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Very Large Telescope
Paranal Science Operations
MATISSE User Manual

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Contents

1 Introduction

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.

Starting from ESO Period 103 in April 2019, MATISSE (Lopez et al. 2022, A&A 659, 192) was officially offered for regular operations.

1.1 Scope

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

The instrument webpages are considered an integral part of this manual and contain additional information, including the **most up-to-date determinations of limiting fluxes and other instrument performance indicators**.

In addition to the instrument webpages, this manual should also be used in conjunction with the VLTI User Manual.

1.2 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
GRA4MAT :	Fringe Sensor of GRAVITY + a VLTI OPD actuation for MATISSE
IRIS:	Infra-Red Image Sensor
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
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 - 4.1 μm], M-band [4.6 - 4.9 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 primary scientific motivation for MATISSE is the study of the inner regions of protoplanetary disks and the conditions of planet formation, as well as the study of dusty tori around AGN (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 Figure 2), the four beams are combined simultaneously onto the detectors on an area called the interferometric channel, while the four individual photometric signals are imaged individually on each side (see Figure 3). The superposition of the 4 individual beams to form

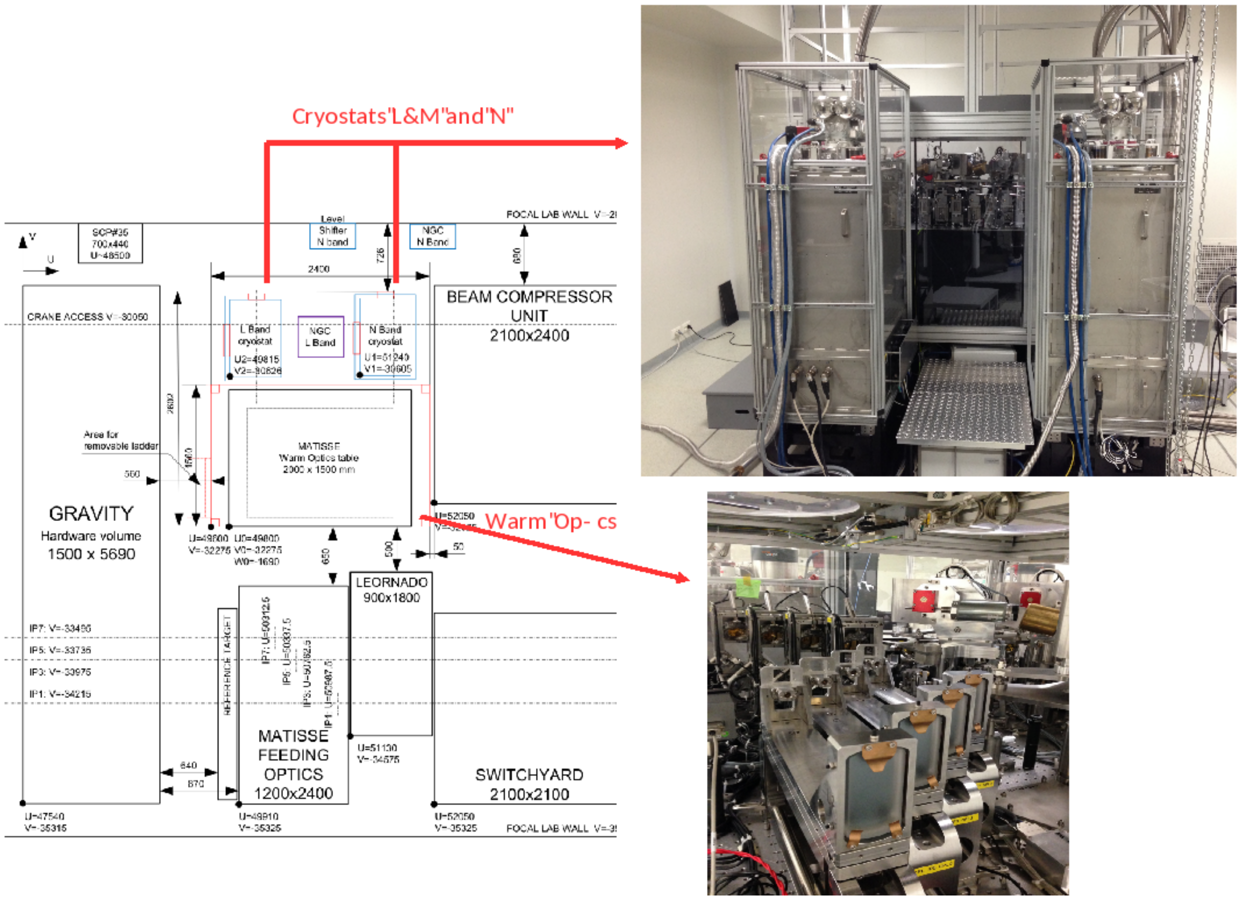

Figure 1: MATISSE during testing in Nice.

the interferometric beam is achieved by the camera optics.

