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Very Large Telescope
Paranal Science Operations
VLTI User Manual

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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
MIDI	MID-infrared Interferometric instrument
NAOMI	New Adaptive Optics Module for Interferometry
OB	Observation Block
OPC	Observation Program Committee
OPD	Optical Path Difference
P2PP	Phase-2 Proposal Preparation
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 P101 (running from 1 April 2018 to 30 September 2018). This document is a mandatory complement to the user manuals of the VLTI instruments (AMBER, PIONIER and GRAVITY), since it contains very important information to prepare the proposals for AMBER, PIONIER or GRAVITY. In particular, the requirements by the VLTI sub-systems for the feasibility of an observation are listed at the end of this manual.

This version is released for Phase I of P101 and contains a new configuration offered for observations with the ATs as well as a description of the new off-axis adaptive optics CIAO systems to be used with the UTs and GRAVITY. Minor corrections were also done over the document.

The **bold** font is used in the paragraphs of this document to put emphasis on the important facts regarding VLTI in P101.

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

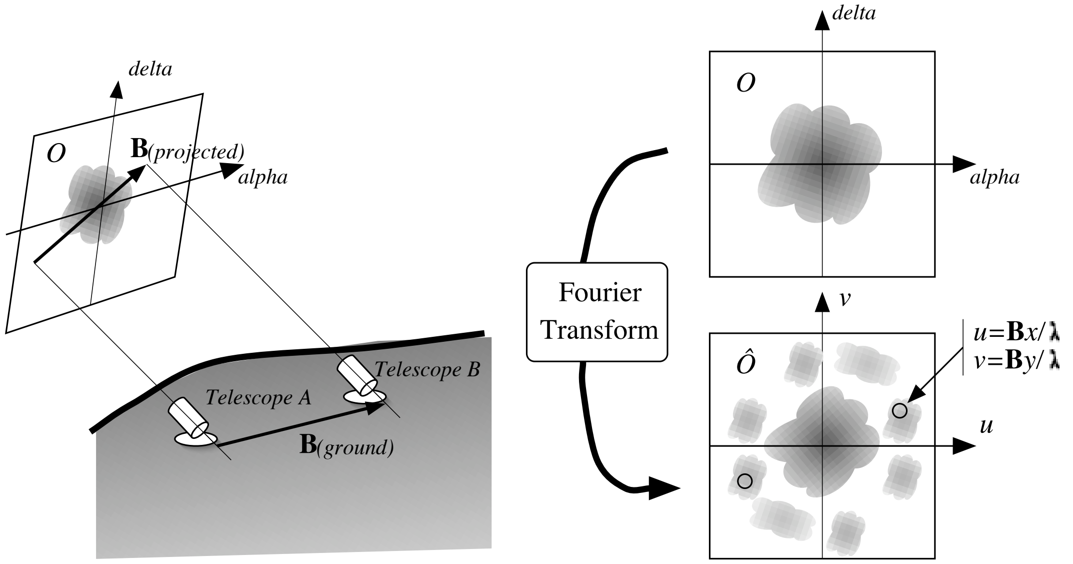

Figure 1: Basic principle of ground-based long-baseline optical interferometry. The sample of $\hat{O}$ for the given projected baseline and wavelength is given by the small circle (the graphical representation of $\hat{O}$ is fictive).

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

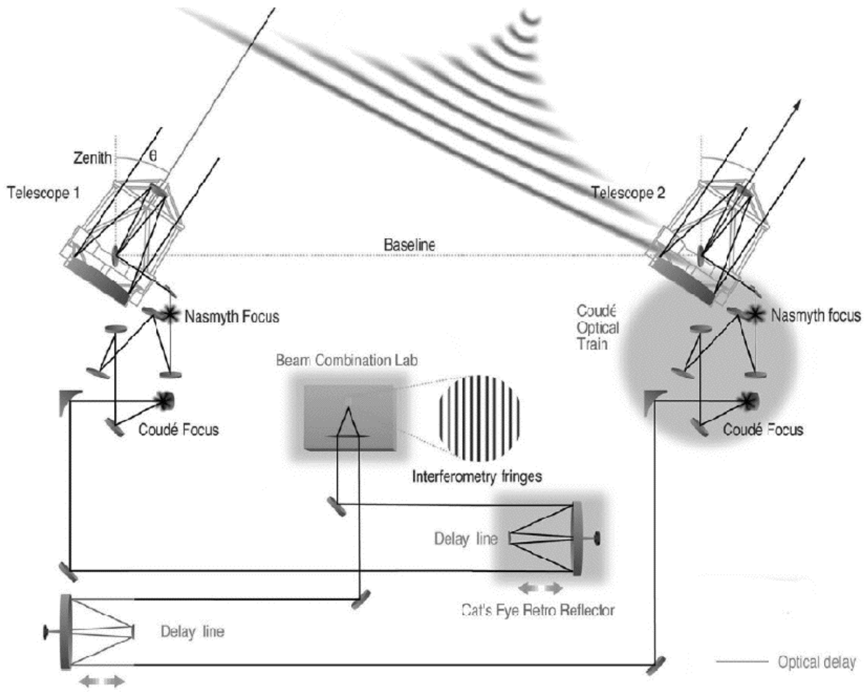

Figure 2: The optical path in the VLTI (when two telescopes are used).

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, FINITO, 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 P101 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 ≈ 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, AMBER or PIONIER), and
- one for the CIAO infrared wavefront sensors.

The use of the UT-STS is completely transparent to AMBER, 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 4 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 57.5 arcsec of the target. 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).

