EUROPEAN SOUTHERN OBSERVATORY

Organisation Européene pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

ESO - European Southern Observatory
Karl-Schwarzschild Str. 2, D-85748 Garching bei München

Very Large Telescope

Paranal Science Operations

VLTI User Manual

Doc. No. VLT-MAN-ESO-15000-4552

Issue 115.0, Date 21/08/2024

Prepared . . . . X. Haubois
Date Signature

Approved . . . .
Date Signature

Released . . . . S. Mieske
Date Signature

This page was intentionally left blank

Change Record

Issue	Date	Section/Parag. affected	Remarks
98.0	27/02/2016	GRAVITY; AT- and UT-STS	Release for P98 Phase-1
99.0	12/09/2016	GRAVITY single/dual feed restrictions on AT baselines	Release for P99 Phase-1
100.0	03/02/2017	Precision on GRAVITY single/dual feed restrictions on AT baselines	Release for P100 Phase-1
101.0	16/08/2017	Astrometric AT baseline offered, CIAO-off axis offered for GRAVITY+UT, introducing NAOMI for ATs	Release for P101 Phase-1
102.0	25/02/2018	AMBER and FINITO are decommissioned, clarification of the off-axis coude guiding distances	Release for P102 Phase-1
103.0	31/08/2018	MATISSE is introduced, further clarification of the off-axis coude guiding distances for mixed N/S configurations.	Release for P103 Phase-1
104.0	28/02/2019	CIAO on-axis is introduced, NAOMI is further described, the new nomenclature for the configurations is presented	Release for P104 Phase-1
105.0	28/08/2019	imaging programmes descriptions was modified	Release for P105 Phase-1
106.0	28/02/2020	CIAO on-axis is no longer offered, MACAO magnitudes are revised	Release for P106 Phase-1
108.0	28/02/2021	Introduction of the imaging slots (ISLs)	Release for P108 Phase-1
110.0	24/02/2022	Modified STS sections and added section 6 including a description of GRAVITY-wide optical layout	Release for P110 Phase-1
111.0	22/08/2022	Clarification on time-series programmes and CIAO bright-end limiting magnitude.	Release for P111 Phase-1
112.0	22/02/2023	Introduction of the extended configuration and discontinuation of the large configuration	Release for P112 Phase-1
113.0	11/08/2023	MACAO decommissioning, BC-DDL commissioning	Release for P113 Phase-1
114.0	01/02/2024	Introducing GPAO-NGS and BC-DDL	Release for P114 Phase-1
115.0	21/08/2024	Updated BCDDL information	Release for P115 Phase-1
Editor: Xavier Haubois, VLTI System Scientist ; `xhaubois@eso.org`			

Contents

List of Figures

List of Abbreviations

AGB	Asymptotic Giant Branch
AGN	Active Galaxy Nucleus
AMBER	Astronomical Multi-BEam Recombiner
AT	Auxiliary Telescope
CIAO	Coudé Infrared Adaptive Optics
DDL	Differential Delay Lines
BC-DDL	Beam Compressor Differential Delay Lines
ESO	European Southern Observatory
FINITO	FrInge-tracker (designed by) NIce and TOrino observatories
FOV	Field Of View
GRAVITY	General Relativity Analysis via VLT InTerferometrY
GPAO	Gravity Plus Adaptive Optics
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
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 P115 (running from 01 April 2025 to 30September 2025). 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 P115. 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 AGNs.
- 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

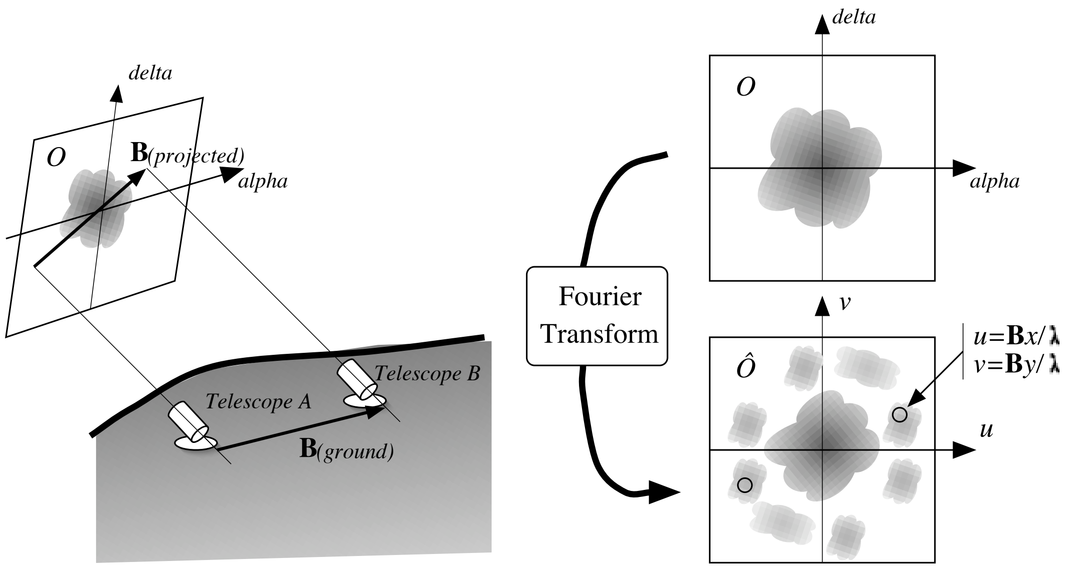

Figure 1: Basic principle of ground-based long-baseline optical interferometry. The sample of $\hat{O}$ for the given projected baseline and wavelength is given by the small circle (the graphical representation of $\hat{O}$ is fictive).

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, summing the phases that are measured in all the baselines leads to a quantity called "closure phase" which is free of atmospheric corruption.

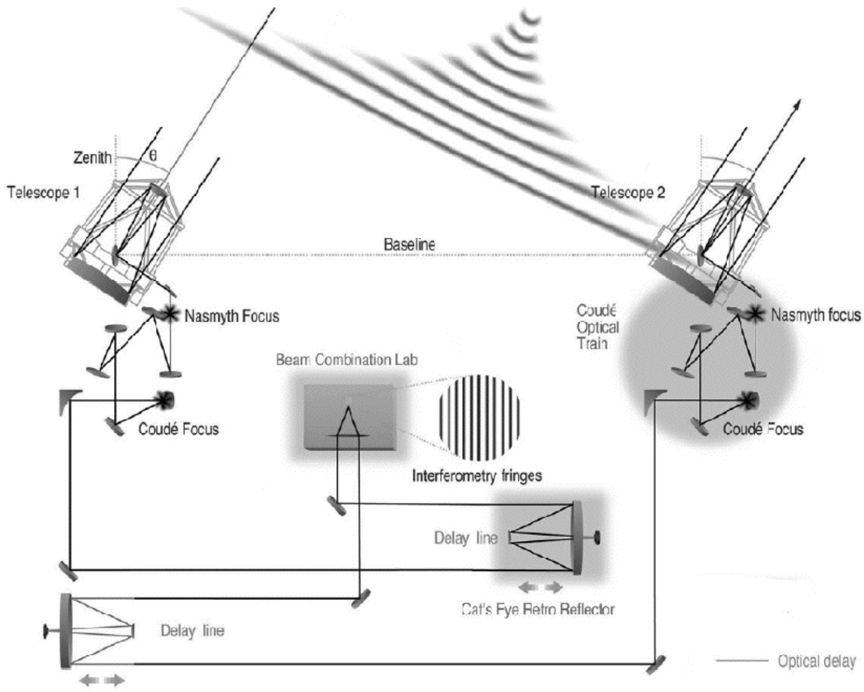

Figure 2: The optical path in the VLTI (when two telescopes are used).

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. 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 main delay-lines and differential delay-lines (used only with the GRAVITY-wide mode)
- 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 P115 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

When VLTI is used with UTs, the light is sent to the Coudé focus of each UT (located underneath the azimuth platform of the telescope) from the Nasmyth focus and then 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 ≈ 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. For VLTI observations, we currently use the AUTOGUIDING mode where the tip-tilt command is sent to the telescope axes.

