EUROPEAN SOUTHERN OBSERVATORY

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Very Large Telescope

Paranal Science Operations

MATISSE User Manual

Doc. No. VLT-MAN-ESO-289268

Issue 1.0, Date August 10, 2025

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Change Record

Issue/Rev.	Date	Section/Parag. affected	Reason/Initiation/Documents/Remarks
103	2018-08-15	All	First published version
105	2020-01-15	Updated Sect. 2.5.2, 3.1, and 4.	Release for P105-Phase2
106	2020-03-26	Updated Sect.4, added Sect. 2.5.3	Release of P106 and GRA4MAT SV
106	2020-04-20	Updated Sect. 2, 3 and 4	Updates for P106

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Contents

1 Introduction

MATISSE is a four-telescope beam combiner for the Very Large Telescope Interferometer (VLTI) operating in three atmospheric windows simultaneously, in the L, M, and N bands. It is a second generation VLTI instrument that is fully integrated in the VLTI infrastructure. It can both operate as a standalone instrument and use the fringe tracker of GRAVITY to stabilise the optical path differences of MATISSE.

Following the first light of the two-telescope VLTI instrument MIDI in 2002, the idea of developing a mid-infrared interferometric imager began to take shape. Initially conceived as an upgrade to MIDI (APreS-MIDI, Aperture SynthesiS with MIDI), the first laboratory prototype was built and presented at the ESO/EII (European Initiative for Interferometry) VLTI workshop "The Power of Optical/Infrared Interferometry", held in April 2005 in Garching, as reported in the ESO Messenger (No. 120, June 2005). Encouragement and recommendations to develop a dedicated second-generation instrument for the mid-infrared domain were expressed. This led to the formation of the MATISSE (Multi AperTure mid-Infrared SpectroScopic Experiment) Consortium, which initiated the conceptual study of the present instrument.

The Preliminary Design Review of MATISSE was held five years later, in December 2010 at ESO-Garching. The Final Design Reviews followed, taking place in September 2011 for the Cryogenics and Optics subsystems, and in April 2012 for the entire instrument. The Preliminary Acceptance in Europe took place in September 2017 (see Fig. 1), and first light at Paranal was achieved in February 2018.

The use of GRAVITY as an external fringe tracker for MATISSE was proposed by ESO in 2013, supported by the consortium and the ESO counsel in 2014, followed by a phase A review in 2015. After significant upgrades to the VLTI system, the a new adaptive optics system of the ATs, the project's final design review was passed in August 2019. Being mainly a software implementation to the infrastructure, the mode was incrementally tested and offered for regular operations, following closely the upgrades to the instruments and VLTI infrastructure. Such upgrades concerned the update of the GRAVITY fringe tracker (Nowak et al. 2024, A&A, 684, 184), the installation of the GRAVITY+ adaptive optics (GPAO) system, and the deployement of the Laser Guide Stars (LGS) on all four Unit Telescopes (UTs).

Starting from ESO Period 103 in April 2019, MATISSE (Lopez et al. 2022, A&A, 659, 192) was officially offered for regular operations. The GRAVITY for MATISSE (GRA4MAT, Woillez et al. 2024, A&A, 688, 190) mode has been offered to the community since 2020.

1.1 The current state of MATISSE

The instrument can be used either for so called *snapshot*, *imaging*, or *time-series* observations. In these observing modes, interferometric fringes are acquired, giving visibilities, coherent fluxes, spectra, closure phases, and differential quantities. These quantities can then be used to infer the object's wavelength-dependent brightness distribution, to spatially locate spectral line emission or absorption or to reconstruct an image.

A new upgrade on the VLTI will be the LGS, which will be installed and commissioned over P116. Performances on the instrument are therefore not understood fully, and will be verified in the upcoming periods, starting from a science verification in P116. As of P117, MATISSE is offered as:

- Standalone instrument (MATISSE standalone) with:
  - ATs (using NAOMI) with natural guide star (*NGS VIS*) guiding.
  - UTs (using GPAO with either the optical (GPAO_NGS_VIS) wavefront sensor, (*NGS_VIS*) or LGS (*LGS_VIS*).
  - Telescope chopping on both ATs and UTs (i.e. the option for simultaneous photometry, providing chopped *LM* observables and absolute visibilities in *N*).
  - Low (R = 34), medium (R = 506) and high (R = 3300) spectral resolution in the *LM* band.
  - Low (R = 34) and high spectral resolution (R = 218) in the *N* band.
- MATISSE with GRAVITY as external fringe tracker (GRA4MAT) with:
  - ATs (using NAOMI) with natural guide star (*NGS_VIS*) guiding.
  - UTs (using GPAO with either the optical (GPAO_NGS_VIS) wavefront sensor, (*NGS_VIS*) or LGS (*LGS_VIS*).
  - Telescope chopping on both ATs and UTs (i.e. the option for simultaneous photometry, providing chopped *LM* observables and absolute visibilities in *N*).
  - Low (R = 34), medium (R = 506), high (R = 959) and high+ (R = 3300) spectral resolution in the *LM* band.
  - Low (R = 30) and high spectral resolution (R = 218) in the *N* band.
  - The special GRA4MAT mode called the **narrow-field off-axis**. For this mode, telescope chopping is not offered.