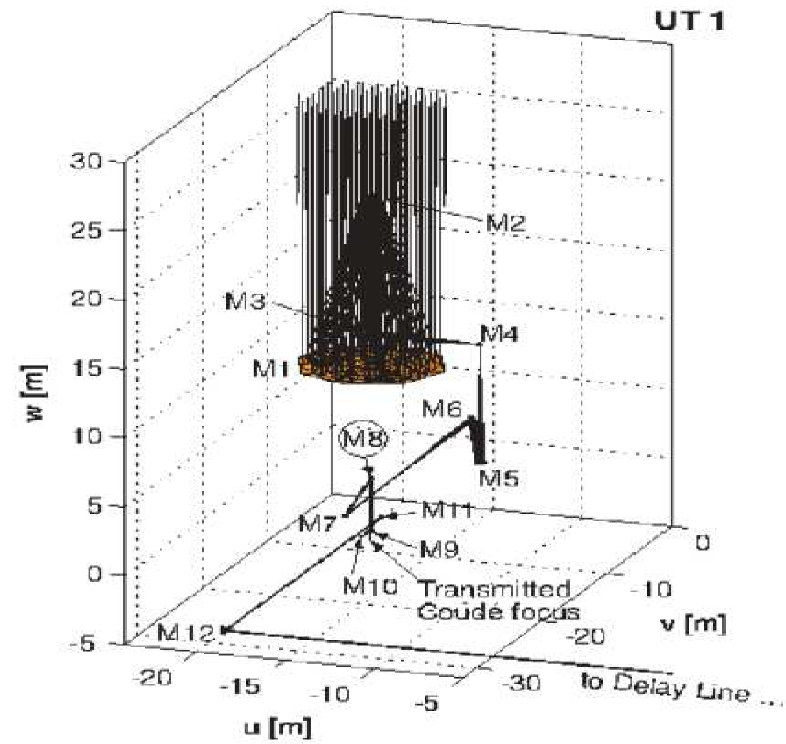

Figure 3: The optical layout of the lower part of the Coudé train and the relay optics

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.

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.

In the case where FINITO is used the limitation for the off axis guiding are more stringent and observation can only be performed if the guide star is closer than 13 arcsec.

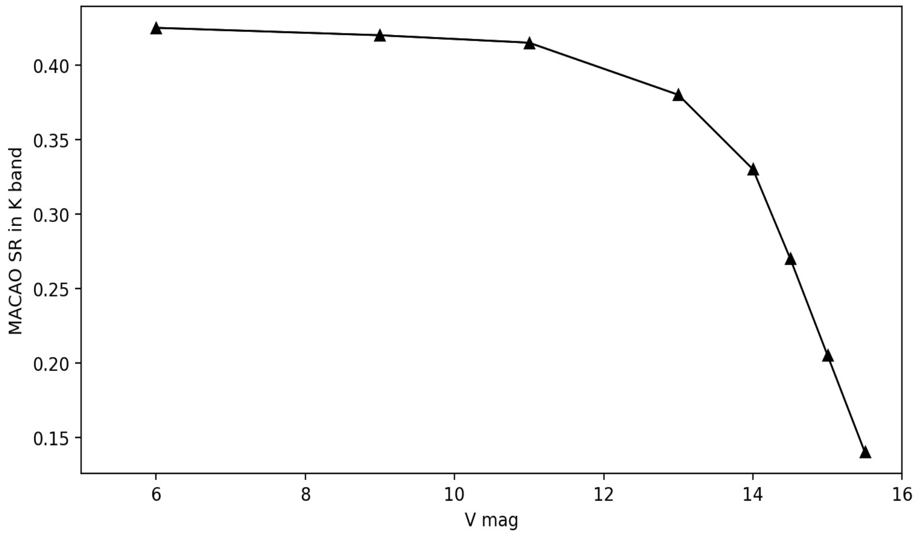

Figure 4: MACAO Strehl ratio (SR) in K-band as a function of V magnitude. From Haguenauer et al., 2016, SPIE Proceedings, 9909, 99092Y.

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 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 AMBER and 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. This attenuation has to be taken into account to assess the feasibility of the target on AMBER, using the K-magnitude of the target.** A similar magnitude loss can be used in H-band for FINITO, as an approximation. The theoretical SR loss due to anisoplanetism is presented in Fig. 5.

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

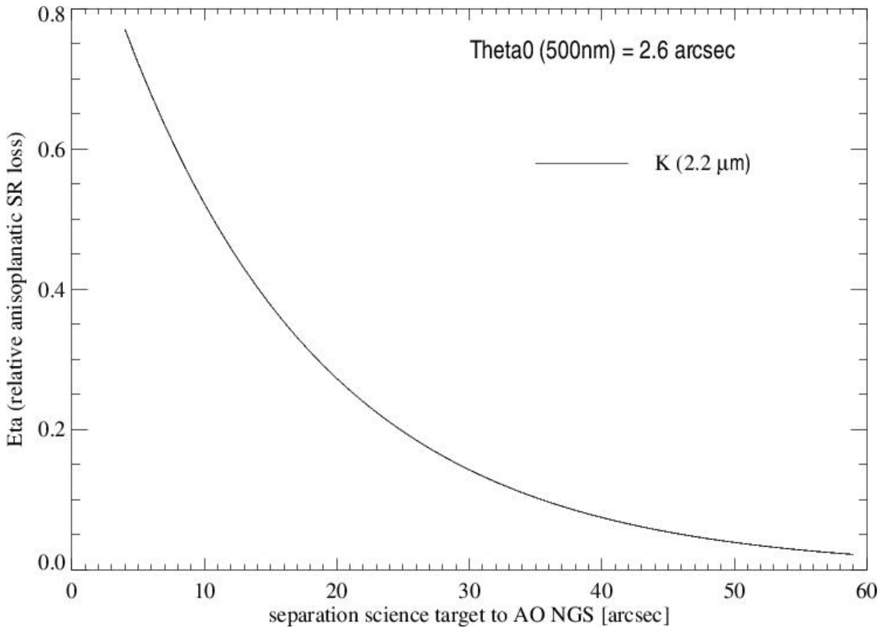

Figure 5: SR loss due to anisoplanatism as a function of the separation between the natural guide star (NGS) and the center of the VLTI field of view. An anisoplanetic angle of Theta0 (500nm) = 2.6 arcsec was assumed here as an average value for Paranal.

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:

- 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. 5.
- 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. 6.

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.