4.1.2 GPAO

From 114, each UT Coudé is equipped with a new adaptive optics system called GPAO (GRAVITY+ Adaptive Optics), developed by the GRAVITY+ consortium. The visible mode of GPAO (NGS-VIS) replaces entirely the former visible MACAO system: wavefront sensor, corrective optics, RTC. GPAO uses ERIS (Davies et al. 2023 (A&A)) Adaptive Optics as a baseline. It consists in a 43x43 magnetic-actuator driven ALPAO Deformable Mirror (M8, see Figure 3) placed on a gimbal mount that sends the corrected wavefront to the Coudé room located below the telescope. The Real Time Control (RTC) platform is SPARTA upgrade (ESO). The wavefront sensor is a 40x40 Shack-Hartmann with sub-electron read-noise OCAM2 cameras running at 2kHz from First Light Imaging (Oxford Instruments).

GPAO was designed to be a high-order laser-assisted adaptive optics system. The number of sub-apertures (∼1600) being higher than for MACAO, the flux received by each GPAO sub-aperture from a same object is then lower (also lower than for AT/NAOMI). This means that before the GPAO system is fully implemented with the Laser Guide Stars (LGS) modes in P117, the limiting magnitude for the NGS-VIS mode that can be offered will be lower than the previous MACAO limiting magnitudes. Based on ERIS performances and taking into account the VLTI optical path particularities, the limiting magnitude for P115 is:

$$\mathbf{G_{rp}=12.5\ mag}.$$

The transmission profile of the Gaia Red Path (G_{rp}) can be found here.

The NGS WFS saturates at G_{rp}= 0 mag. But it incorporates the possibility for a Neutral Density filter wheel in order to ensure that stars as bright as G_{rp}= -3 mag can be observed even when using the shortest possible integration time of the OCAM2 camera.

If the target is fainter than G_{rp}= 12.5 mag it is possible to perform "off-axis 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 G_{rp}

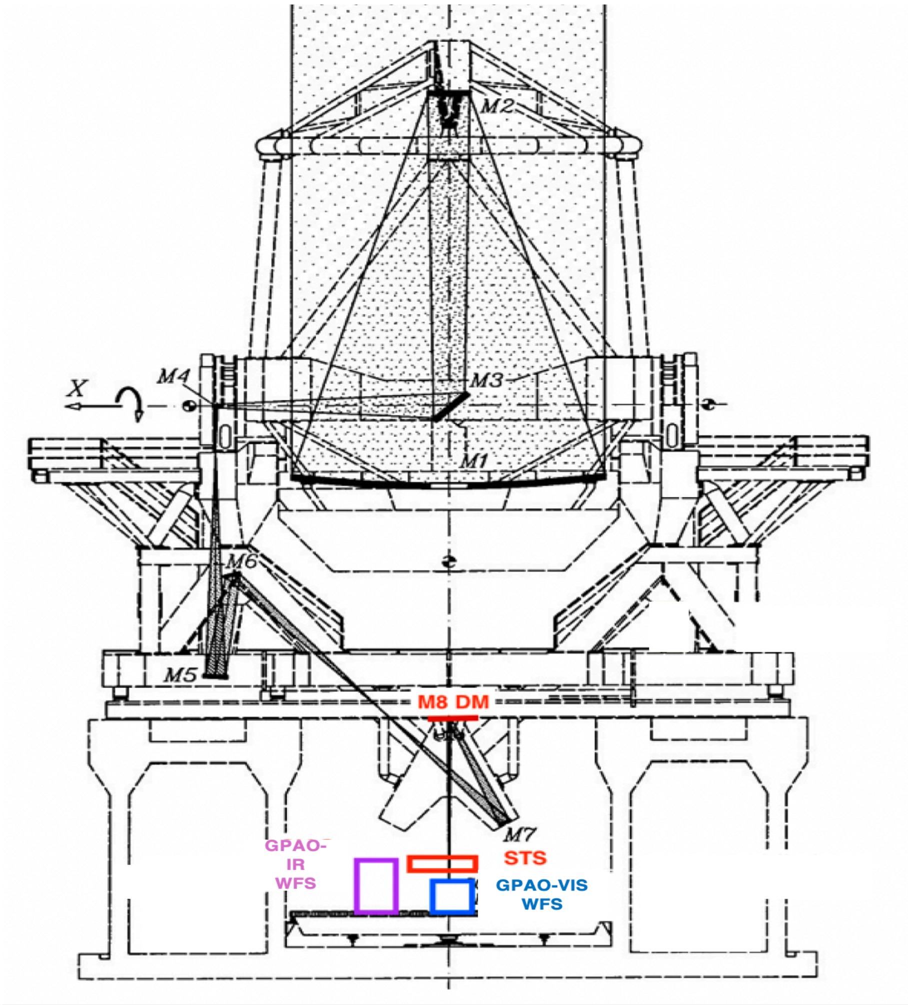

Figure 3: The optical layout of the UT configured for VLTI. In the Coudé room below, the telescope two adaptive optics systems (visible and near-infrared) can be used to correct the wavefront before sending it to the VLTI tunnel.

12.5 but if the G mag is too close to this limiting magnitude, there is still a risk that the Coudé guiding could fail depending on the off-axis distance and sky conditions (seeing, τ_0). **WARNING: those distances are given in a plane. Be careful when using distances from catalogs that can be defined in a sphere.**

In case of extended objects, users are expected to take into account the magnitude of the core of the objects resolved by a UT.

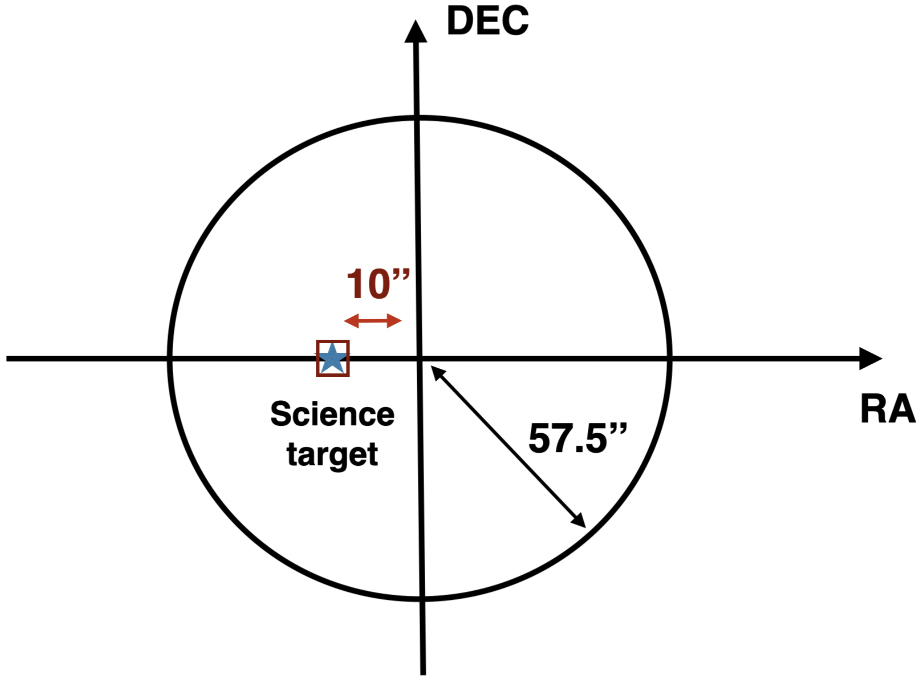

Figure 4: The circle above represents the area where a star can be chosen for an off-axis Coudé guiding. The current use of the STSs imposes that the science object should be located -10 arcseconds in RA (to the West) away from the optical axis. This constrains the guide star distance for the off-axis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

GPAO 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 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.

