depends on the instrument. Please read the PIONIER, GRAVITY and MATISSE user manuals and P2 documentation for details.

7.9 Target coordinates and magnitude

For both ATs and UTs, the telescope pointing models are done with the Hipparcos - FK6 reference frame. The coordinates of any object (scientific target, calibrator, guide star) to be observed by the VLTI should be given, if possible, in this system. If the star has proper motion, the correct values should be given in order for the system to work properly both at the telescopes and delay line level. References magnitudes for the guiding should be properly entered. In particular the visible magnitude should be correctly given for the use of MACAO or NAOMI. H and K Band magnitude should be given properly for the use of IRIS.

8 APPENDICES

8.1 Feasibility matrices

The following matrices summarize the characteristics of the scientific target (magnitudes in different bands, visibility....) that are required to use the VLTI sub-systems for the observations in different instrument modes. These matrices should be used along with the instrument manuals, since the limiting magnitudes of the instrument are not in the scope of this manual. Mandatory requirements are framed by boxes. If the target does not fulfill a requirement that is not in a box, the observation remains possible, but the data quality may be affected.

The values correspond to nominal conditions of observation: seeing between 0.7 and 1.4 arcsec, $\tau_0 > 2.0$ ms, sky transparency "photometric" or "clear", airmass lower than 2.0.

8.1.1 Observations with the UTs and MACAO

	MACAO guide star
On-axis Coudé guiding	$V < 16$
Off-axis Coudé guiding	$\boxed{V_g < 16}$ $\boxed{\text{target - guide: see Fig. 4}}$
IRIS guiding	$\boxed{K < 11.5}$
Pupil alignment	$K < 8.5$

Notes:

1. V_g= V-magnitude of the guide-star.

8.1.2 Observations with the UTs and CIAO

For observations with GRAVITY and CIAOs off-axis, the reader is referred to section 4.1.4 and 4.1.5.

8.1.3 Observations with the ATs

	PIONIER, MATISSE	**GRAVITY**
On-axis Coudé guiding	$\boxed{-1.7 < V < 13.5}$	$\boxed{-1.7 < V < 13.5}$ $\boxed{\text{elevation}\geq 40 \text{ degrees}}$
Off-axis Coudé guiding	$\boxed{V_g < 13.5}$ $\boxed{\text{target - guide: see Fig. 4}}$	$\boxed{V_g < 13.5}$ $\boxed{\text{target - guide: see Fig. 4}}$ $\boxed{\text{elevation}\geq 40 \text{ degrees}}$
IRIS guiding	$\boxed{K < 8.0}$	N/A
IRIS Pupil alignment	$K < 5.0$	N/A

8.2 Sky Coverage

We plot here the various sky coverage of all offered quadruplets and triplets. Sky coverage is limited by the UT dome shadowing, as well as delay line limits.

- Fig. 13: UTs
- Fig. 14: ATs, small configuration
- Fig. 15: ATs, medium configuration
- Fig. 16: ATs, large configuration