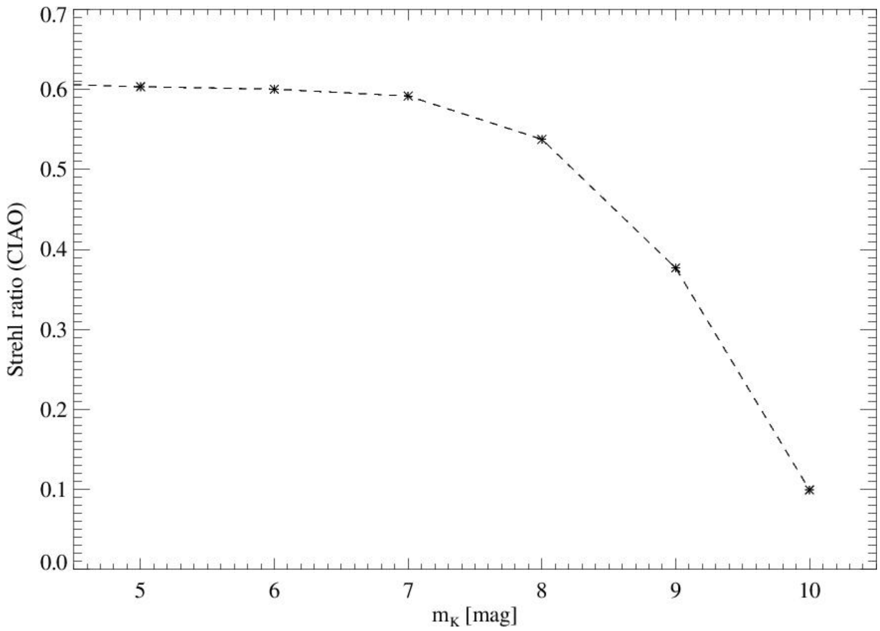

Figure 6: CIAO Strehl ratio in K-band as a function of the m_K apparent magnitude. This off-axis SR measured has been corrected for the Eta factor.

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. 4 and 6 .
- Estimate the attenuation of the Strehl ratio, Eta, due to anisoplanatism, presented in Fig. 5.
- 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), but only two or three are used at the same time 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. 7.

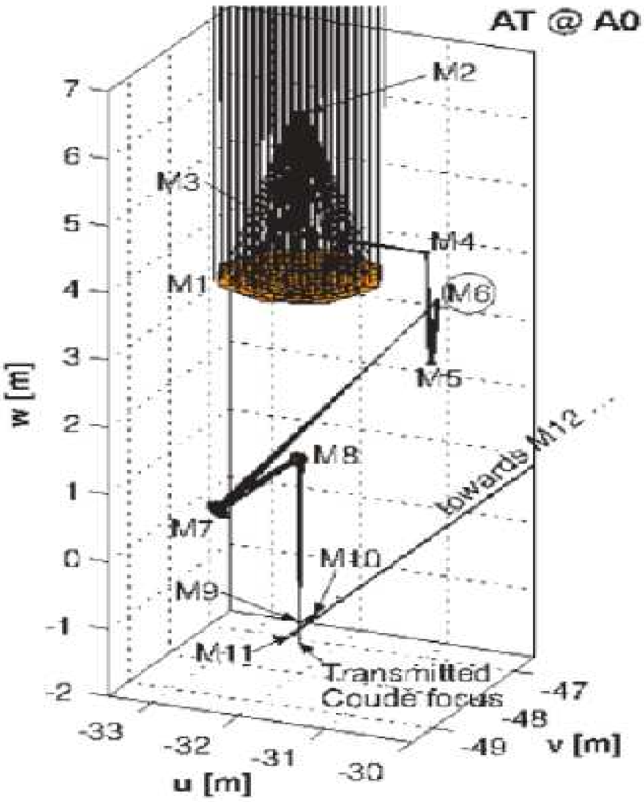

Figure 7: Optical layout of an AT with the telescope optic (M1..M3), Coudé train (M4..M8) and relay optic (M9..M11). Note that the lower part of the diagram is not valid since 2015, because the relay optics have been replaced by the Star Separators.

4.2.1 STRAP

Each AT is equipped with the tip-tilt corrector called STRAP. It consists of four avalanche photo-diode quadrants which measures the tip-tilt of the incoming wavefront. The measured tip-tilt is compensated by acting on the M6 mobile mirror of the telescope. When reaching the limit, the M6 position is offloaded to the alt-az axes of the telescope.

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 **closer than 57.5arcsec** to the science target. If V >12, there is a risk that Coudé guiding cannot be performed, depending on the off-axis distance and on the sky conditions (seeing, τ_0). In the case where FINITO is used the off-axis guide star has to be **closer than** 15 **arcsec** for the observation to be possible.

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.

 

Figure 8: A unit telescope (left) and an auxiliary telescope (right).

- 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).

4.2.2 NAOMI

Foreseen to be completed in P101, 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. 9.

During P101, 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.