The specifics and use of these modes are elaborated on in this manual. Note that GPAO_NGS_IR, formerly known as CIAO, is currently not available for MATISSE. Before starting a MATISSE proposal, users are advised to also consult the VLTI user manual and the MATISSE instrument webpage to familarise themselves with the VLTI and the instrument, and these contain additional information, including adaptive optics performances, the most up-to-date determinations of limiting fluxes, and other instrument performance indicators.

1.2 Scope

The purpose of this document is to introduce the user to the instrument. The instrument modes available in service, visitor, and delegated vistitor mode, as well as the capabilities and limitations of the instrument, are discussed. Additionally, useful information for the user regarding proposal preparation is provided.

1.3 Definitions, Acronyms and Abbreviations

This document uses a number of abbreviations and acronyms to concisely refer to various items after their initial introduction. The purpose of the following list is to assist the reader in recalling the full meaning of each abbreviation.

AT:	Auxiliary Telescope
BCD:	Beam Commuting Device
DIT:	Detector Integration Time
DRS:	Data Reduction Software
ESO:	European Southern Observatory
FOV:	Field Of View
FWHM:	Full Width at Half Maximum
GPAO:	GRAVITY + Adaptive Optics
GRA4MAT :	Fringe Sensor of GRAVITY + a VLTI OPD actuation for MATISSE
IRIS:	Infra-Red Imager Sensor
LGS:	Laser Guide Star
MATISSE:	Multi AperTure mid-Infrared SpectroScopic Experiment
MIDI:	MID-infrared Interferometric instrument
MIR:	Mid-InfraRed
NAOMI:	New Adaptive Optics Module for Interferometry, used for ATs
NGS:	Natural Guide Star
OB:	Observation Block
OPD:	Optical Path Difference
OPL:	Optical Path Length
OS:	Observation Software
P2:	Phase 2 preparation tool
QC:	Quality Control
SM:	Service Mode
SNR:	Signal-to-Noise Ratio
USD:	User Support Department
UT:	Unit Telescope
VCM:	Variable Curvature Mirror
VLT:	Very Large Telescope
VLTI:	Very Large Telescope Interferometer
VM:	Visitor Mode

Table 1: Spectral signatures accessible with MATISSE.

L-band [2.9 - 4.2 μm], M-band [4.5 - 5.0 μm]	
H_2O (ice)	3.14 μm
H_2O (gas)	2.8-4 μm
H recombination lines	Brα: 4.05 μm, Pfβ: 4.65 μm
Acetylene (C_2H_2) and hydrocyanic acid (HCN)	3.17 μm
Polycyclic Aromatic Hydrocarbons (PAH)	3.3 μm, 3.4 μm
Methane (CH_4)	3.32 μm
Nano-diamonds (NDs)	3.52 μm
SiO band heads	4 μm
CO fundamental transition series	4.6-4.78 μm
CO (ice)	4.6-4.7 μm
N band [8.0-13.0 μm]	
Amorphous silicates	9.8 μm
Crystalline silicates (olivines and pyroxenes)	9.7, 10.6, 11.3, 11.6 μm
PAHs	8.6, 11.4, 12.2, 12.8 μm
Fine structure lines (e.g. [NeII])	10.5, 10.9, 12.8 μm

2 Instrument description

2.1 Scientific drivers of the instrument development

The original primary scientific motivators for MATISSE were the study of the inner regions of protoplanetary disks and the conditions of planet formation, as well as the study of dusty tori around active galactic nuclei (B. Lopez et al., ESO Messenger No 157, September 2014). MATISSE was designed to address key scientific questions, such as the complexity of disk structures in planet-forming zones, the mechanisms behind inner disk clearing, and the properties and evolution of dust grains. For those interested in investigating these areas with angular resolution down to 3 milliarcsecond, MATISSE is an essential instrument.

In addition to its primary science goals, MATISSE also contributes to other important fields, including the study of evolved stars, the early evolution of minor bodies in the Solar System, the characterization of exozodiacal disks, and the study of hot Jupiter-like exoplanets.

MATISSE observations provide access to important spectral features related to gas and dust phases, as listed in Table 1.