MATISSE observes in three bands simultaneously: L, M and N bands. The instrument contains two detectors – Hawaii2rg for the L&M band, Aquarius for the N band – and 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 observing sequence with BCDs alternatingly in and out is always used.

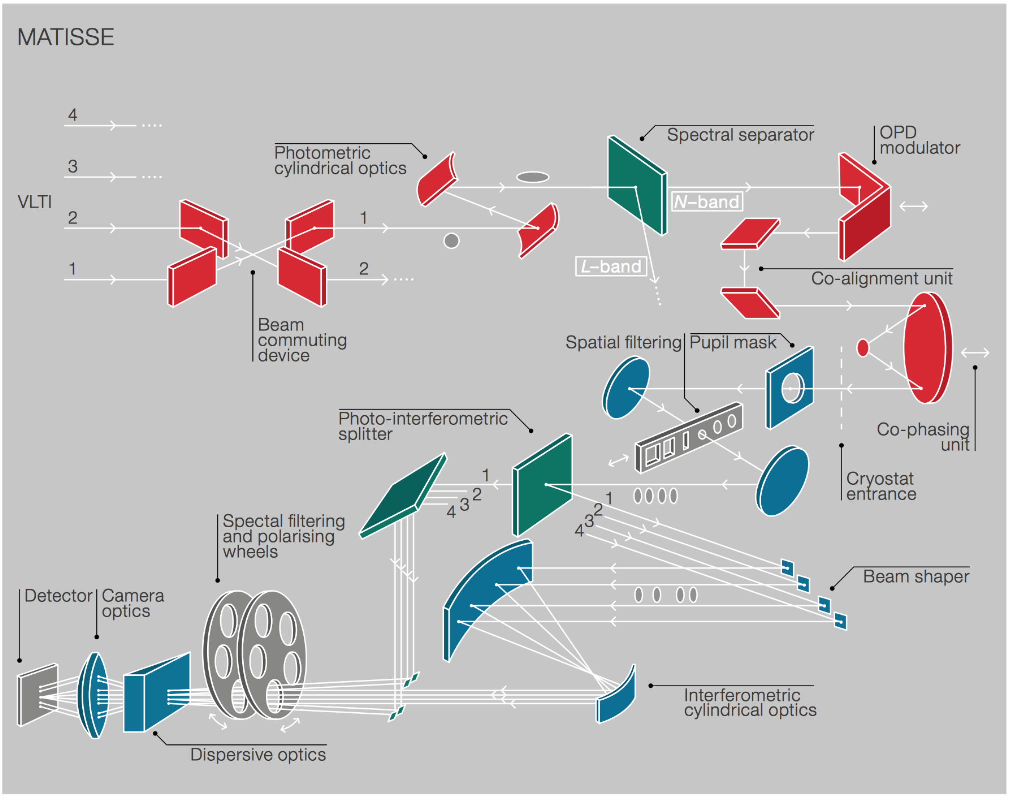

Figure 2: Schematic of the MATISSE optical path. The red components represent optical elements located on the warm optics table at ambient temperature. The blue components represent optical elements of the Cold Optics located in the cryostats. Acknowledgements to J. R. Walsh and A. C. da Fonte Martins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