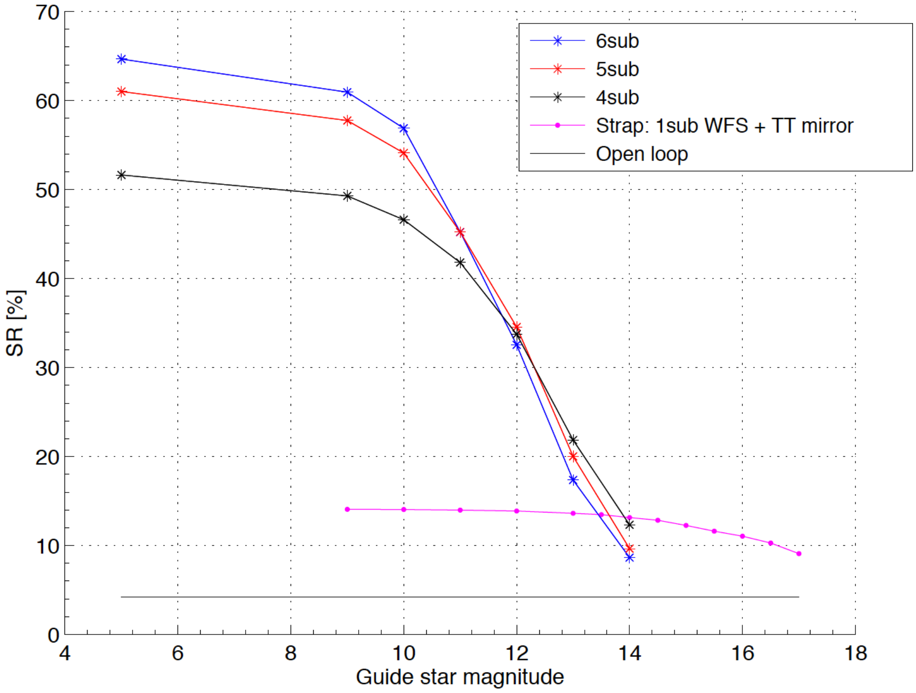

Figure 9: Expected Strehl ratio for NAOMI compared to the current STRAP system and the open loop case versus the R-band magnitude of the guide star. From Dorn et al. 2014, article in the ESO Messenger.

- 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 is because they offer 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 completely transparent to AMBER 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. With AMBER, three baselines (three telescopes) are used simultaneously, four telescopes are used simultaneously with PIONIER or GRAVITY. 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): 3T for AMBER and 4T for

PIONIER and GRAVITY.

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 (2 for AMBER, 3 with PIONIER or GRAVITY) continuously moves in order to compensate the OPD for the apparent sidereal motion, slow drifts, and (when FINITO is used) atmospheric piston.

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 either from the science instrument itself (AMBER or PIONIER), or from a fringe-tracker (FINITO).

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

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

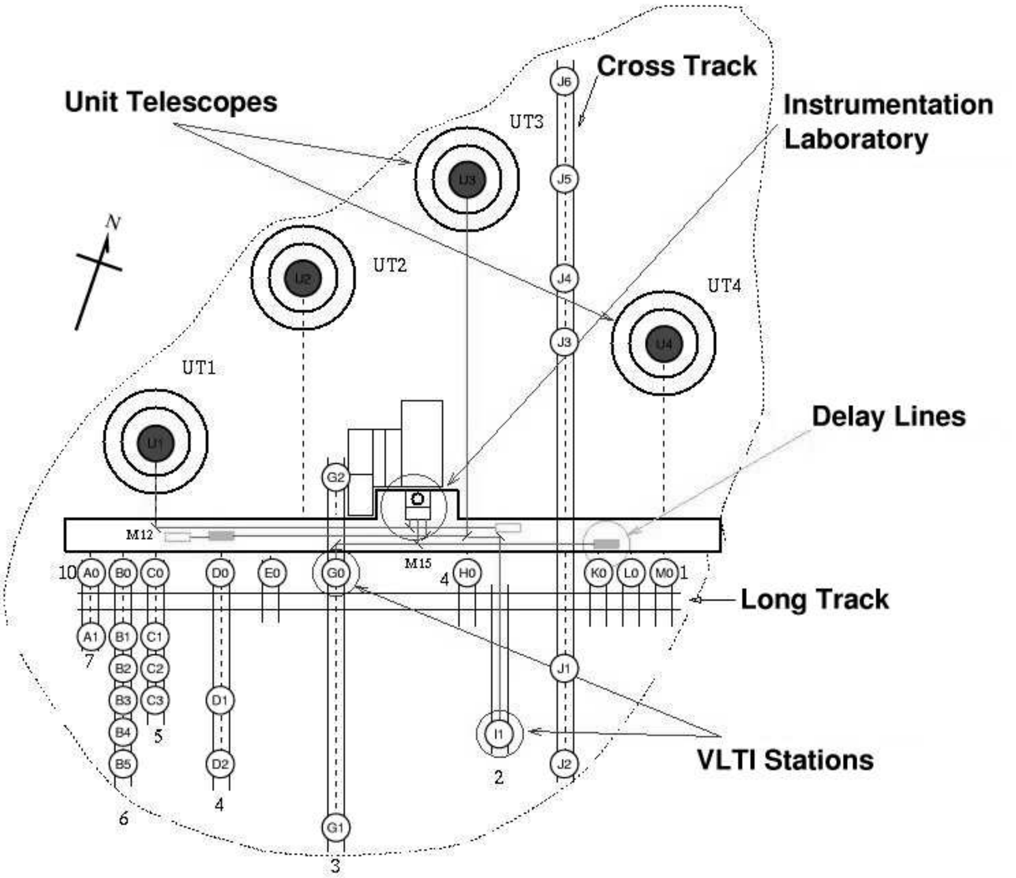

Figure 10: Layout of VLTI telescope locations.

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 P101, **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

Note that we cannot guarantee that these six baselines will actually be offered in P101. The final subset of realized baselines will depend on the number of requests for each baseline.

Therefore, users might be asked later to switch to the next-best baseline. They can already indicate an alternative baseline in their proposals (as a comment to the interferometric table).

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. 7.4) 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/

5.4 AT baselines

Auxiliary Telescopes are offered as 4 telescopes configurations. In these 4-telescopes setups, every possible 3 telescopes configurations can be used for operations during the same night by AMBER. The change from one of the available triplet to a different one only requires a configuration at the level of the VLTI Laboratory. **Such a change of configuration takes about 10 minutes.** 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 explicitely offered. 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 limit idle time, service mode programs requesting the Large configuration might see their observations executed on the astrometric configuration instead (similar baseline length and sky coverage).

The list of available quadruplets of telescopes offered for P101 is listed below:

AT Configurations	AMBER, PIONIER, 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. Particularly for AMBER observations, the decision on which specific baselines will be used at the time of the observation will be made at the time of the Phase II or in preparation of the visitor run. AMBER observations can be carried out with any of the triplets of a given quadruplet.