2.2 Optical principle, detector and signal

MATISSE uses an all-in-one multi-axial beam combination scheme with 4 beams. This type of combination is very suitable for an interferometric instrument with more than two apertures and operating in the mid-infrared. In the multi-axial beam combination scheme of MATISSE (see Fig. 2), the four beams are combined simultaneously onto the detectors on an area called

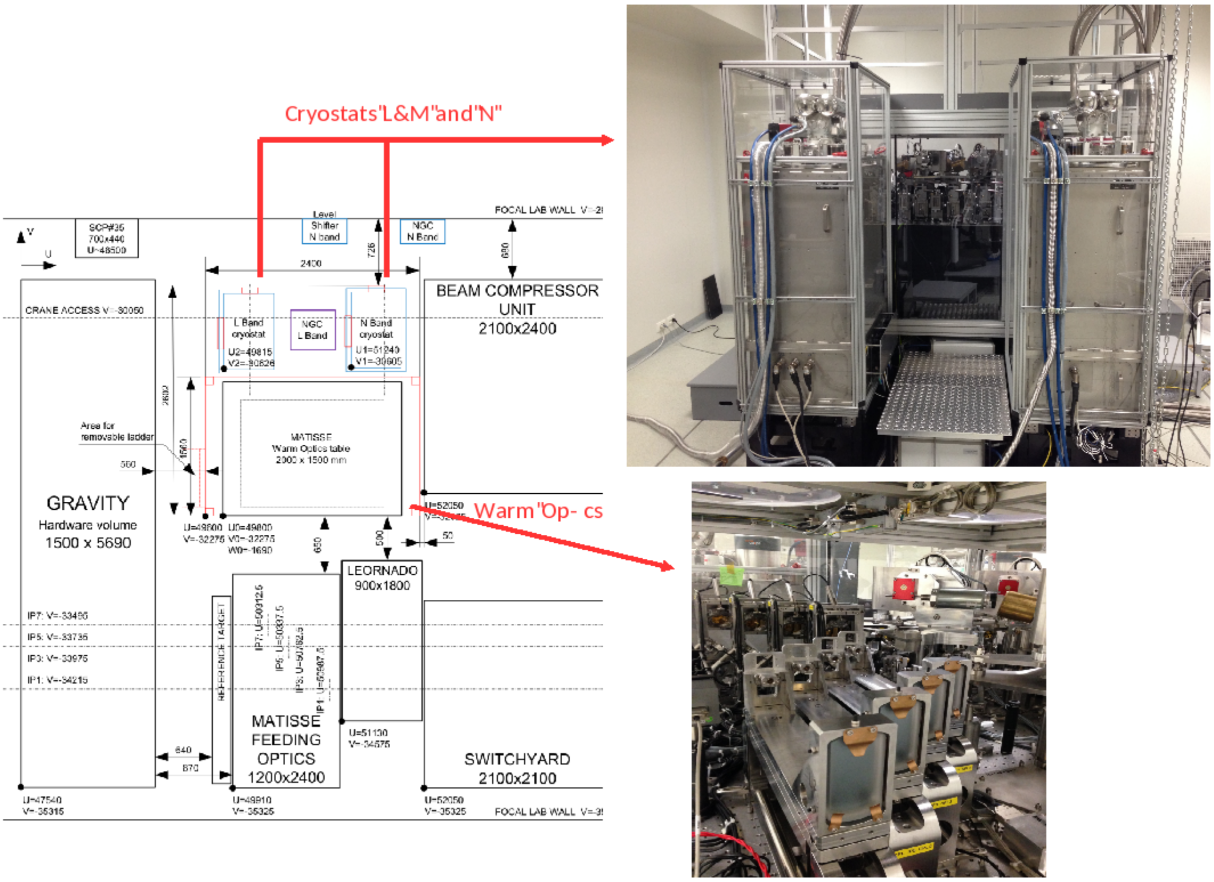

Figure 1: MATISSE during testing in Nice.

the interferometric channel, while the four individual photometric signals are imaged individually on each side (see Fig. 3). The superposition of the 4 individual beams to form the interferometric beam is achieved by the camera optics.

The instrument contains two twin Cold Optics and Cryostats. The spectral separation of the L&M band from the N band is achieved in the Warm Optics. In the Cold Optics, the interferometric pattern and the photometric signals are spectrally dispersed using grisms. The spatial extent of the interferometric pattern is larger than the photometric channels to optimize the sampling of the six different spatial fringe periods. In this plane the beam configuration is non-redundant to produce different spatial fringe periods, and thus to avoid crosstalk between the fringe peaks in the Fourier space. The separation B_{ij} between beams i and j in the output pupil is respectively equal to $3D$, $9D$ and $6D$, where D is the beam diameter.

2.2.1 Beam Commuting Devices

The optical path on the warm bench can be modified by inserting two Beam Commuting Devices (BCDs). Each BCD exchanges two input beams with each other, such that the instrument cold optics is fed by the input beams in order 1-2-3-4 with BCD OUT, but 2-1-4-3 with BCD IN. This enables to remove instrumental effects on the phase and closure phase during the data reduction process. The standard observing sequence uses BCDs combinations alternatingly IN and OUT. As such, one exposure cycle is composed of the four exposures corresponding to the four BCD combinations.