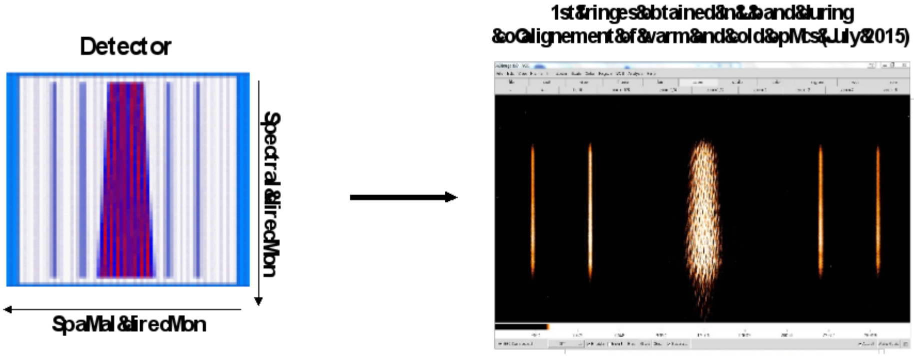

Figure 3: Left, layout of the interferometric pattern (central detector blocks, dispersion direction is vertical) and the four photometric signals on one of the two MATISSE detector, in SiPhot mode. Right: first fringes obtained in laboratory in July 2015.

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 (see Sect. 2.6.1**) and will provide a resolution of a few thousand (Table 3).

2.3 Detectors

The limitations of the two detectors, Hawaii2rg for the L&M band, Aquarius for the N band, are mostly set by the background radiation in N, and partly M-band, the linearity and cosmetic behavior (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 OPD.

MATISSE in standalone mode and with the SLOW detector reading, allows observing only part of LM bands. In L-band the chosen DIT limits the size of the window to about $\Delta\lambda = 0.04\,\mu$m and to $0.08\,\mu$m in high and medium resolution, respectively. In low resolution the DIT enables to observe one full band, i.e., either L or M. A Table with the DIT values which should be used in the proposal preparation as well as in phase 2 is given in the Template Manual. MATISSE in GRA4MAT mode (see Sect. 2.6.1) enables longer DITs **that allows to** observe the full LM bands.

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	–

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, we need 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. This section deals with general description of the sequence of observations of MATISSE. The GRA4MAT mode is detailed in the sub-section below.

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 SiPhot.

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 HiSens.

A standard MATISSE observation is obtained in Hybrid mode, employing SiPhot in L&M bands and HighSens 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. Moreover, commissioning results on the variability of the background in the L and M bands have shown 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, starting from period 105, it is strongly advised to include the N-band photometry step when possible. 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 (1.5 Jy on the UTs); (iii) only coherent flux measurements are needed.

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

2.6.1 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**.

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.**

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.

2.6.2 MATISSE limits and performances

For instrumental performance, operational limits and execution time estimates see the instrument webpage. **The filter curves are available in Sect. A.**

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

3 Observing with MATISSE

3.1 Creating Observing Blocks and Concatenations

All observing at ESO telescopes is defined through OBs. OBs can be created (in ESO's phase 2 tool).

The individual OBs follow an identical scheme, except a keyword identifying the target type as either SCI or CAL. Each OB consists of two templates; the acquisition and the observation template.

For SM a typical MATISSE observation will consist of three OBs executed back-to-back that the user has grouped in a concatenation. The first and last OB are interferometric calibrators, bracketing the science target. This sequence is commonly referred to as CAL-SCI-CAL. Whether a SM observation was successful will then be determined by evaluating the results of the full concatenation.

The CAL–SCI–CAL mode is the standard observing sequence. **It is rare to find calibrators**

that are acceptable in both the LM- and N-bands, so programs that wish to exploit both bands should expect to need CAL_L–SCI–CAL_N (or vice versa) sequences. The sequence CAL–SCI should be considered in the following cases: (i) users interested in calibrating only one of the bands (i.e. LM or N), (ii) a *hybrid calibrator*[2] is available for the science. The sequence CAL_L–SCI–CAL_N–SCI is not offered in Service mode. The user should not count on README requests of concatenations CAL_L–SCI, CAL_N–SCI to be observed back-to-back. For calibrator selection and calibration strategy see the MATISSE instrument website.

3.2 N-band photometry

The acquisition of N-band photometry for the purpose of visibility calibration is **highly recommended**. It can be skipped in case of a target with a N-band magnitude below the sensitivity limits, or when the user requires only coherent N-band fluxes, not absolute visibilites. The proper calibration and hence scientific use of coherent fluxes requires some expertise and should only be done by experienced users. In summary, coherent fluxes can either be calibrated by using calibrators with very well known N-band spectrophotometric fluxes, or by obtaining own flux calibrated spectrophotometry of the calibrator. External flux calibrated spectrophotometry of the target, that needs to be quasi-simultaneously for variable targets, enables to recover the visibilities.

For an observation without N-band photometry, the duration of each individual OB is **reduced** by 10 minutes. For details and numbers see the instrument webpage.