-

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/

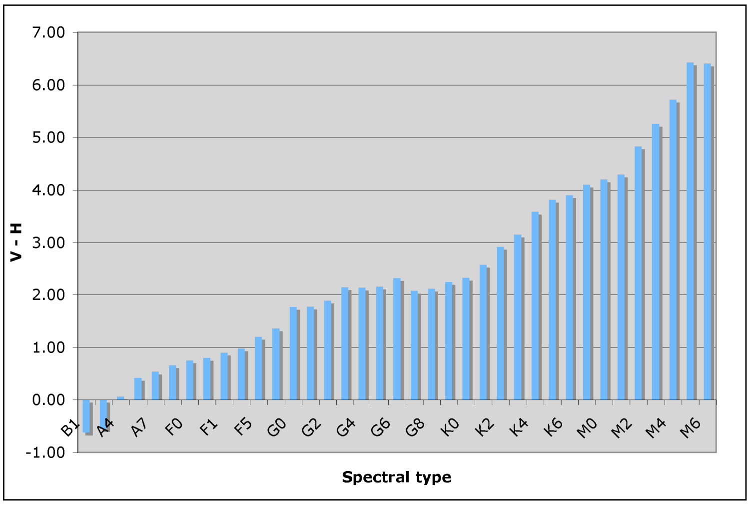

Figure 11: Difference of magnitude between V and H bands, depending on the spectral type.

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.

There are two modes for IRIS: slow-guiding, and fast-guiding. 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. The fast-guiding is used for FINITO (see Sect. 6.4) and for AMBER. In this mode, the tip-tilt corrections are sent to the FINITO ACUs, and corrections are sent every 10 ms.

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. 11.

The limiting magnitudes in K-band for IRIS are:

- In slow-guiding:
  - $K = 8.0$ with the ATs.
  - $K = 11.5$ with the UTs.
- In fast-guiding (required for FINITO):
  - $K = 5.0$ with the ATs.
  - $K = 8.5$ 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.

6.4 FINITO

FINITO is the VLTI fringe-tracker. Its purpose is to compensate at high rate the atmospheric piston between the telescopes that are used by an interferometric instrument, in order to stabilize the fringes produced by this instrument. FINITO produces and measures fringes in H-band. It is fed by either two beams or three beams. In this later case, fringes are made on two pairs (i.e., two baselines) only. Therefore, in three-beam mode, one of the three beams is common to the two interferometric channels of FINITO.

For each channel/baseline, FINITO measures the position of the fringe packet and its phase, and sends this information to the OPD controller which moves the delay-line. When FINITO is used with three beams (for AMBER observations), the reference delay-line (the one set to a fixed position) corresponds to the beam-0 of FINITO which is common to the two interferometric channels. This, coupled with the fact that the order of the baselines (which telescopes goes into which input channel of Finito) will introduces extra limits in the sky accessibility (already limited by the delay-line range and the shadowing of the telescopes.). As such the observability of targets with or without FINITO maybe different.

In standard operation, FINITO performs cophasing whenever the fringe SNR is enough. If the fringe SNR decreases, FINITO switch to coherencing and switches back to cophasing when the SNR improves.
The performances of FINITO are:

- Typical residual phase (ATs): 200 nm RMS.
- Limiting magnitude ATs: -2 $< H <$ 5.5
- Limiting magnitude UTs: 1 $< H <$ 8.
- Limiting visibility in H: 15 % (ATs), 10% (UTs)

IRIS has to be used on fast-guiding mode. More detailed information are available on the performance of AMBER+FINITO are available on the AMBER Web page at:
http://www.eso.org/sci/facilities/paranal/instruments/amber/inst/

7 ORGANIZATION OF THE VLTI OBSERVATIONS

7.1 General

For P101, VLTI observations can be performed either in service mode or in visitor mode (for PIONIER and AMBER only). For the phase-1 of a period, the unique contact point at ESO for the user is the User Support Department (see Sect. 1.5). 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/observing/p2pp/VisitorMode.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 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. 7.5). Alternatively, the JMMC tool named SearchCal can be used.

7.3 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 or AMBER or GRAVITY).
- The "VisCalc" tool.
- The "CalVin" tool.

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

7.4 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.

7.5 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...

7.6 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 (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.

7.7 Instrument-specific constraints

Observations in SM can be performed with extra constraints (e.g. seeing) which depends on the instrument. Please read the PIONIER, AMBER and GRAVITY user manuals and P2PP pages for details.

7.8 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 STRAP. H and K Band magnitude should be given properly for the use of IRIS or FINITO.

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

	without FINITO	**with FINITO**
On-axis Coudé guiding	$V < 16$	
Off-axis Coudé guiding	$\boxed{V_g < 16\text{; target - guide} < 57.5\text{ arcsec}}$	$\boxed{V_g < 16\text{; target - guide} < 13\text{ arcsec}}$
IRIS guiding	$\boxed{K < 11.5}$	$\boxed{K < 8.5}$
FINITO tracking	N/A	$\boxed{H < 8\text{ ; V in H} > 10\%}$
Pupil alignment	$K < 8.5$	

Notes:

1. V_g= V-magnitude of the guide-star. Using off-axis guiding with AMBER and/or FINITO leads to an attenuation of 1 K-magnitude (or H-magnitude) per 15 arcsec when seeing is 0.8 arcsec. More detailed information can be found on the performance of AMBER+FINITO on the AMBER Web page http://www.eso.org/sci/facilities/paranal/instruments/amber/inst/.

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

	without FINITO	**with FINITO**	**GRAVITY**
On-axis Coudé guiding	$\boxed{-1.7 < V < 13.5}$	$\boxed{-1.7 < V < 11.5\text{; airmass} \leq 1.5}$	
Off-axis Coudé guiding	$\boxed{V_g < 13.5}$ $\boxed{\text{target - guide} < 57.5''}$	$\boxed{V_g < 11.5\text{; target - guide} < 15''\text{; airmass} \leq 1.5}$	
IRIS guiding	$\boxed{K < 8.0}$	$\boxed{K < 5.0}$	N/A
FINITO tracking	N/A	$\boxed{H < 5.5}$ $\boxed{\text{Vis in H} > 15\%}$	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. 12: UTs
- Fig. 13: ATs, small configuration
- Fig. 14: ATs, medium configuration
- Fig. 15: ATs, large configuration