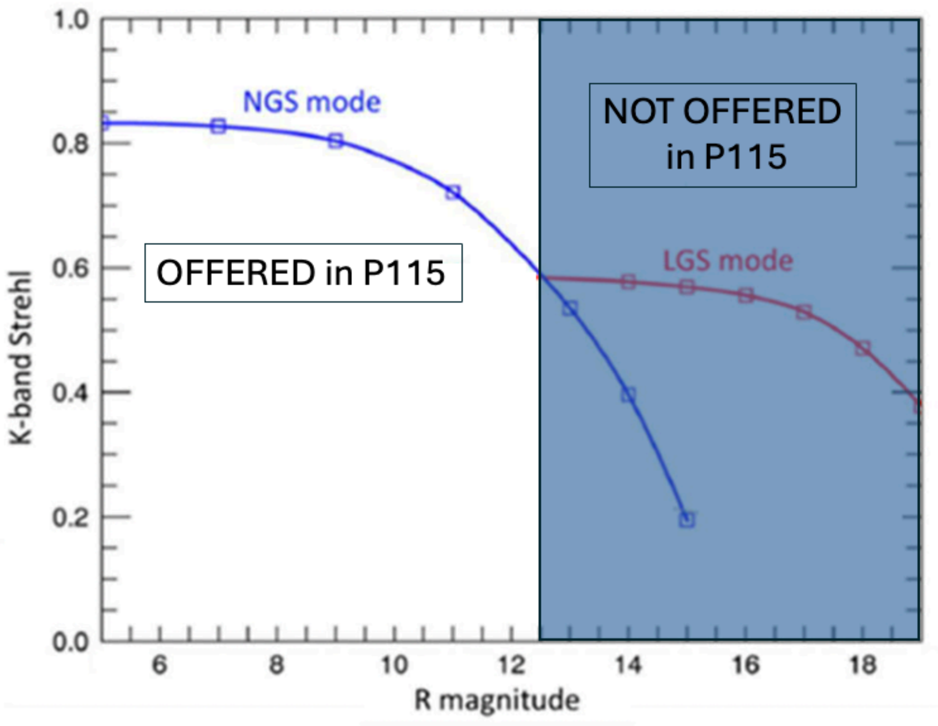

Figure 5: Expected Strehl ratio (SR) in K-band of NGS-VIS in P115 and LGS-VIS (foreseen for P117) modes.

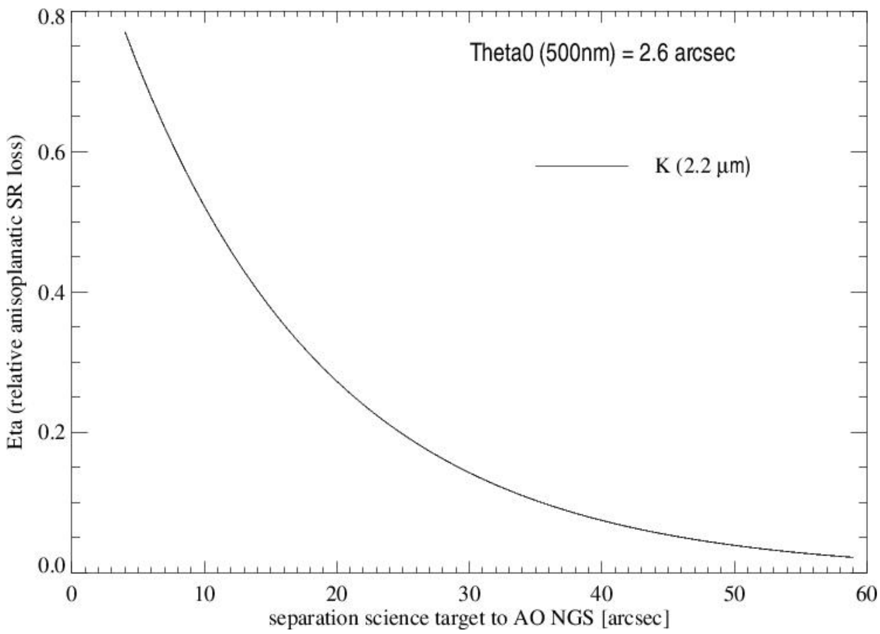

Figure 6: SR loss due to anisoplanatism as a function of the separation between the natural guide star (NGS) and the center of the VLTI field of view. An anisoplanetic angle of Theta0 (500nm) = 2.6 arcsec was assumed here as an average value for Paranal.

4.1.3 NGS-IR (formerly CIAO)

With the arrival of GPAO, CIAO (Coudé Infrared Adaptive Optics) systems remain but will be integrated in the GPAO infrastructure and will use the new GPAO deformable mirrors and RTC. They are renamed as NGS-IR (and LGS-IR when used with Lasers).

Those wavefront sensors analyse the light in the infrared (H and K bands) and command the M8s deformable mirrors to increase fiber coupling and instrument sensitivity. In P115, NGS-IR is only offered in the off-axis mode and with GRAVITY.

In the off-axis mode, the WFS get the light from the second STS beam, getting 100% of the infrared light. The WFS are composed of 9x9 Shack-Hartmann wavefront sensors equipped with SAPHIRA detectors recording frames at 100-500Hz. In the NGS-IR, the AO loops close in the following conditions:

- Point source with K<= 10 mag for NGS-IR off-axis.
- Seeing (500nm) <= 1.1 arcsec
- Coherence time (500nm) > 1.5 ms
- Airmass <= 2.0
- in the off-axis case, the separation between AO source (NGS) and scientific target must be higher than 4 arcseconds and smaller than 57.5 arcseconds (Fig.4). Strehl ratio performances decrease with separation as shown on Fig. 6.

Typical performances during commissioning are reported on Fig. 7. Note that if $m_K > 8$ and $m_G < 12.5$, it is advised to choose NGS-VIS. If the SR achieved on-axis is not satisfying and if there are potential off-axis stars in the field: decide between NGS-VIS and NGS-IR off-axis following the instructions presented in the next section.

NGS-IR WFS are equipped with neutral density filters to avoid saturation on the detector. Using these, observations of Alpha Centauri A (H=-1.4mag, Ks=-1.5mag) were demonstrated during commissioning. This corresponds to the current limiting magnitude of the bright-end capabilities.

4.1.4 NGS-VIS or NGS-IR?

The NGS-IR 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 NGS-IR mode is therefore recommended for red AO reference sources with m_V-$m_K \geq 5$ mag.

To decide between NGS-VIS and NGS-IR adaptive optics, and identify the best NGS, do the following:

- For each potential NGS within 57.5 arcsec of the science target, derive the on-axis Strehl ratio $SR_{NGS-VIS}$ and the off-axis SR_{NGS-IR} from Fig. 5 and 7 .
- Estimate the attenuation of the Strehl ratio, Eta, due to anisoplanatism, presented in Fig. 6.

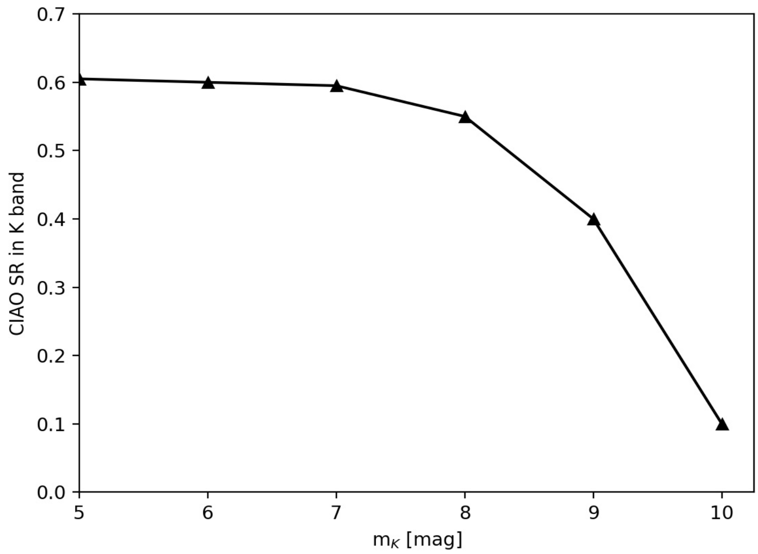

Figure 7: NGS-IR Strehl ratio in K-band as a function of the m_K apparent magnitude. The off-axis SR measurement has been corrected for the Eta factor.

- Multiply both numbers (i.e. $Eta_{NGS-VIS}$* $SR_{NGS-VIS}$ and Eta_{NGS-IR}*SR_{NGS-IR}) 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.