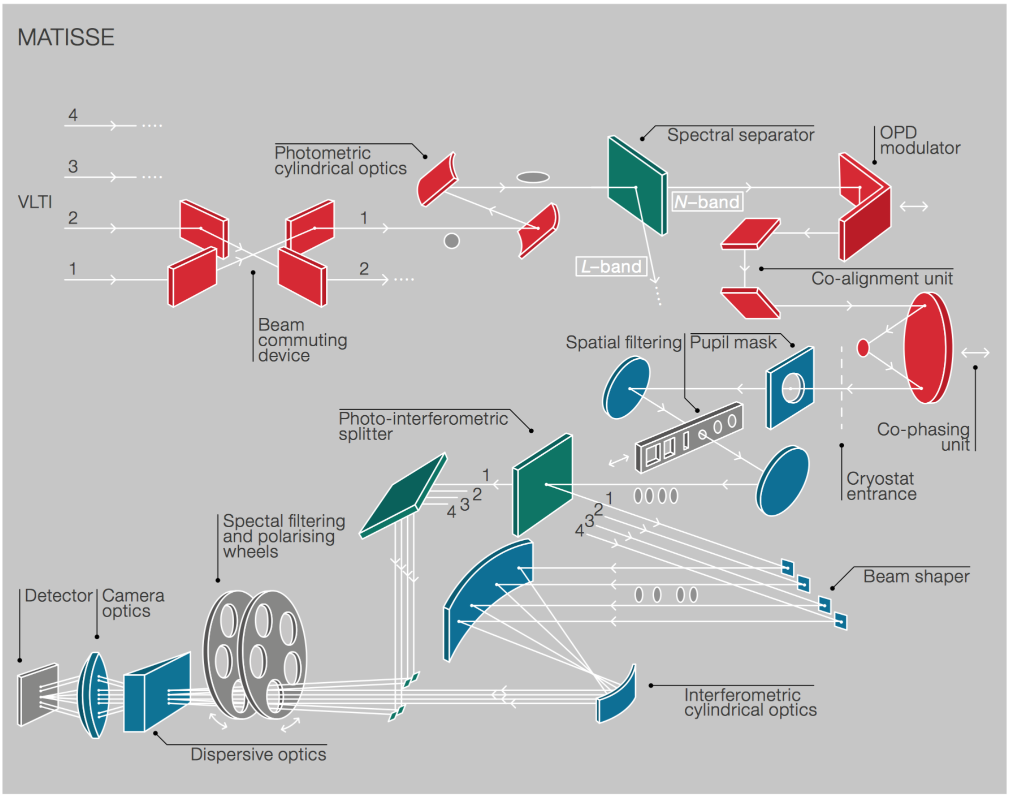

Figure 2: Schematic of the MATISSE optical path. The red components represent optical elements located on the warm optics table at ambient temperature. The blue components represent optical elements of the Cold Optics located in the cryostats. Acknowledgements to J. R. Walsh and A. C. da Fonte Martins for having generated the figure.

2.2.2 Spatial Filters

The instrument is fed through spatial filters primarily to reduce the background on the detector. Spatial filters include both pinholes and slits. These spatial filters also define the photometric field of view (FOV), so that for example the 1.5 λ/D pinhole at λ=4 μm when using the ATs (D = 1.8 m) the diameter of the FOV would be 0.7". For standard observing, including service mode, a fixed combination for *L&M* and *N* band spatial filters is defined, chosen such that a coherent flux accuracy of 1% can be achieved. The standard values are highlighted in Table 2. Other spatial filters might be used for specific goals, but in *visitor mode* only. In the most general terms, the smaller a spatial filter is, the higher the accuracy of the final measurement should be, while in turn the largest spatial filters should give the best sensitivity.

Table 2: Spatial filters in MATISSE. Dimensions are in units of λ/D. The default configuration for SM is highlighted.

Spectral Bands	L&M	N
Pinholes	1.00, **1.50**, 2.00	1.50, **2.00**, 2.50
Slits	N/A	1.0x5, 1.5x5, 2.0x5

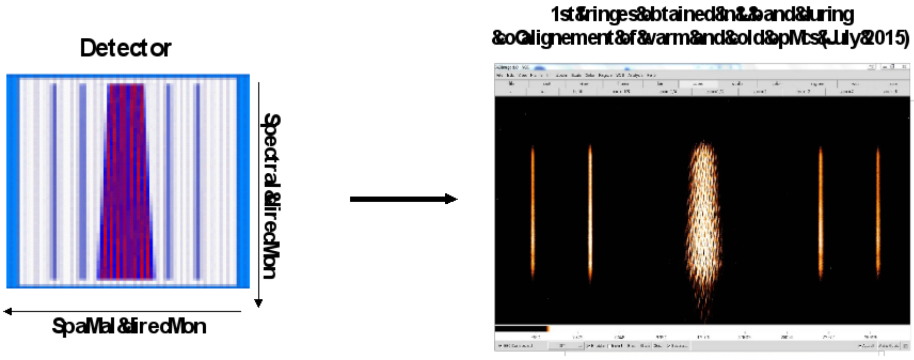

Figure 3: Left, layout of the interferometric pattern (central detector blocks, dispersion direction is vertical) and the four photometric signals on one of the two MATISSE detector, in SI-PHOT mode. Right: first fringes obtained in laboratory in July 2015.