3.3 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).

4 MATISSE in P116

MATISSE is offered based on commissioning results. Please find below the list of modes offered:

Hybrid is the only observing mode offered.

L-band observations are offered with low (R = 34), medium (R = 506), and high (R=959). Additionally, very high spectral resolution (R = 3300) is available with GRA4MAT.

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[2] Hybrid calibrators are defined as those suitable for both LM and N-band (see also Cruzalebes et al. 2019, MNRAS 490, 3158).

M-band observations are offered with low (R = 34) and medium (R = 506) resolution. The latter mode is not available for monitoring programs. M-band measurements need the photometry step. **Additionally, very high spectral resolution (R = 3300) is available with GRA4MAT.**

N-band observations are offered with low resolution (R = 30) and high resolution (R = 218).

GRA4MAT is available on both the ATs and UTs. If coherent flux, differential phase, and closure phase are not sufficient for fainter targets and the chopping sequence cannot be carried out, the observations may be paired with MATISSE standalone chopped observations.

Execution time is fixed per setup, see the instrument website.

Limiting magnitudes and observing conditions see the instrument webpage.

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.

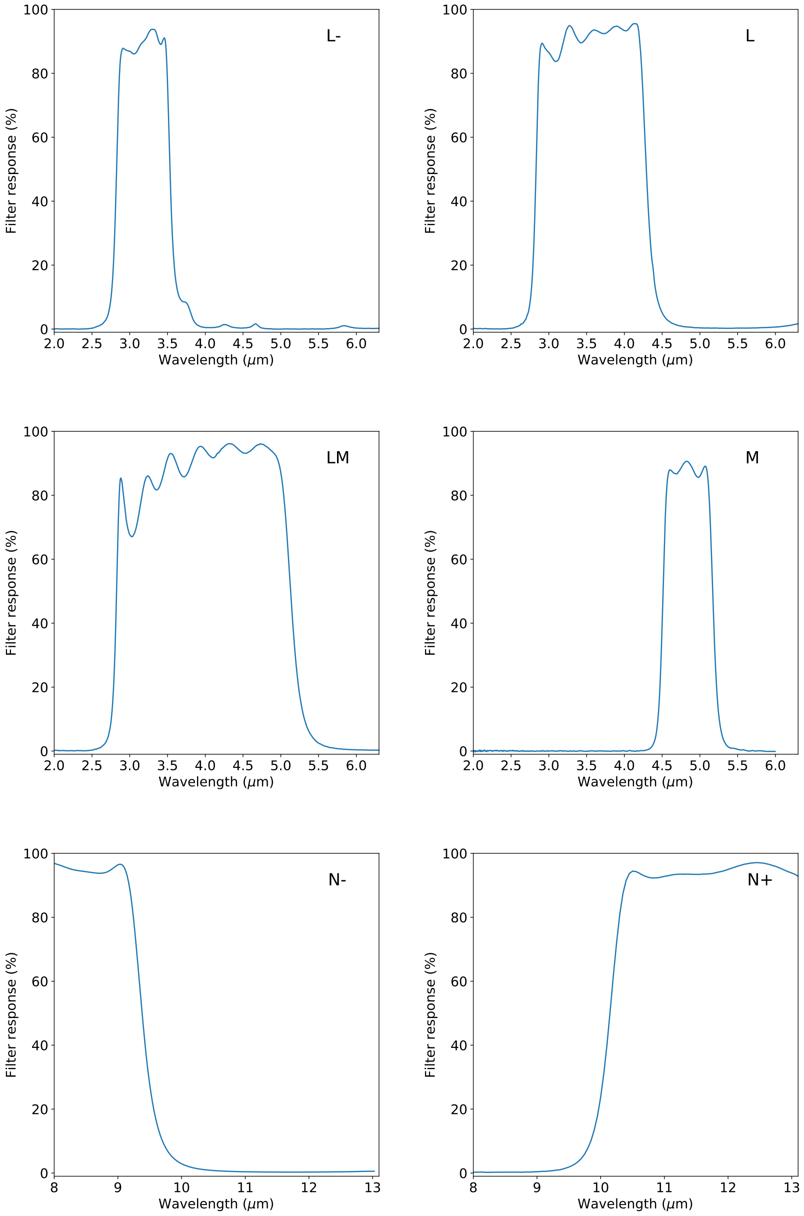

Figure 4: Filter curves for MATISSE in different spectral settings.