The list of available AO modes for VLTI instruments is described below:

AO mode Instrument	NGS-VIS NGS-VIS + TCCD	NGS-IR NGS-IR + TCCD
PIONIER	TEL.COU.TYPE = ADAPT_OPT TEL.COU.TYPE = ADAPT_OPT_TCCD	Not offered Not offered
GRAVITY	COU.AG.TYPE = ADAPT_OPT COU.AG.TYPE = ADAPT_OPT_TCCD	COU.AG.TYPE = IR_AO_OFFAXIS COU.AG.TYPE = IR_AO_OFFAXIS_TCCD
MATISSE	COU.AG.TYPE = ADAPT_OPT COU.AG.TYPE = ADAPT_OPT_TCCD	Not offered Not offered

Table 1: GPAO modes (VLTI-UTs) for the 3 VLTI instruments.

4.1.5 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 A and B. These are the main use cases:

- with NGS/LGS-VIS only beam A is used for the VLTI instrument axis (GRAVITY, MATISSE or PIONIER),

- with NGS/LGS-IR, beam B is used by the infrared wavefront sensors (WFS) located in the Coudé room, beam A is sent to the VLTI instruments

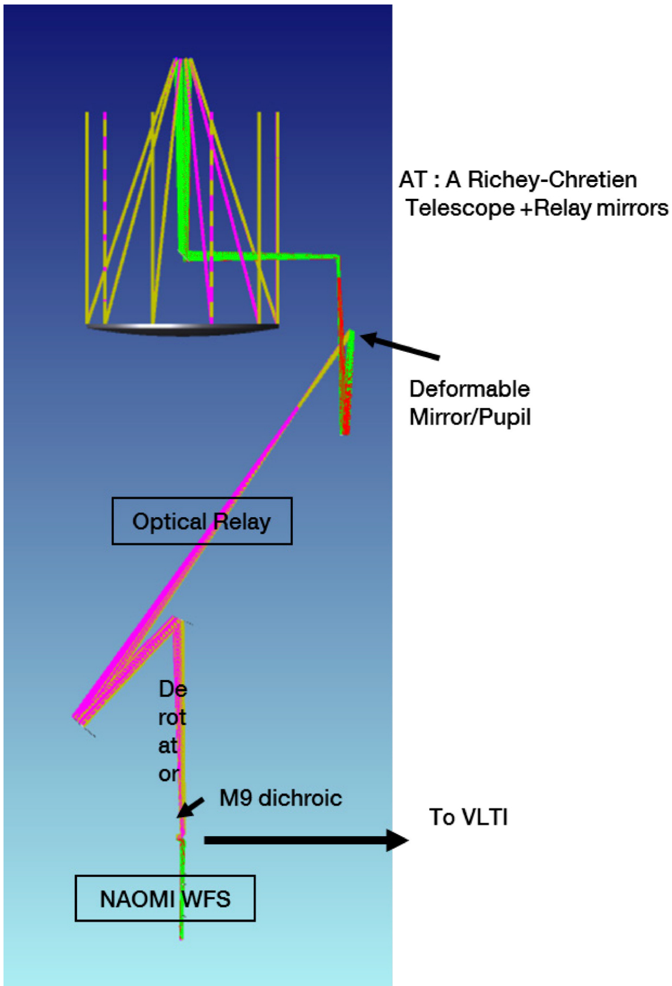

Figure 8: Optical layout of an AT with the telescope optics and NAOMI.

- from P110 with the GRAVITY-wide mode, beam A and beam B are both sent to the VLTI tunnel and lab for wide-separation (up to 30”) fringe tracking. This mode is compatible with NGS/LGS-VIS only (since NGS/LGS-IR would block beam B).

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).

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 NAOMI

Since November 2018, the four ATs at VLTI are equipped with the adaptive optics NAOMI (New Adaptive Optics Module for Interferometry) systems. By delivering a higher and more stable Strehl ratio during turbulent conditions, the NAOMI systems allow a more robust fiber coupling in the VLTI instruments which will translate into a higher sensitivity and precision in the interferometric data. NAOMI can also provide chopping capabilities up to 4 Hz to subtract the thermal background seen by MATISSE.

Saturation effects stops the loop from closing for $G < -3$. The sensitivity of NAOMI on the ATs is G =12.5 in service mode with turbulence categories 20% and above, leading to a Strehl ratio in H-band varying between $\sim$ 40-60 % depending on the conditions. For turbulence categories 10%. the limiting magnitude is G=14. For fainter guide stars, whose observing is allowed only in visitor mode, the Strehl delivered by NAOMI degrades to $\sim$ 10% for $G = 15$ in median seeing conditions. The table below summarizes the offering:

Service Mode T. Cat > 10%	Service Mode T. Cat = 10%	Visitor Mode
$G = 12.5$	$G = 14$	$G = 15$

If the science target is not suitable for guiding with NAOMI, it is possible to perform "off-target Coudé guiding", provided a suitable guide-star exists. This guide-star must be brighter than G =12.5 and within a radius of **50 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 and +10 arcsec in RA when the telescope is located at a South station. Users who want 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 **40 arcseconds** radius from the science object, see Fig 19 at the end of the document. If G >12.5, there is a risk that Coudé guiding cannot be performed, depending on the off-axis distance and the on- sky conditions (seeing, τ_0). Note that the Gaia G band filter is the closest to the NAOMI transmission profile. Users are therefore encouraged to use guide-star magnitudes obtained in this G filter when possible. If nor G nor R magnitude are available, V-band magnitude is also possible but color effects are to be expected.

During the NAOMI commissioning, the AO loop closure was tested against different guide star brightnesses and separations to the moon while it was almost fully illuminated. The following restrictions due to the moon on the ATs' guiding with NAOMI were derived:

- If the FLI is ≥95%, and the guide star is fainter than 9th magnitude in the G-band, guiding is not possible for distances to the moon lower than 5 degrees.
- If the FLI is ≥95%, and the guide star is brighter than 9th magnitude in the G-band, guiding is not possible for distances to the moon lower than 3 degrees.

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).

More details about NAOMI can be found in Woillez et al. 2019 (A&A).


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

4.2.2 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 (≥4" in diameter as opposed to ≤2" for SF), which is mandatory for GRAVITY. The uses of the AT-STS is mostly transparent to GRAVITY, MATISSE and PIONIER users. Similarly to the UTs (section 4.1.5), from P110, the GRAVITY-wide mode offers the possibility to propagate the two AT-STS beams to the VLTI tunnel and lab.

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 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.

[1] http://www.eso.org/observing/etc/
[2] http://www.jmmc.fr/aspro

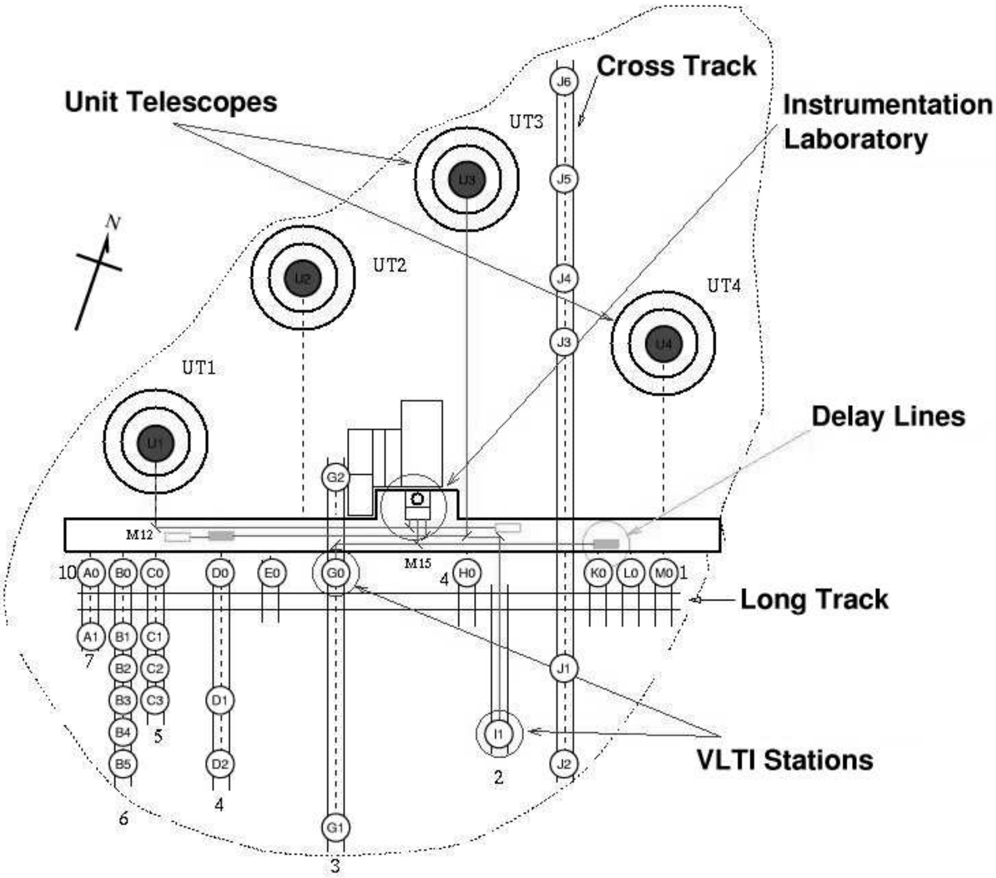

Figure 10: Layout of VLTI telescope locations.