2.2.3 Dispersive Elements

MATISSE has four dispersive elements providing four spectral resolutions for the L&M bands. For the N band, two dispersive elements are available. The High+ grism can be used in two orders in the $L\&M$ bands with the GRA4MAT mode and provides a resolution of a few thousand (Table 3). The respective filter curves are available in Sect. A.

2.2.4 Detectors

The instrument contains two detectors – an 2048 x 2048 pixels HAWAII-2RG detector for the L&M band, and an 1024 x 1024 pixels AQUARIUS detector for the N band. The limitations of the two detectors are mostly set by the background radiation in N, and partly M-band, the linearity and cosmetic behaviour (hence the Hybrid mode as standard observing mode), the typical atmospheric coherence time in the given band, as well as by the need to synchronize both shutter systems with the telescope chopping frequency and the modulation of the optical path difference (OPD).

The L-band detector has two frame modes: the slow and the fast. The standard readout mode is the slow, which has a slow pixel readout clock (100 kHz) at low read out noise $< 15e^{-}$). The fast readout mode has a readout noise of $\sim 75e^{-}$. In practice, it is only used for very bright targets ($F_L > 300$ Jy) with the ATs to avoid LM detector saturation even in low spectral resolution.
The standard slow readout mode implies a detector readout time of about 1.3 s, which is

Table 3: Dispersive elements in MATISSE. Resolving power is given in $\lambda/\Delta\lambda$.

	LM-bands	N-band
Low	34	30
Medium	506	–
High	959	218
High+	3666	–

longer than the typical atmospheric coherence time by a factor ~ 10 in L. For this reason, for MATISSE standalone, windowing of the detector is needed to reduce the readout time, which is at the expense of spectral coverage and resolution. As such, the full LM band with slow detector reading, can be read only with the low spectral resolution setting. For higher spectral resolutions, the size of the spectral window depends on the user defined central wavelength, λ_0, to about $\Delta\lambda = \lambda_0 \pm 0.08\,\mu$m and $\Delta\lambda = \lambda_0 \pm 0.16\,\mu$m in high and medium resolution, respectively. A list of the allowed values for the central wavelenghts depend on the chosen spectral resolution and can be found on the instrument webpage.

Another way to overcome the readout speed of the LM band detector is the stabilisation of the fringes in GRA4MAT mode. This allows the integration time to be set at or above the detector readout time without coherence loss, allowing to cover the full LM band range with higher spectral resolutions.

Users are advised to consult the table with the corresponding wavelength coverage and DIT values in the proposal preparation and set in phase 2 from the Template Manual.

2.3 General description of the observing sequence

The standard MATISSE observing mode is called HYBRID since different principles for obtaining the target photometry are used in L&M- and N band, respectively.

In the L&M bands the variability of the slit losses due to the atmosphere requires that the interferometric information and the photometric data are recorded simultaneously. This is achieved by inserting a beam splitter, transferring 1/3 of the flux of each beam to a photometric channel for that beam, and 2/3 of the flux to the combined interferometric channel (see Fig. 3). This observing mode is called SI-PHOT (SImulatenaous PHOTometry). In the N band the slit-losses are much more stable, while in turn the detector properties make it unfavourable to reduce interferometric data with photometry obtained on a different detector area. Therefore no beam splitter is used and the observation is split into two parts. First the interferometric data are recorded without chopping. This is followed by four individual photometry exposures, in which beam shutters 1 to 4 are opened, respectively. This observing mode is called HI-SENS (HIgh SENSitivity).

2.4 Dealing with background radiation

Since the so-called thermal background level in the mid-infrared usually exceeds the astrophysical source coherent flux and is variable, it is important to limit the crosstalk between the low frequency peak and the high frequency fringe peaks to a level below the thermal background photon noise limit. Two methods are used in MATISSE to ensure this result and estimate the coherent flux with high accuracy: spatial optical path differences (OPD) modulation, as it is done in the former VLTI instrument AMBER, and temporal OPD modulation, as in MIDI or GRAVITY. The rejection of the background level from the coherent flux is thus based on two methods in the multi-axial scheme used by MATISSE:

a) the Fourier filtering: the background low frequency signal is concentrated in the central low frequency peak while the fringe signals are contained in 6 fringe peaks at the spatial frequencies nD/λ, with $n = 1 \ldots 6$.

b) the OPD modulation of the input beams providing a specific temporal signature of each of the 6 pairs of beams and fringe peaks and thus allowing, thanks to a demodulation process, to reject the contribution of the background continuum (and of any possible cross-talk).

To measure the visibility in the N band, one needs to extract the source photometry by separating the stellar flux from the sky background using sky chopping. Chopping is the alternate observation of the sky and target fluxes. By switching between sky and target, the target's photometric information can be measured by subtracting the contribution of the thermal background. As such, the thermal background fluctuations occurring at frequencies higher than the chopping frequency will be the most important contribution to the photometric error (and to the resulting visibility error). Fortunately, chopping is unnecessary to measure the coherent flux only, as well as the differential and closure phases.