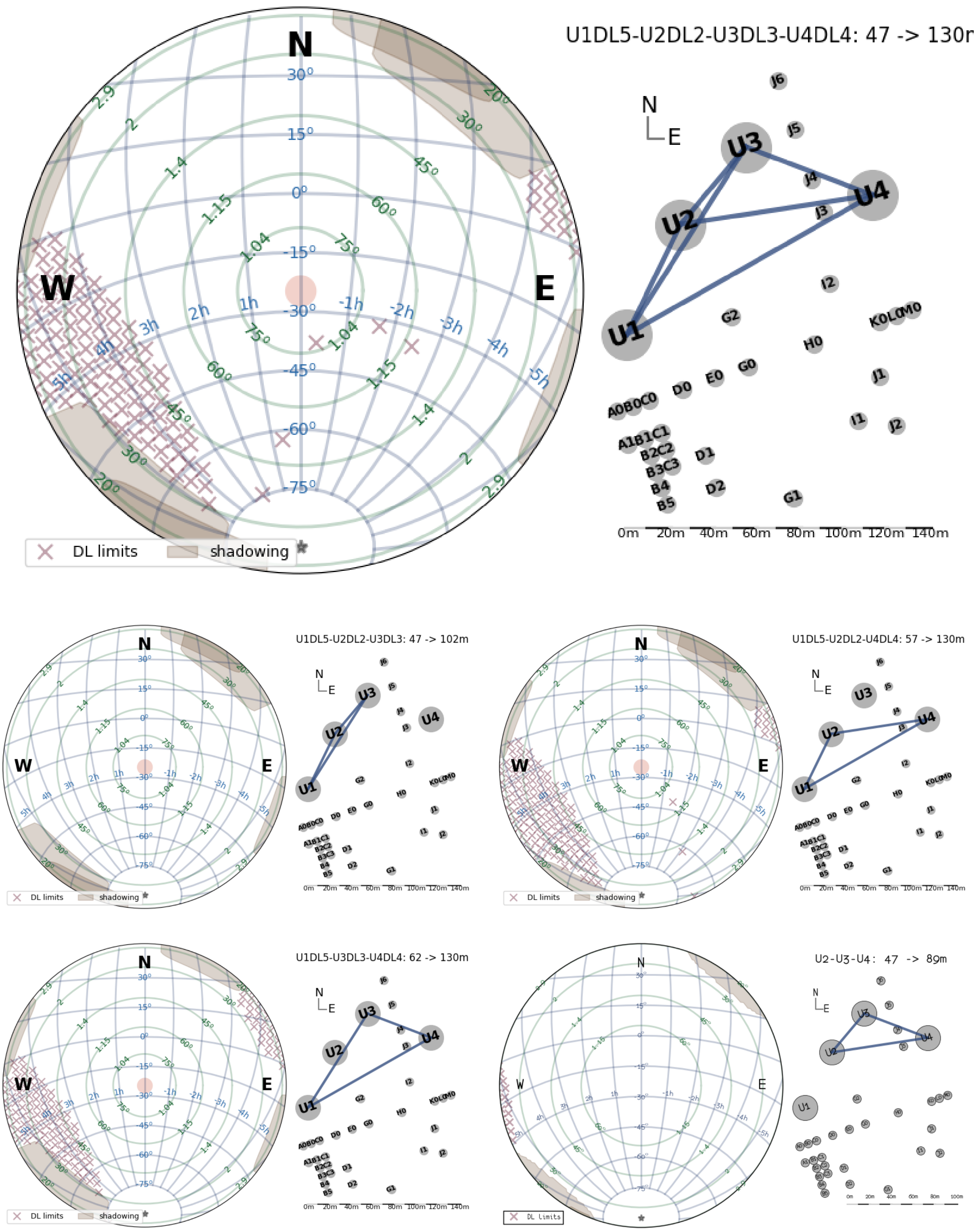

Figure 12: UT sky coverage

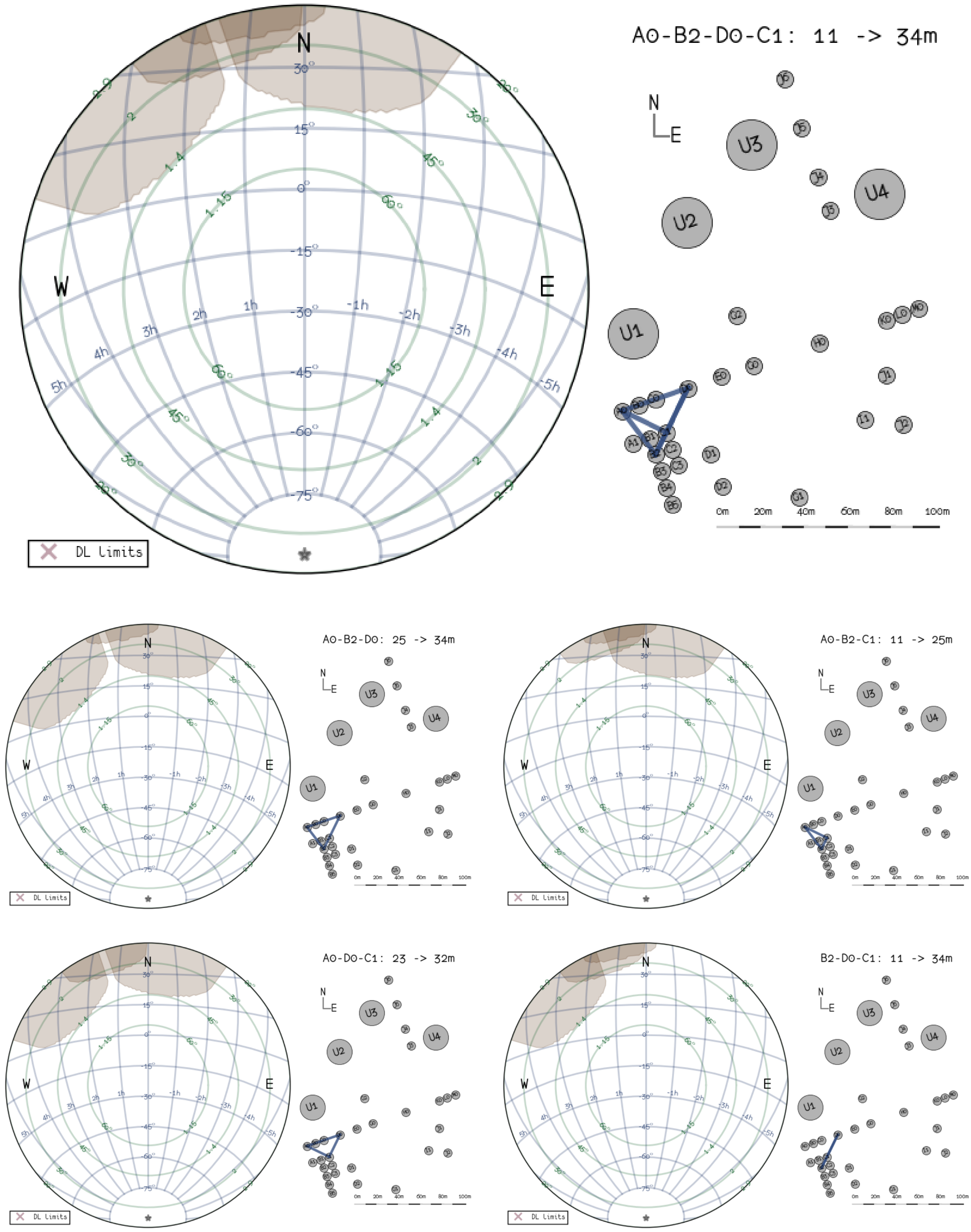

Figure 13: AT sky coverage, small configuration