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 (except when on the extended configuration). 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.

5.3 UT Baselines

The following table gives the characteristics of the UT 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. 8.6) 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 9.2), as well as on the following page:

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

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 up to 2 days are required to change quadruplet.

AT configurations are requested by generic names (”small”, ”medium”, ”large” and ”extended”) rather than explicit configurations. The standard configurations used for a given period are detailed on ESO web page and should be used for phase1 and phase2 preparation:

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

This new scheme allows a more flexible execution of service-mode OBs. For operational reasons, observations may take place (although rarely) on ”intermediate” configurations which occur during a transition between two standard configurations. A criteria of at least 50% baseline length overlap will be used. This scheme will be primarily used for imaging programmes. The overlap in baseline length between standard and relocation configurations is detailed on the aforementioned web page.

The list of available quadruplets of telescopes offered for P115 is listed below:

AT Configurations	PIONIER, MATISSE GRAVITY single-feed	GRAVITY dual-feed and GRAVITY-wide
Small	yes	yes
Medium	yes	no
Large	yes	yes
Extended	yes	no

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, 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 9.2), as well as on the following page:

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

6 THE VLTI LABORATORY

After compensation for geometrical optical delay with the delay lines, the beams are sent to the VLTI laboratory that hosts the VLTI instruments as well as alignment and stabilization opto-mechanical systems. Figure 11 shows a drawing and a picture of the main VLTI Lab systems and instruments.
We can list:

1. the VLTI instruments: currently PIONER, GRAVITY, MATISSE
2. the IRIS lab-guiding camera
3. the Beam Compressors - Differential Delay Lines: (BC-DDLs) they fulfill the double function of compressing the beam size from 80mm to 18mm before entering the instruments, and provide differential optical delay between the two STS beams. This is currently used by the GRAVITY-wide mode where the STS A beam is used by the GRAVITY the fringe tracking object and the STS B beam is used by the object observed on the science channel. See Fig. 12.
4. the switchyard: it is a series of mirrors that can redirect the 8 input beams to the proper systems (BC-DDLs, or direct propagations to the instruments), they also include periscopes for the GRAVITY wide mode and MATISSE feeding optics.
5. MARCEL: it is an internal coherent light source in the laboratory

Except for the GRAVITY-wide mode, the input beams follow the same path. They go through the beam compressors and then are redirected by the switchyard to the instrument feeding optics. In the GRAVITY-wide mode, the 2 STS beams coming from each telescope go directly through the switchyard to be compressed and being delayed relatively to each other. Then the switchyard redirects the FT beams (STS A beams) to GRAVITY while the SC ones (STS B beams) are redirected to GRAVITY via periscopes. See Fig. 12.

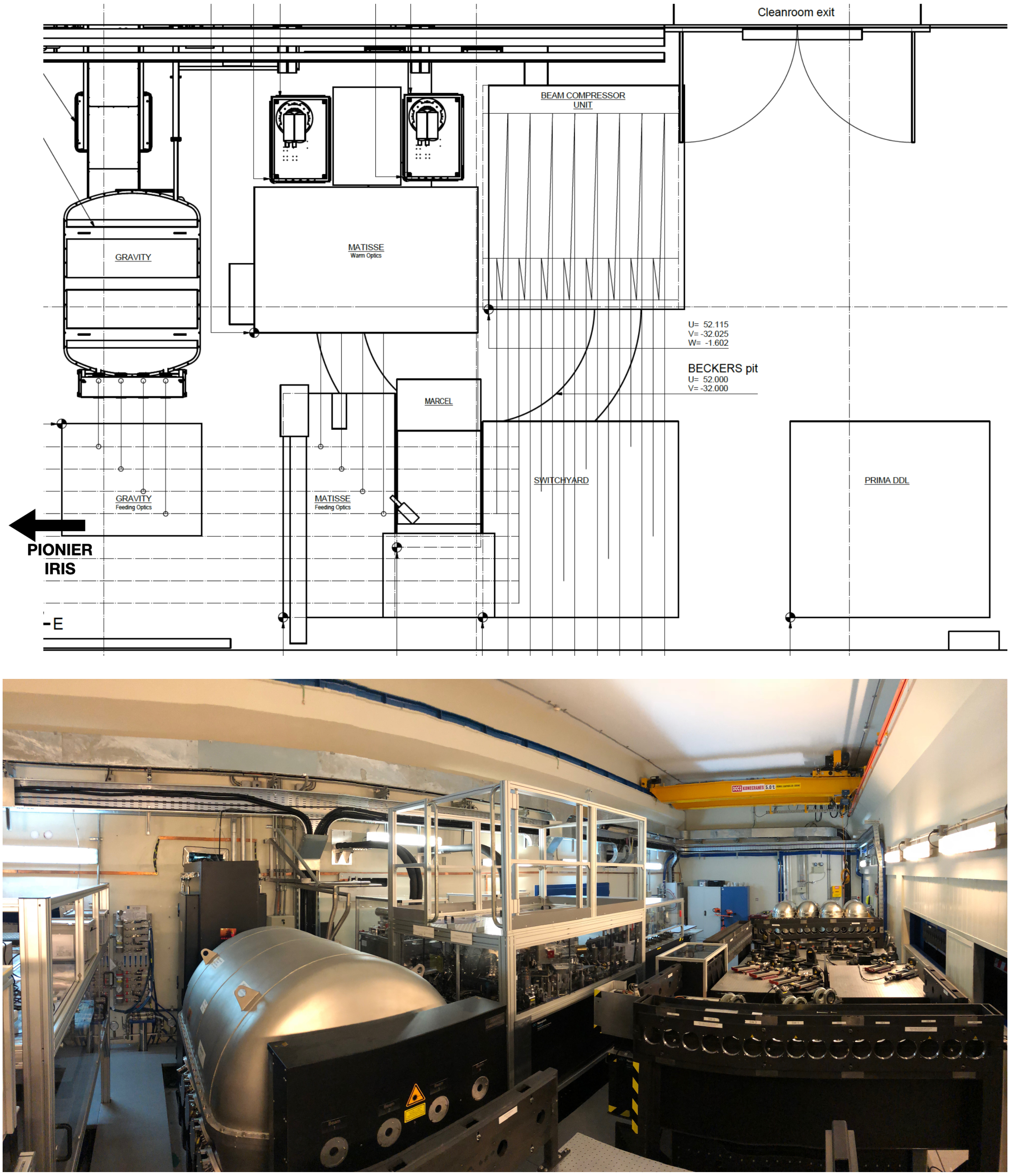

Figure 11: VLTI lab: Top: drawing showing the main sub-systems. Bottom: Picture of the same elements taken next to the GRAVITY feeding optics.

7 VLTI STABILIZATION

7.1 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...).