2.5 MATISSE characteristics and observable quantities

2.5.1 Characteristics and observable quantities

For each of the six baselines used, the observable quantities, in each spectral channel, are the following:

Spectra: $S_i(\lambda)$, defined as the spectro-photometric measurements of MATISSE recorded for the i^{th} beam.

Coherent flux: $C_{ij}(\lambda)$, defined as the flux of the source interfering 'coherently', from the i^{th} and j^{th} beams.

Visibility: $V_{ij}(\lambda)$, derived from the coherent flux measurements normalized by the spectro-photometric measurements:

$$V_{ij}(\lambda) = \frac{C_{ij}(\lambda)}{\sqrt{S_i(\lambda)S_j(\lambda)}}$$

Differential visibility: $V_{ij}(\lambda)/ < V_{ij} >_\lambda$, where $< V_{ij} >_\lambda$ is the average visibility over the spectral bandwidth (excluding the considered wavelength λ). The differential visibility represents the change of visibility versus the wavelength.

Differential phase: $\phi_{ij}(\lambda) - < \phi_{ij} >_\lambda$, represents the change of phase with wavelength.

Closure phase: $\psi_{ijk}(\lambda)$, the sum of the phases of the 3 baselines ij, jk, ik forming a triangle. This sum is independent from any instrumental and atmospheric phase offset. With 4 beams, 4 measurements of the closure phase are available.

2.6 MATISSE observing modes

MATISSE observations may be carried out either using the internal coherencing ("MATISSE standalone") or by using the GRAVITY fringe tracker to stabilize the fringes (GRA4MAT) and reach lower flux limits, or to record observations of targets off-axis such as in the case of exoplanets observations.

2.6.1 MATISSE standalone

The classical MATISSE observing mode is MATISSE standalone. In this context, MATISSE is choherencing its own fringes, meaning that its internal delay lines follow the drift of the fringe pattern introduced by the atmosphere, both in LM and N bands. It uses the infrared-imager sensor (IRIS), the infrared tip-tilt sensor of VLTI, for focal laboratory guiding, providing image stabilisation.

2.6.2 MATISSE with the GRAVITY fringe tracker (GRA4MAT)

MATISSE observations can also be carried out with fringes stabilised by the GRAVITY fringe tracker. The use of GRAVITY external fringe tracker stabilises the instrument transfer function in variable atmospheric conditions, improves the SNR in the lower spectral resolution modes (or alternatively extends the limiting magnitudes to slightly fainter targets), and makes LM full-band observations possible.

GRA4MAT uses the single-field off-axis mode of GRAVITY, setting the fringe tracker fibre on the object and the science fibre on the empty sky. In GRA4MAT, the GRAVITY fringe tracker operates currently only in the high flux regime (fringe tracker modes 1 and 2, see the GRAVITY template manual). This means that the fringe tracker is running at a DIT of 0.85 ms.

When observing with GRA4MAT, the G band magnitude for the adaptive optics system and the K band magnitude for the fringe tracker must be within the advertised limits for the given atmospheric conditions. The use of the GRA4MAT mode is recommended as soon as fringe tracking is possible on a MATISSE science target.

With GRA4MAT fringe jumps occur more frequently then with MATISSE standalone or GRAVITY standalone. Such fringe jumps are dispersion-induced and cause a loss of signal and hence a reduction of the SNR. Fringe jumps can be limited by observing in low precipitable water vapour (PWV) atmospheric conditions. The current recommendation is to use GRA4MAT only with PWV<5 mm. The PWV observing constraint should already be set in p1.

2.6.3 Narrow-field off-axis mode

From P112 onwards GRA4MAT is offered with the capability to track fringes with GRAVITY, while MATISSE points to a nearby offset position to record fringes (**GRA4MAT narrow-field off-axis**). This is useful to observe, e.g., planets or brown dwarf companions to stars that can be tracked by GRAVITY, when the relative position is well known. In principle, the same performance limits as for on-axis observations apply. However, for small offsets the contrast between the central star and the off-axis target might prove problematic and users should take the different size of the point-spread functions of UTs vs. ATs into account when proposing observations. The maximum distance from the central target is 1 arcsecond for UTs and 3 arcseconds for ATs. Offsets can be defined in the normal GRA4MAT observing template. A cumulative sequence of offsets can be given in a single template. The narrow field off-axis mode is offered in service mode. The chopping sequence is currently not supported for narrow-field observations. For data reduction of the narrow field off-axis the users should contact the VLTI Expertise Centers.

2.7 MATISSE sensitivity

The up-to-date target flux in limits in L, M, and N, K magnitude and corresponding turbulence categories for the MATISSE modes can be found on the MATISSE instrument webpage. They are defined in such a way that the typical errors for:

- Low resolution MATISSE standalone and GRA4MAT in all spectral resolutions give better than 5° in the closure phases, 4° in the differential phases, and better than 10% on absolute visibilities.

- Medium resolution MATISSE standalone observation give better than 10° for closure phase data and better than 20% on absolute visibilities

- Attempting to obtain absolute calibrated quantities with high resolution with MATISSE standalone is not recommended unless the targets are very bright.