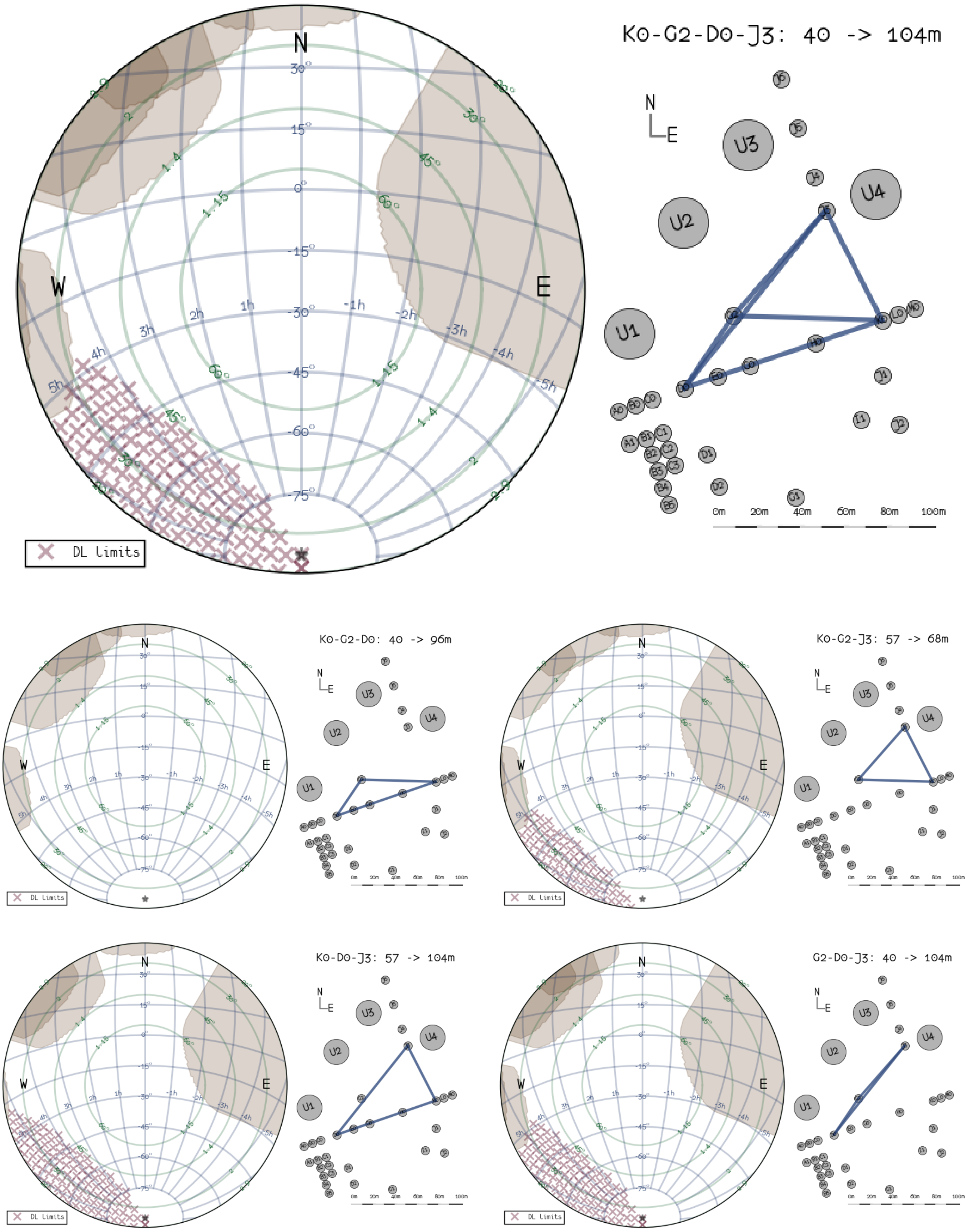

Figure 14: AT sky coverage, medium configuration

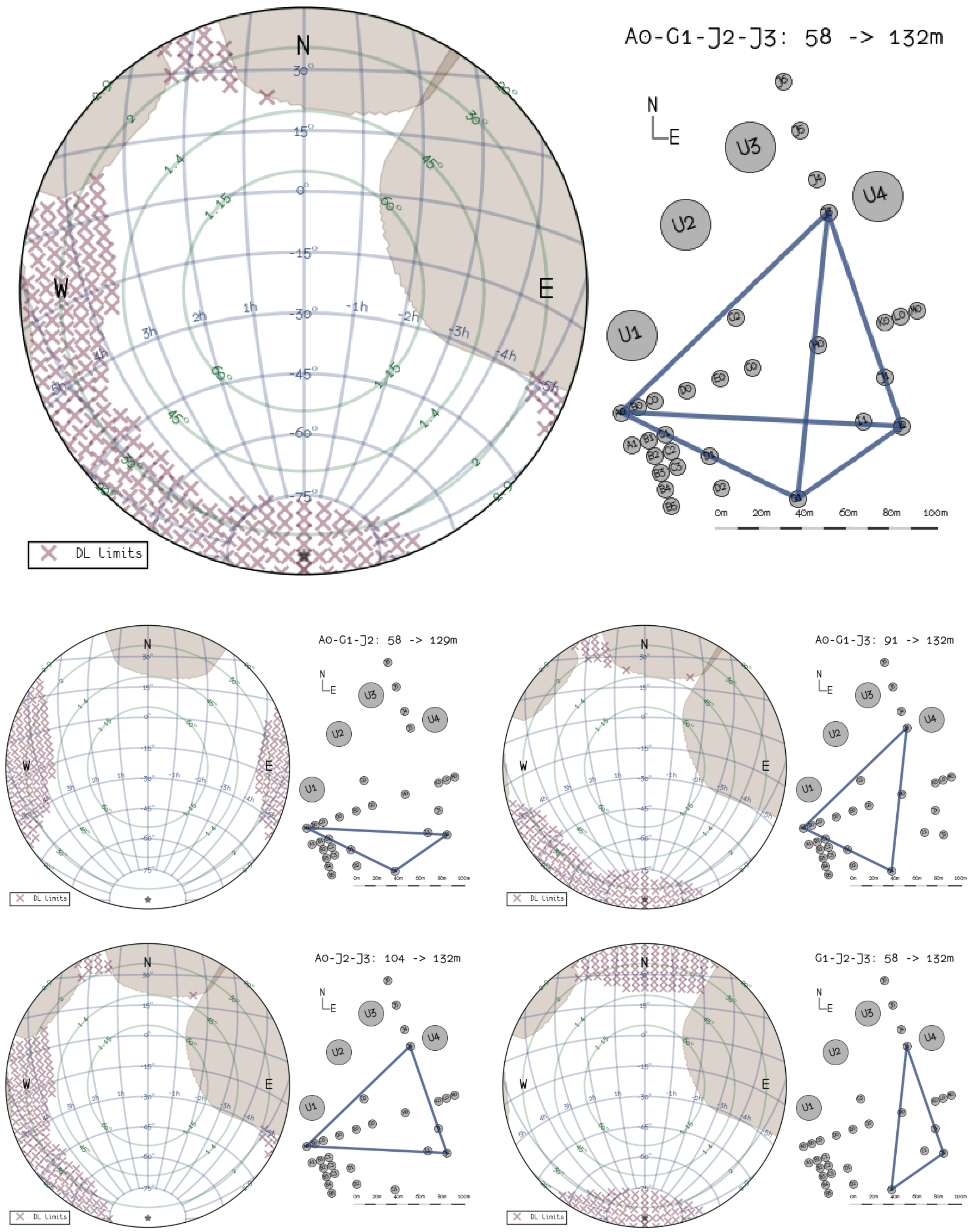

Figure 15: AT sky coverage, large configuration