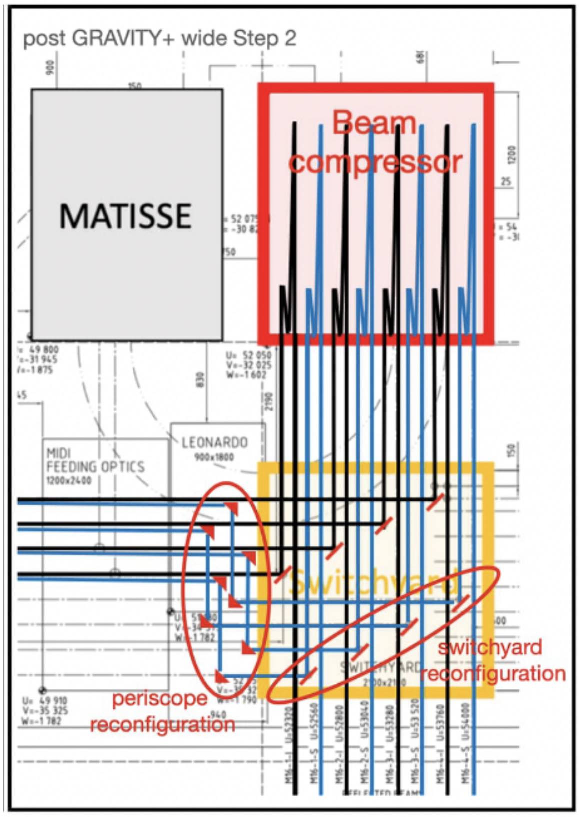

Figure 12: Optical layout in the VLTI laboratory when the GRAVITY-wide mode is used. Black beams represent the fringe tracker beams and blue ones the science channel beams.

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.

7.2 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. 13.

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

- $K = 8.0$ with the ATs.

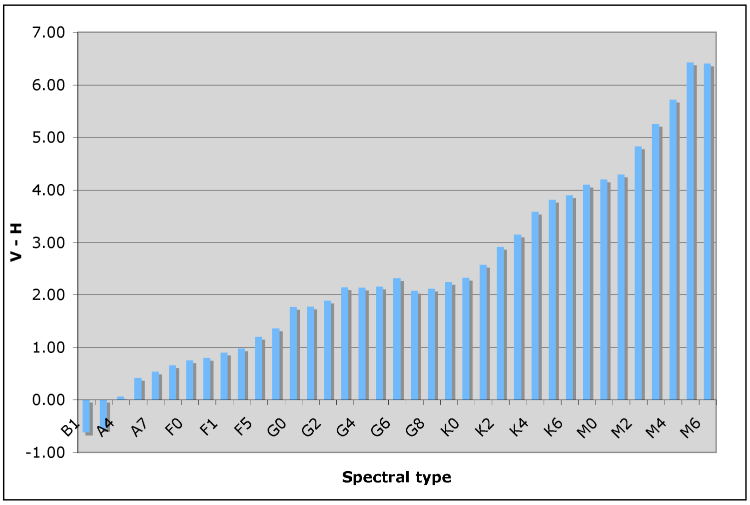

Figure 13: Difference of magnitude between V and H bands, depending on the spectral type.

- $K = 11.5$ with the UTs.

7.3 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.

8 ORGANIZATION OF THE VLTI OBSERVATIONS

8.1 General

For P115, 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*.

For VLTI users needing assistance to prepare their VLTI proposals, the community-supported VLTI Expertise Centres - distributed throughout Europe - can offer in-depth support. They also offer support for observation preparation, advanced data reduction and interpretation: see the VLTI Expertise Centres website.

8.2 Observation types

From P104, PIs need to select one or more of the following types of interferometric observations:

- snapshot: standalone concatenations (SCI, CAL-SCI, CAL-SCI-CAL or CAL-SCI-CAL-SCI-CAL, depending on the instrument) without further links to other observations in terms of time links or filling the uv plane
- time series of concatenations that are repeated once or more often over the period ; a cadence of typically 1 week on a given configuration is not realistic given the need to cycle through several configurations in the AT schedule. As a guideline, possible cadences are either a few days in a row or not more than 2-3 times per period per AT configuration.
- imaging: a set of concatenations with different baseline configurations to fill the uv plane for the purpose of image reconstruction. In this case special care is taken by ESO at execution to fill uniformly the uv plane.
- astrometry: GRAVITY dual-feed observations with the purpose of extracting astrometric information

For each observing run, one or more of these categories shall be specified in the instrument mode section of the proposal that best describe the proposed observations.

8.3 The Imaging scheme

In P115, ESO will continue 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 image reconstruction using any of the VLTI instruments with the ATs are marked as such using the "imaging" observation type (see previous section). In addition, such proposals should request time corresponding to a minimum number of 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. The reason for this is to ensure a minimum reliability and dynamic of the reconstructed image. Depending on the object declination, the observability might be reduced. PIs should request a number of concatenations accordingly and by respecting the Imaging programme instructions presented at the following webpage:

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

PIs 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 minimum/maximum time interval between AT configurations can be specified using the Special Remark section.

As of P108, ESO introduces the so-called imaging slots (ISLs) in the VLTI-AT telescope schedule in order to further improve the efficiency of VLTI imaging observations. ISLs are periods of about 2 weeks of un-interrupted service mode time with flexibility on the exact dates of changing configurations within this slot. This means that certain times are reserved for ISLs: two weeks are set aside centred on new moon in November, February, May, and August of every year. PIs of GTO, Large Programmes, programmes requiring Visitor Mode are requested to adhere to this restriction for their planning. ISLs are primarily intended to support imaging observations, but they are not restricted to this type of VLTI observations. ISLs are regular SM time, and OBs are executed according to their priority. Likewise, imaging observations are not restricted to ISLs, but can be completed in SM time outside of the ISLs. PIs of VLTI imaging programmes can request to repeat all observations of a time-critical imaging campaign if it was not finished within the requested time under the following conditions:

- The run is A-ranked.
- The time interval during which the image needs to be completed (Imaging Time) is specified in the P1 proposal.
- The Imaging Time is not shorter than 1 month (length of an ISL plus margin).
- The guarantee concerns not more than the ESO-recommended number of uv points for imaging (currently 15 concatenations per target). Possible additional points are taken on a best-effort basis, and expire outside the Imaging Time interval.

8.4 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. 8.7). Alternatively, the JMMC tool named SearchCal can be used.

8.5 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.

8.6 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.

8.7 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...

8.8 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 NGS-VIS (for the UTs) or NAOMI (ATs) from working correctly. Please refer 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 the guide star should be located more than 20 degrees away from the Moon if its magnitude is higher than $V = 9$ mag ('faint case') and more than 10 degrees away if it is lower than $V = 9$ mag ('bright case'). Those numbers will probably change following the tests done during the GPAO commissioning.

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.

8.9 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.

8.10 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 UT/NGS-VIS or NAOMI. H and K Band magnitude should be given properly for the use of IRIS.

9 APPENDICES

9.1 Feasibility matrices

The following tables 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 tables 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 0.5 and 1.4 arcsec, $\tau_0 > 2.0$ ms, sky transparency "photometric" or "clear", airmass lower than 2.0.

9.1.1 Observations with the UTs and NGS-VIS

	NGS-VIS guide star
On-axis Coudé guiding	$-3 < G_{rp} < 12.5$
Off-axis Coudé guiding	$\boxed{-3 < G_{rp} < 12.5}$, see 4.1.2
IRIS guiding	$\boxed{K < 11.5}$
Pupil alignment	$K < 8.5$

Notes:

1. G_{rp}= G-magnitude of the guide-star in the Gaia red bandpass.

9.1.2 Observations with the UTs and in the NGS-IR mode

For observations with GRAVITY in NGS-IR mode, the reader is referred to section 4.1.3 and 4.1.4.