However, bad observing conditions do not only diminish the flux. If a science case is critically dependent on achieving the smallest possible error bars, it is strongly recommended to request good observing conditions regardless of the target brightness. Observations at seeing values worse than 1.15" (corresponding to Turbulence >70% and τ_0 greater than 2.2 ms) are not recommended for any MATISSE mode.

For the performance of the VLTI systems see the VLTI manual linked the instrument webpage.

2.8 Imaging observations

Image reconstruction consists in computing an approximation of the object brightness distribution out of the Fourier components measured by the interferometer. In order to get a meaningful image it is important to measure the maximum number of spatial frequencies in the (u, v) plane. There are two important rule-of-thumb guidelines governing the quality of the resulting image. Firstly, the number of points in the (u, v) plane approximately translates to the "number of pixels" the reconstructed image can distinguish. Secondly, the degree of over resolution (factor between spatial resolution λ/B and the actual target size) translates to the "number of resolution elements" covered by the reconstructed image (in the given direction).

3 Proposal preparations

Proposal submission for any VLT instrument is done in the web-based proposal submission system p1. This section considers preparation guidelines for VLTI/MATISSE.

3.1 Proposal guidelines

3.1.1 Guaranteed time observations

Any science target should be checked against the list of GTO observations. These lists contain targets that have already been reserved for the period.

3.1.2 Calibration sequences and total requested time

A typical MATISSE observation consists of two or three OBs executed back-to-back, grouped by the user in a concatenation. One of the OBs is the science object of interest, the other OB(s) are interferometric calibrators, bracketing the science target. In this way, the typical observing sequences are SCI-CAL or CAL-SCI-CAL. For narrow-field off-axis observations, only a SCI is required.

When preparing MATISSE proposals, one should decide on the observing sequence needed as this determines largely the required observing time. This is because execution times per observing block (OB) are fixed based the requested spectral resolution and whether the photometry step should to be done. Observing times per OB go as follows:

- LM band low or medium resolution → 20 min plus an additional 10 min photometry if required
- LM band high or high+ resolution → 25 min plus an additional 10 min photometry if required

As such, typical concatenations range between 60-105 minutes. These execution times hold for both MATISSE standalone and MATISSE GRA4MAT.

One can opt for a SCI–CAL sequence when the scientific interest is limited to one band or when a so-called hybrid calibrator, a calibrator that is suitable for both bands, is available. More details on the meaning of a hybrid calibrator are described in Cruzalèbes et al. 2019, MNRAS, 490, 3158. When choosing calibrators the user is encouraged to consider the following recommendations:

- Good calibrators should follow the Rayleigh-Jeans approximation, i.e., avoid IR excess. L/N-band flux ratio (at 3.3 and 8.5 microns) should best be within a range of 7 to 9.
- A SIMBAD search on the calibrator should ideally show "star" as object type.
- It is recommended that the calibrator for the LM band has a similar flux in L and a similar airmass to that of the science object, ideally within an angular distance of up to 25°.
- An N band calibrator can be farther away from the science object. Recommended angular distances are up to 30°.
- A calibrator should ideally be small enough to be unresolved at the requested baseline configuration. Another advantage of small calibrators are that those have smaller absolute uncerainties on their sizes, giving better sensitivities.
- Calibrators should be observable directly before/after the science target.
- It is recommended to compute median fluxes in L and N bands using for example the VizieR Photometry viewer provided by CDS-SIMBAD intead of relying on a single source.

Calibrators can be found via the mid-infrared calibrator catalogue provided by the consortium (see Cruzalèbes et al. 2019, MNRAS, 490, 3158) or the Searchcal tool provided by JMMC. When a hybrid calibrator cannot be found and scientific interest is in both LM and N arms,

users should expect to need a CAL_L–SCI–CAL_N (or vice versa) sequence, which is one OB longer.
It is good practice to check whether a hybrid calibrator is available during proposal preparation, even though calibrators are not necessary to specify in p1.

The SCI-CAL, CAL-SCI-CAL and SCI for the GRA4MAT narrow-field off-axis are the standard sequences available in SM. Other observing sequences are not available in SM. The user should not count on README requests of concatenations CAL_L–SCI, CAL_N–SCI to be observed back-to-back.

When using the narrow-field off-axis mode, no CAL is needed and interferometric calibration can be done from the alternating observations of the star and the planet or brown dwarf from the applied sequencial off-sets. As such, only a SCI OB is required. The total requested time depends on the lenght of the off-set lists as an offset is applied after each BCD observing sequence. It is recommended to set OB lenghts of up to 1h to ensure scheduling based on current atmospheric conditions. The chopping sequence is not available for narrow-field off-axis.

Successful proposals can prepare their full OBs is during phase 2 with the phase 2 tool or the API. For the OB preparation, users are advised to consult the Template Manual.