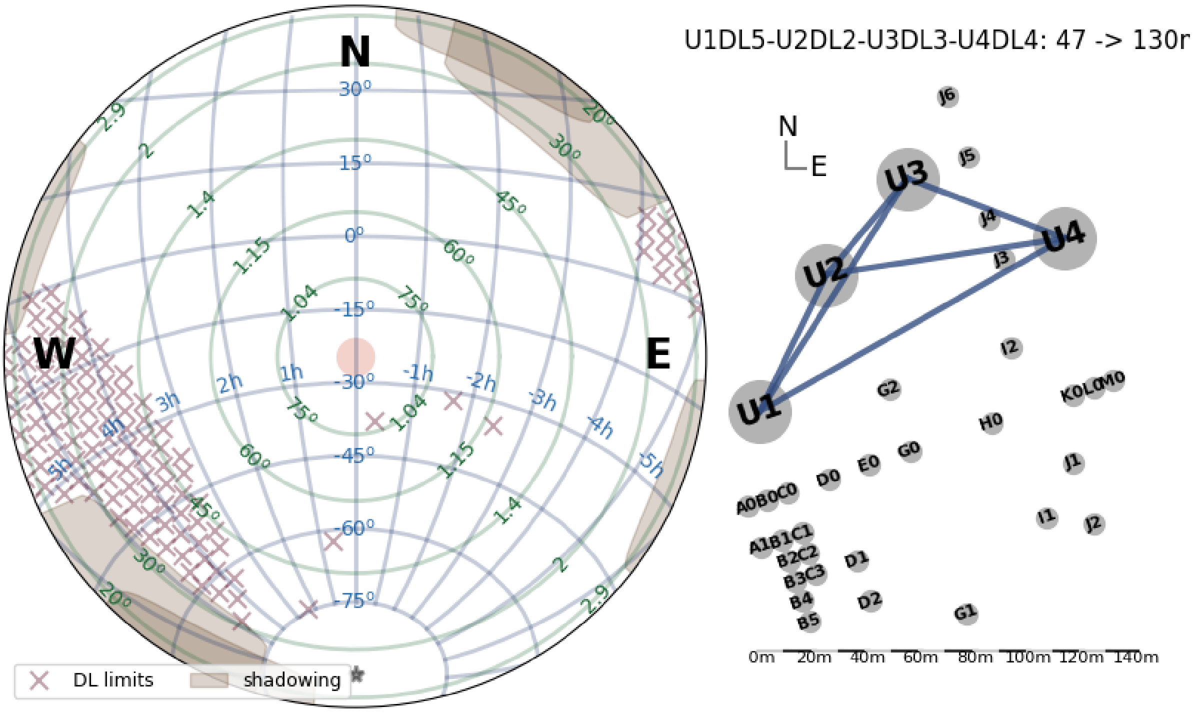

Figure 13: UT sky coverage

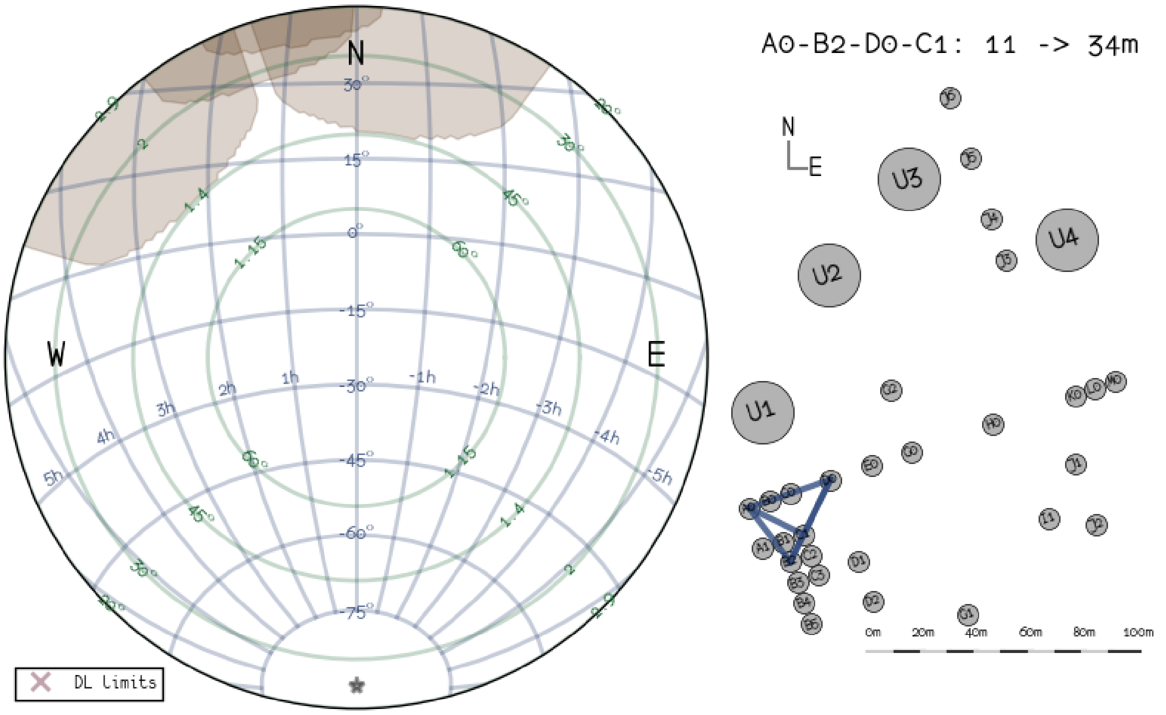

Figure 14: AT sky coverage, small configuration

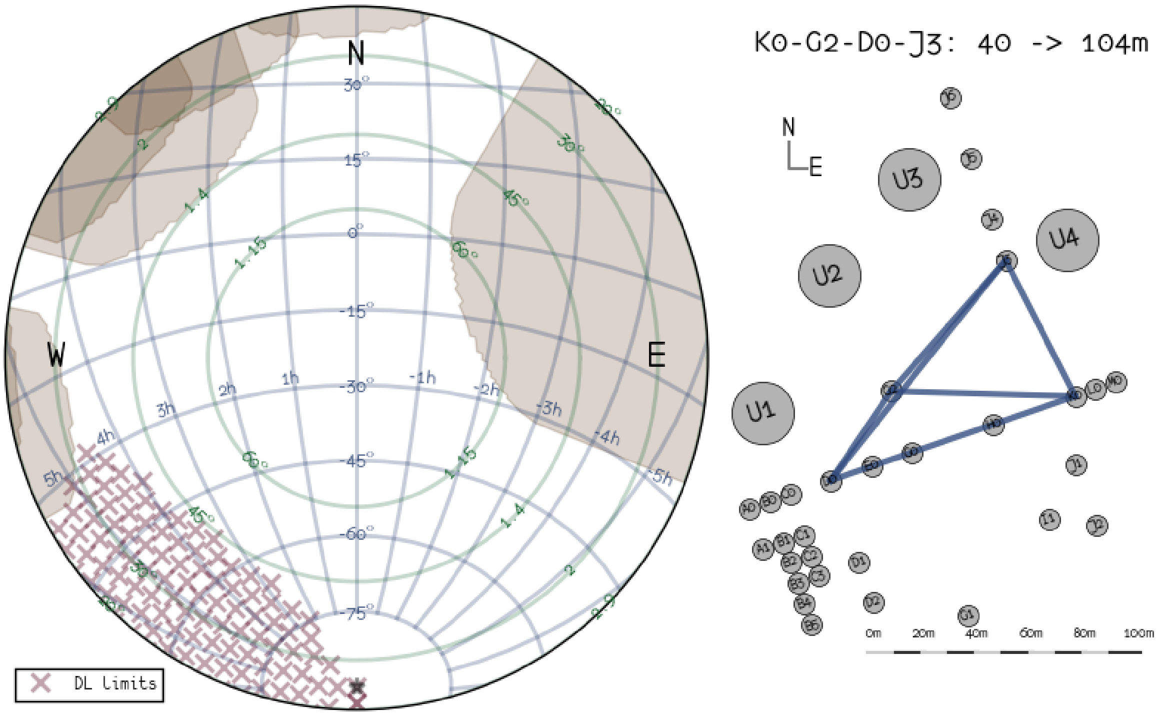

Figure 15: AT sky coverage, medium configuration