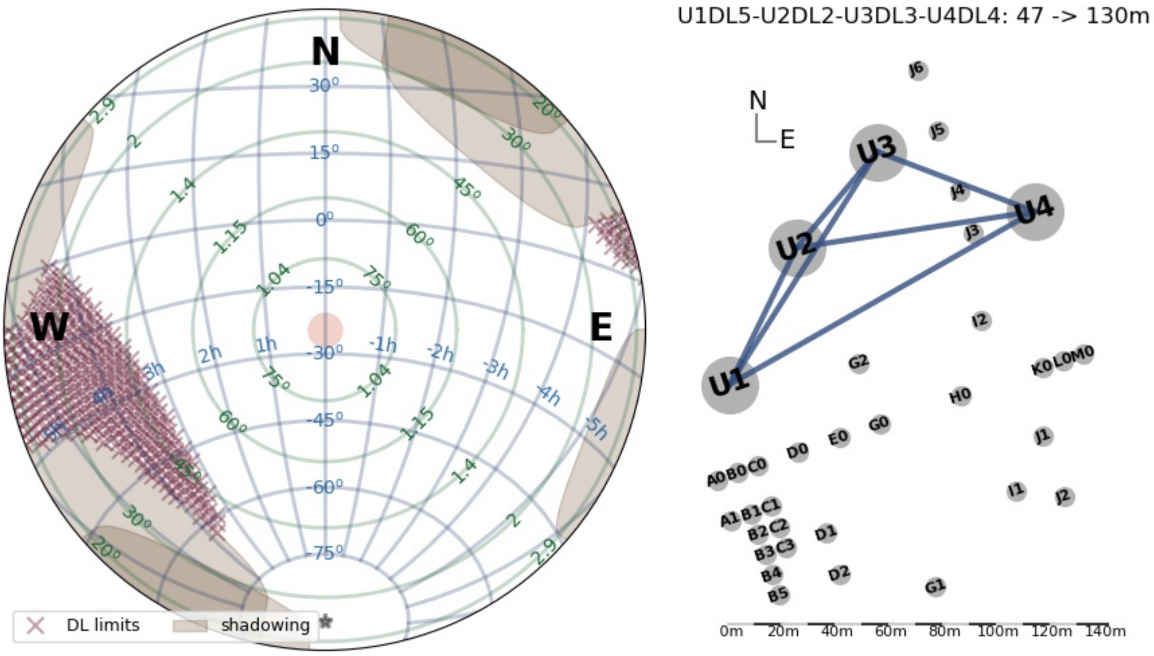

Figure 14: UT sky coverage

9.1.3 Observations with the ATs

	PIONIER, MATISSE	**GRAVITY**
On-axis Coudé guiding	$G < 12.5$ if T cat. $> 10\%$ $G < 14$ if T. cat $= 10\%$	Same as PIONIER/MATISSE but with airmass ≤ 1.6
Off-axis Coudé guiding	$G < 12.5$ see 4.2.1	$G < 12.5$ see 4.2.1 airmass ≤ 1.6
IRIS guiding	$K < 8.0$	N/A
IRIS Pupil alignment	$K < 5.0$	N/A

9.2 Sky Coverage

We plot here the various sky coverage of all the standard offered quadruplets. Sky coverage is limited by the UT dome shadowing, as well as delay line limits. Note that both ATs and UTs have a zenithal avoidance area with a 3 degree radius.