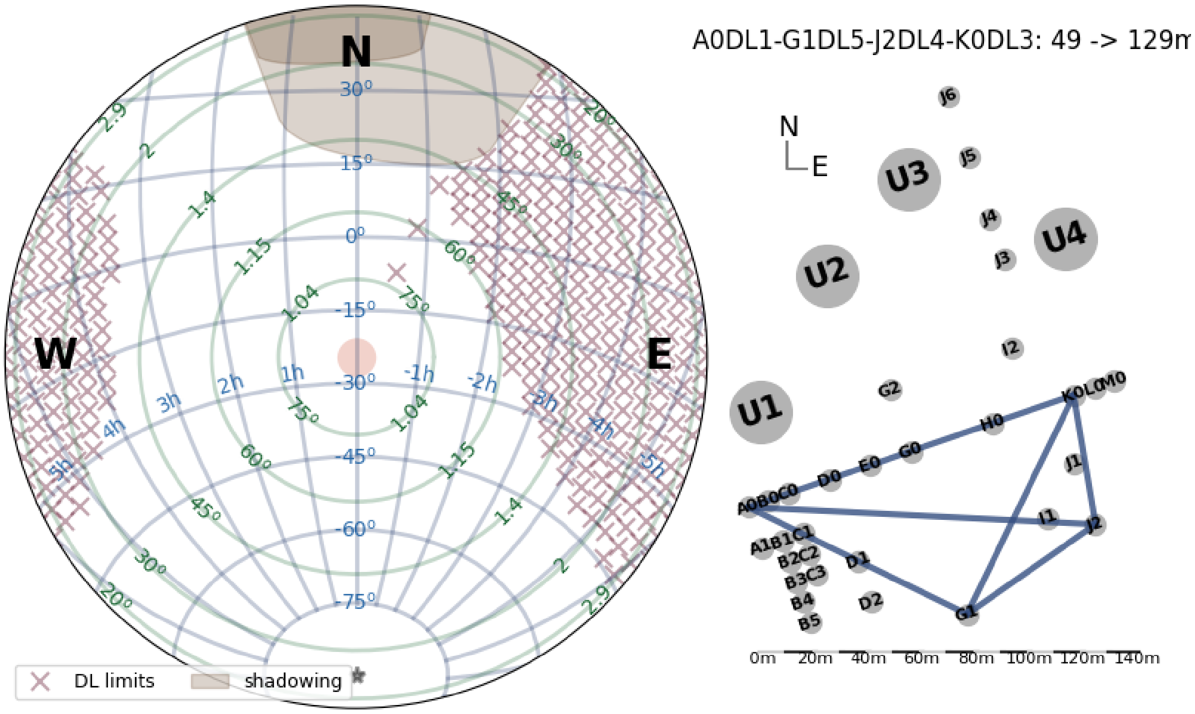

Figure 16: AT sky coverage, astrometric configuration

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