3.2 On chopping with MATISSE

A standard MATISSE observation is obtained in HYBRID mode, employing SI-PHOT in L&M bands and HIGH-SENS in N band. The observing block starts by recording LM photometry, LM interferometry, and N band interferometry simultaneously. If N photometry is requested, the telescopes then start chopping and the observations continue recording: chopped interferometry and photometry in the LM-bands, chopped photometry in the N band. As a consequence users interested in N band calibrated visibility, and not simply coherent flux, must include in their observation the N band photometry step. For MATISSE standalone, it was shown during commissioning concerning the variability of the background in the L and M bands that chopped interferograms must be used to obtain visibilities for targets fainter than $L = 25$ Jy on the ATs, fainter than $L = 1.5$ Jy on the UTs, and in the M band[1]. As a consequence, it is strongly advised to include the N band photometry step when possible. For GRA4MAT, it depends on the K band magnitude of the target, as advertised on the instrument webpage.

The N band photometry can be skipped only in three cases:
(i) scientific interest is limited to the N band, and the target is too faint to acquire N band photometry (i.e. only N band coherent flux is required);
(ii) scientific interest is limited to the L band and both the source and the calibrator are brighter than 25 Jy on the ATs (i.e. only non-chopped files are required);
(iii) only coherent flux measurements in N are needed.

The acquisition of N band photometry for the purpose of visibility calibration is **highly recommended**. When only N band correlated fluxes are obtained, data can be calibrated by if

[1]The up-to-date limiting magnitudes are published on the MATISSE public webpages.

the calibrator(s) have a well known N band spectrophotometric flux(es), or by obtaining own flux calibrated spectrophotometry (e.g. an additional MATISSE standalone OB). External flux calibrated spectrophotometry of the target, that needs to be quasi-simultaneously for variable targets, enables to recover the visibilities.

A Filter curves available for MATISSE

The filter curves available for the MATISSE L, M, and N band are shown in Fig. 4. The table with the values of the filters can be downloaded as a zip file in the MATISSE official webpages under the section Tools.

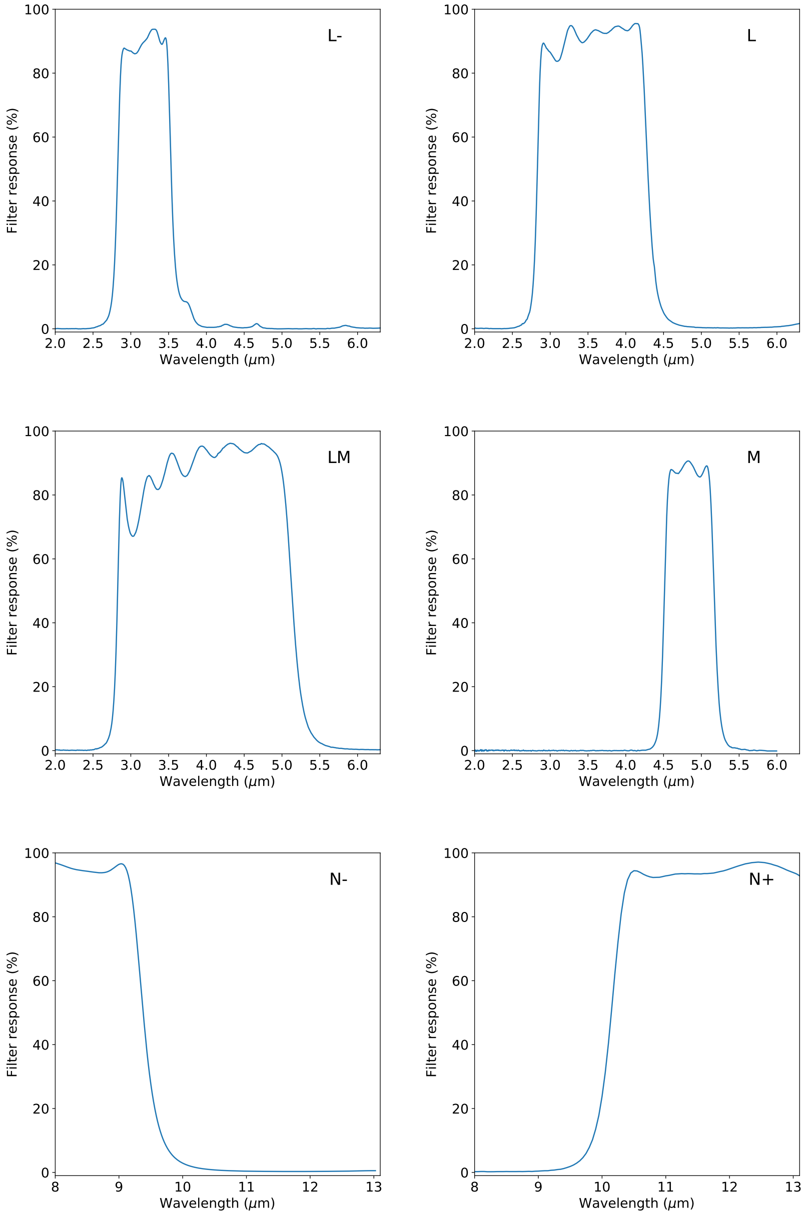

Figure 4: Filter curves for MATISSE in different spectral settings.