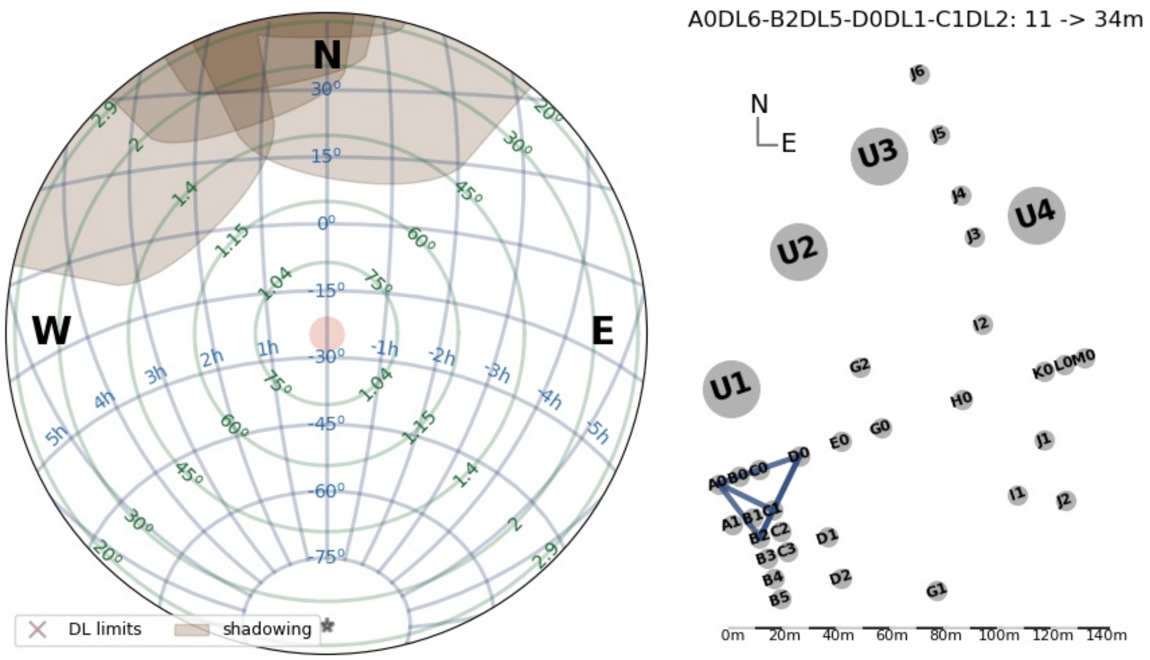

Figure 15: AT sky coverage, small configuration

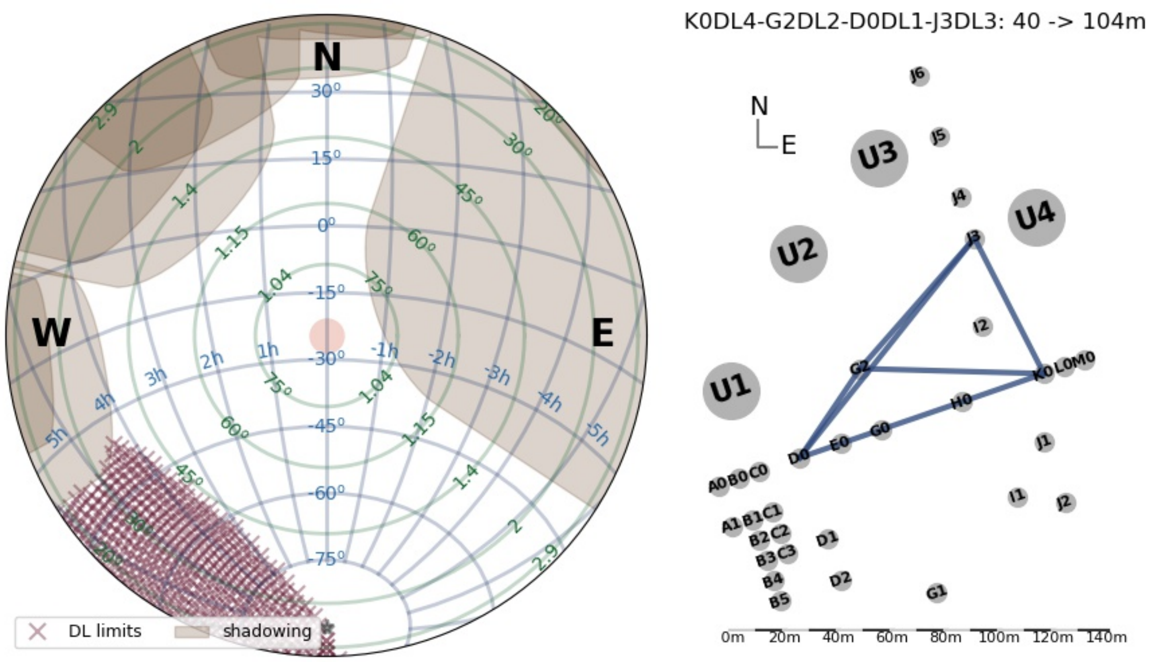

Figure 16: AT sky coverage, medium configuration

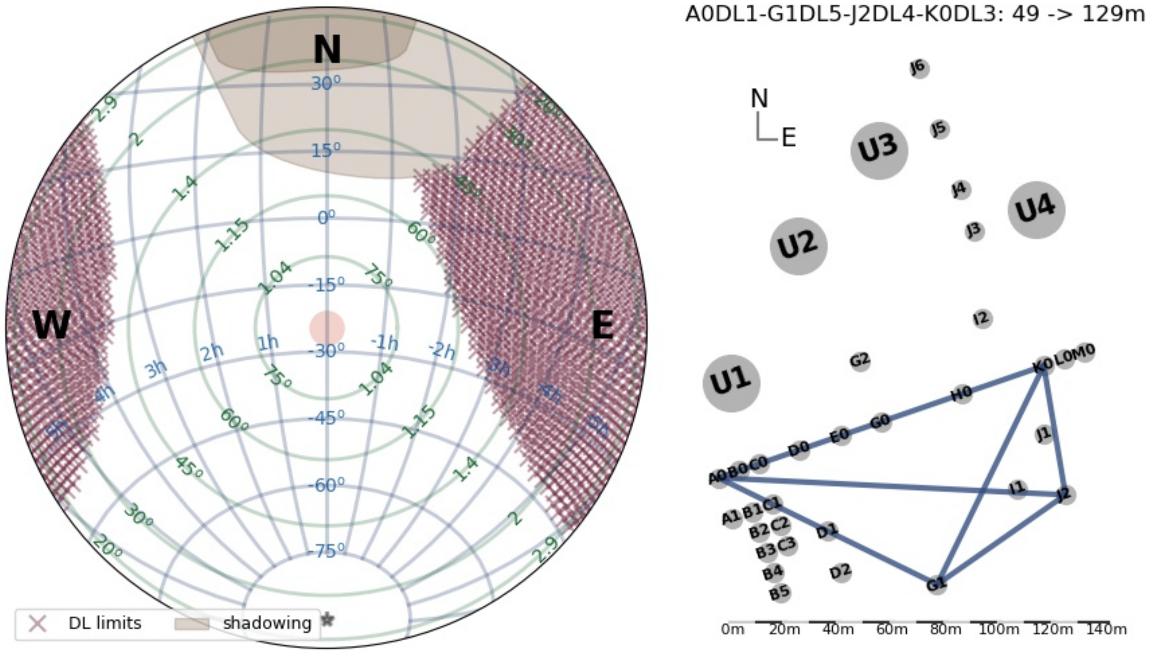

Figure 17: AT sky coverage, large configuration

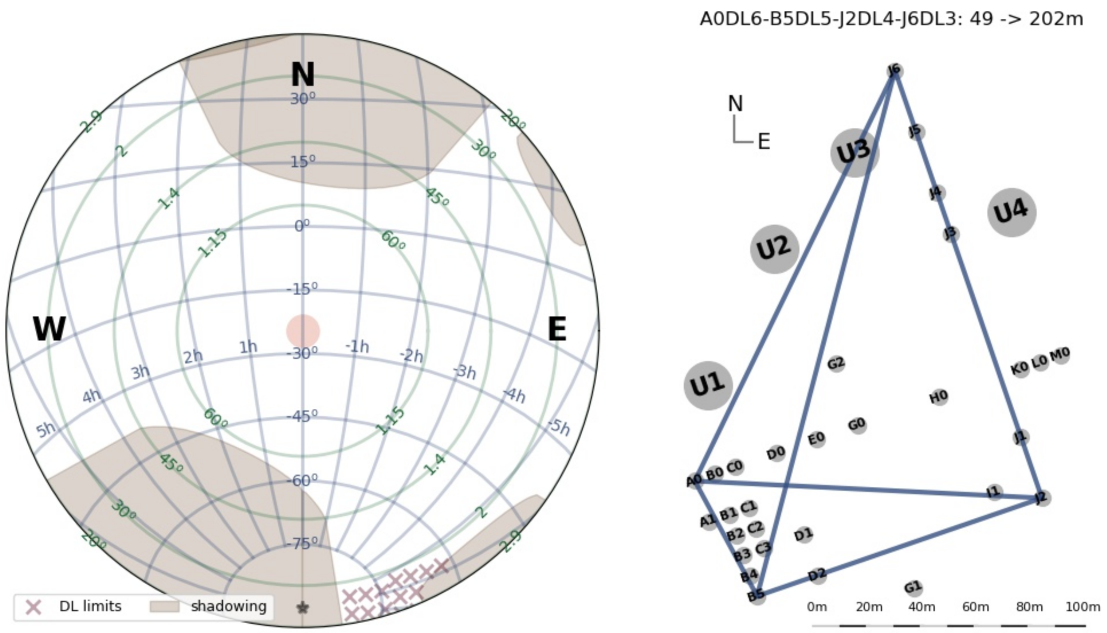

Figure 18: AT sky coverage, extended configuration

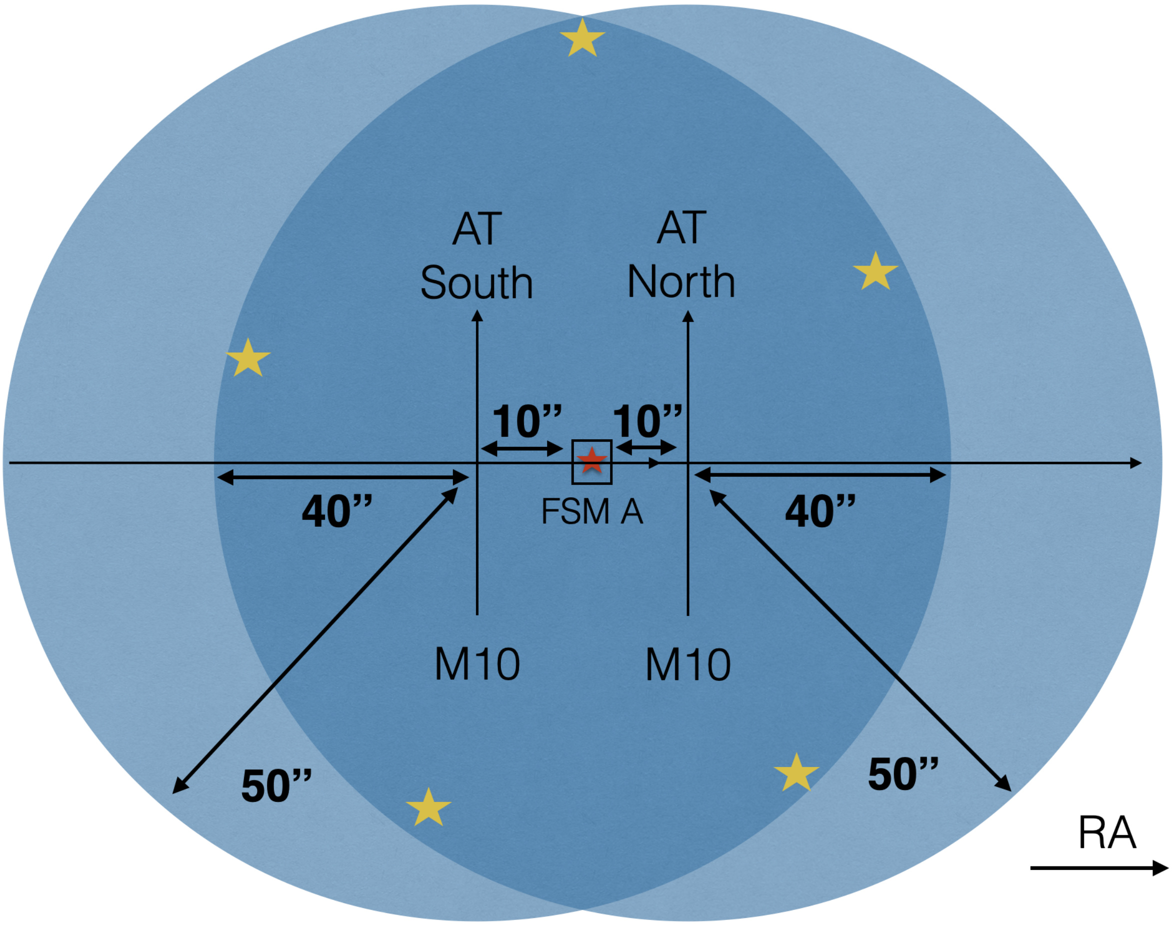

Figure 19: Geometry of the STS configuration when on a mixed North/South baselines (medium and large configurations). In this case, the field of view available for a guide star (darker blue area) is the intersection of the 2 individual STS fields of view. Yellow stars mark the position of potential guide stars. In pure RA, the guide star should not be further than **40 arcsec** away from the science object that is picked in the field by the FSMA mirror (red star).

___oOo___