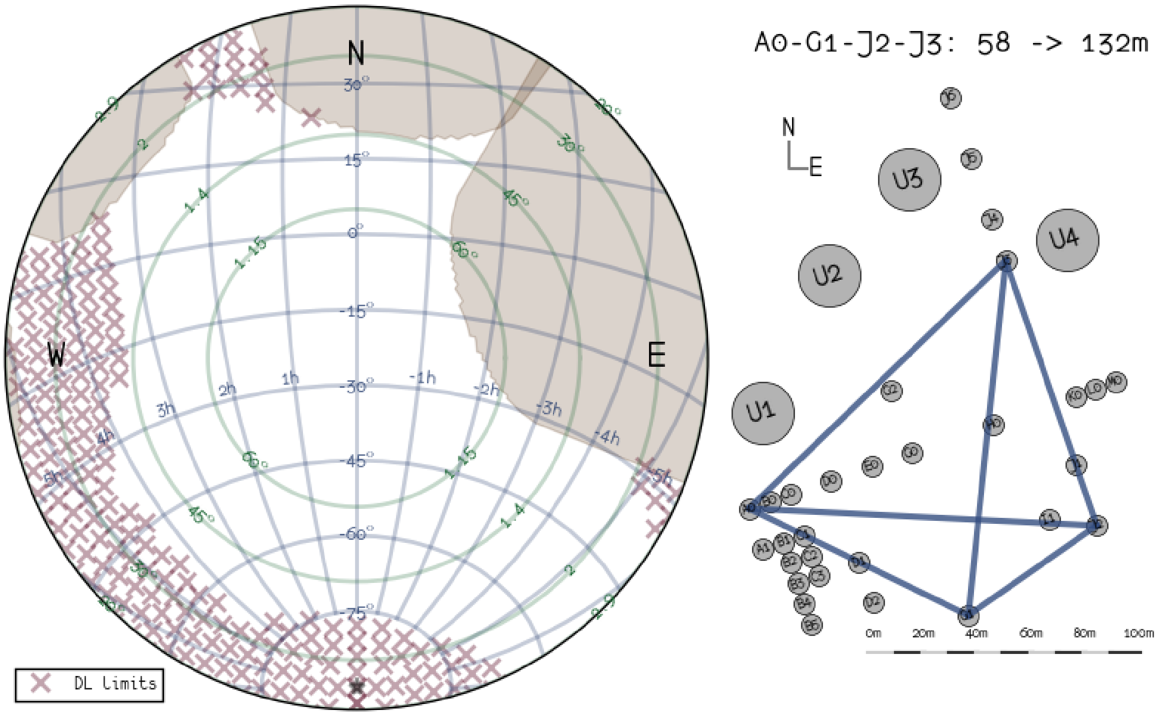

Figure 16: AT sky coverage, large configuration

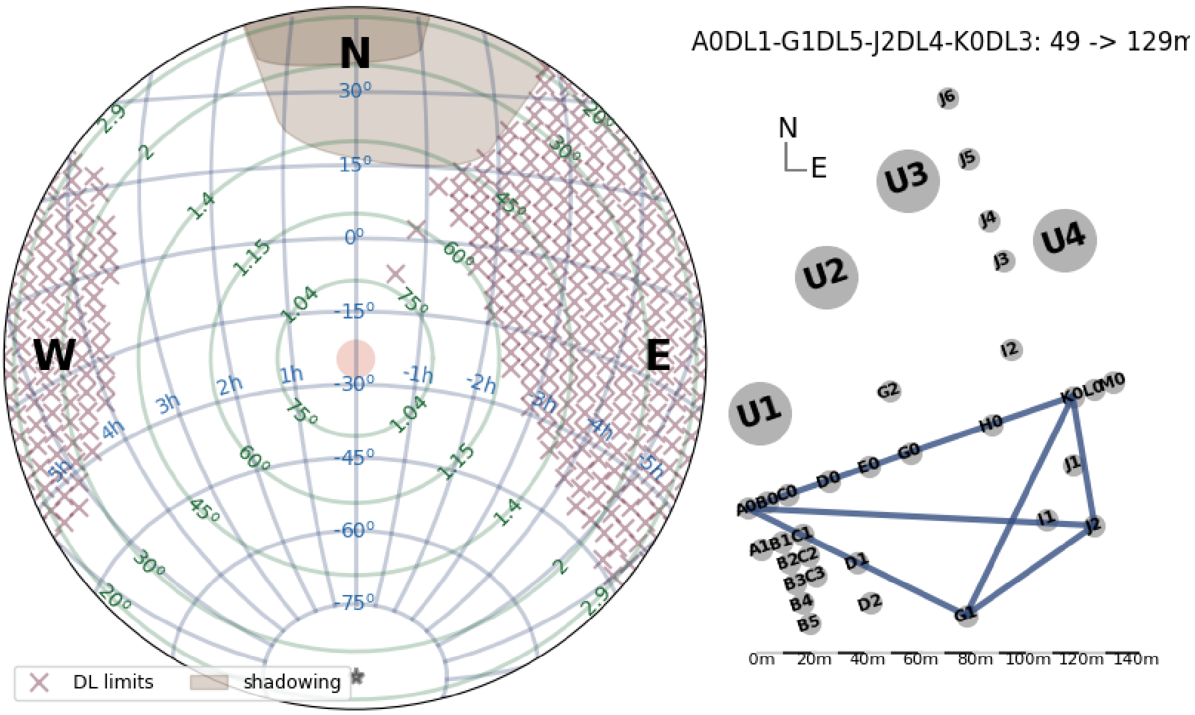

Figure 17: AT sky coverage, astrometric configuration

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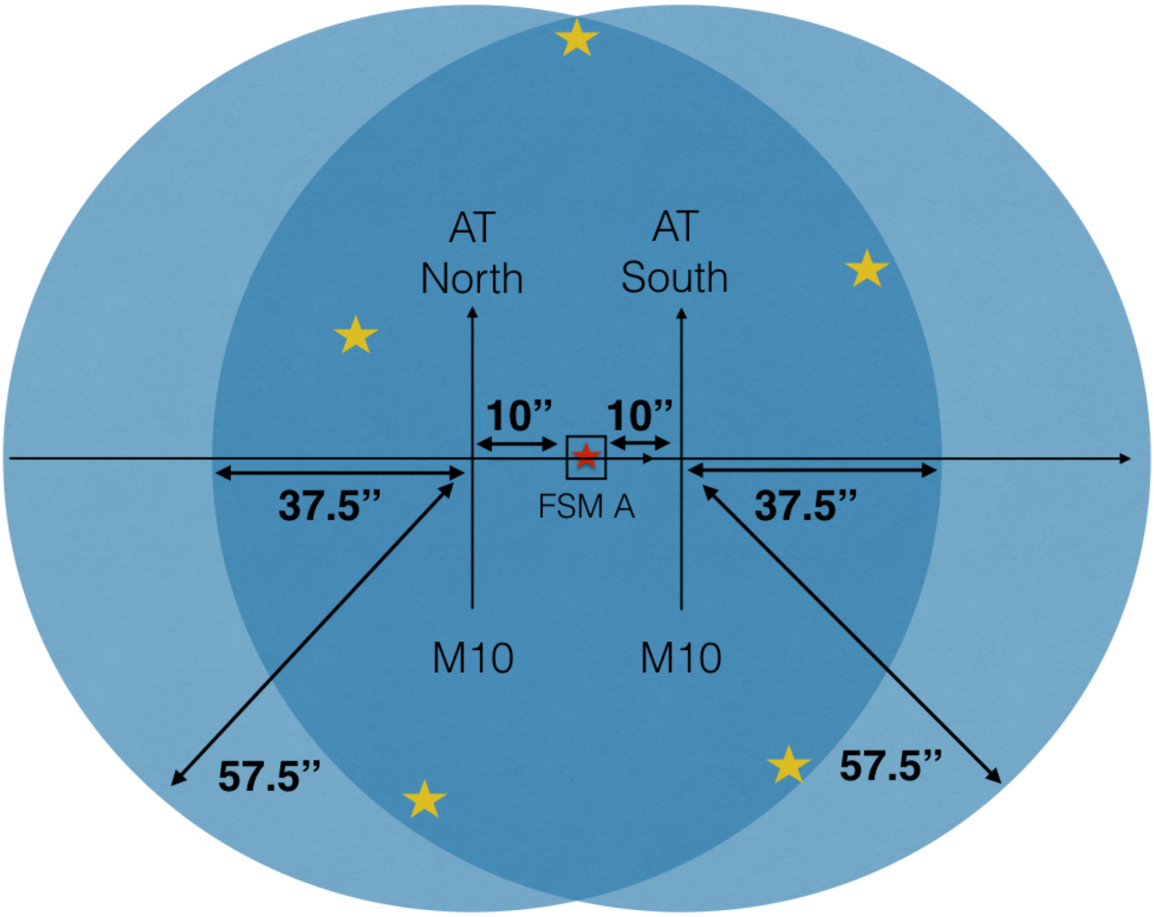

Figure 18: Geometry of the STS configuration when on a mixed North/South baselines (medium and large configurations). In this case, the field of view available for a guide star (darker blue area) is the intersection of the 2 individual STS fields of view. Yellow stars mark the position of potential guide stars. In pure RA, the guide star should not be further than 47.5 arcsec away from the science object (red star).