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Very Large Telescope

Paranal Science Operations

MATISSE User Manual

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1 Introduction

After the first light on the two-telescope VLTI instrument MIDI in 2002, the idea emerged to create a mid-infrared interferometric imager. Originally imagined as a MIDI upgrade (APreS-MIDI, Aperture SynthesiS with MIDI), a first laboratory prototype was built and presented at the ESO/EII (European Initiative for Interferometry) VLTI workshop held on April 2005 in Garching: The power of optical/infrared interferometry: recent results and second generation VLTI instrumentation. Encouragements and recommendations to build a dedicated second generation instrument for the mid-infrared domain were expressed. The MATISSE (Multi AperTure mid-Infrared SpectroScopic Experiment) Consortium formed and initiated the conceptual study of the present instrument. The Preliminary Design Review of MATISSE was held five years after, in December 2010 at ESO-Garching. Then the Final Design Reviews occurred in September 2011 for the Cryogenics and the Optics subsystems, and, in April 2012 for the whole instrument. The Preliminary Acceptance in Europe took place in September 2017 (see Fig. 1), and first light at Paranal in February 2018. In ESO period 103, starting April 2019, MATISSE is first offered for regular operation.

1.1 Scope

The scope of this document is to introduce the user to the instrument. The instrument modes offered in service mode and visitor mode as well as the capabilities and limitations of the instrument are discussed. Information useful for the user for proposal preparation such as execution time of standard observations are given. The instrument webpages, `http://www.eso.org/sci/facilities/paranal/instruments/matisse.html`, are considered a part of this manual and contain more information and in particular the most actual determinations of limiting fluxes and other instrument perfomance indicators.

In addition to the webpages, this manual should also be used in conjunction with the VLTI user manual available from the manual web pages `http://www.eso.org/sci/facilities/paranal/instruments/matisse/manuals.html`.

1.2 Definitions, Acronyms and Abbreviations

This document uses a number of abbreviations and acronyms to refer concisely to an item after it is introduced. The aim of Table 1 is to help the reader in recalling the extended meaning of each short expression.

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
MACAO:	Multi-Application Curvature sensing Adaptive Optics
MATISSE:	Multi AperTure mid-Infrared SpectroScopic Experiment
MIDI:	MID-infrared Interferometric instrument
MIR:	Mid-InfraRed
NAOMI:	Adaptive Optics for ATs ll
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 in the mid-infrared accessible to MATISSE.

L&M band, $\sim$ 2.8–5.0 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
Polycyclic Aromatic Hydrocarbons	3.3 μm, 3.4 μm
Nano-diamonds	3.52 μm
CO fundamental transition series	4.6-4.78 μm
CO (ice)	4.6-4.7 μm
N band, $\sim$ 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 of the instrument is the study of the inner regions of protoplanetary disks and the conditions of planet formation, as well as the study of the dusty tori around AGN (MATISSE ESO Messenger article, B. Lopez et al. Issue of Sept. 2014). The challenging questions, concerning the complexity of disk structures in the planet forming zone of circumstellar disks at various stages of their evolution, the reasons of inner disk clearing in transitional disks, the properties, the growth, and sedimentation of dust grains, the tracers for giant protoplanets, the nature of outbursting young stellar objects, the dust production as an outcome of planetesimal collisions and exocomets evaporation, as well as the launching region of winds and jets and the disk outflow connection, have led the instrument requirements. The instrument observing modes, capabilities and performance will also serve other fields: the birth, structure, dynamics and chemistry of evolved stars; the early evolution of Solar System minor bodies; the exozodiacal disks around main-sequence stars; the properties of hot Jupiter-like exoplanets; and the study of the immediate vicinity of our Galactic Center. Important spectral features for the gas and dust phase will be accessible to MATISSE observations 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 superimposition of the 4 individual beams to form the interferometric beam is achieved by the camera optics.

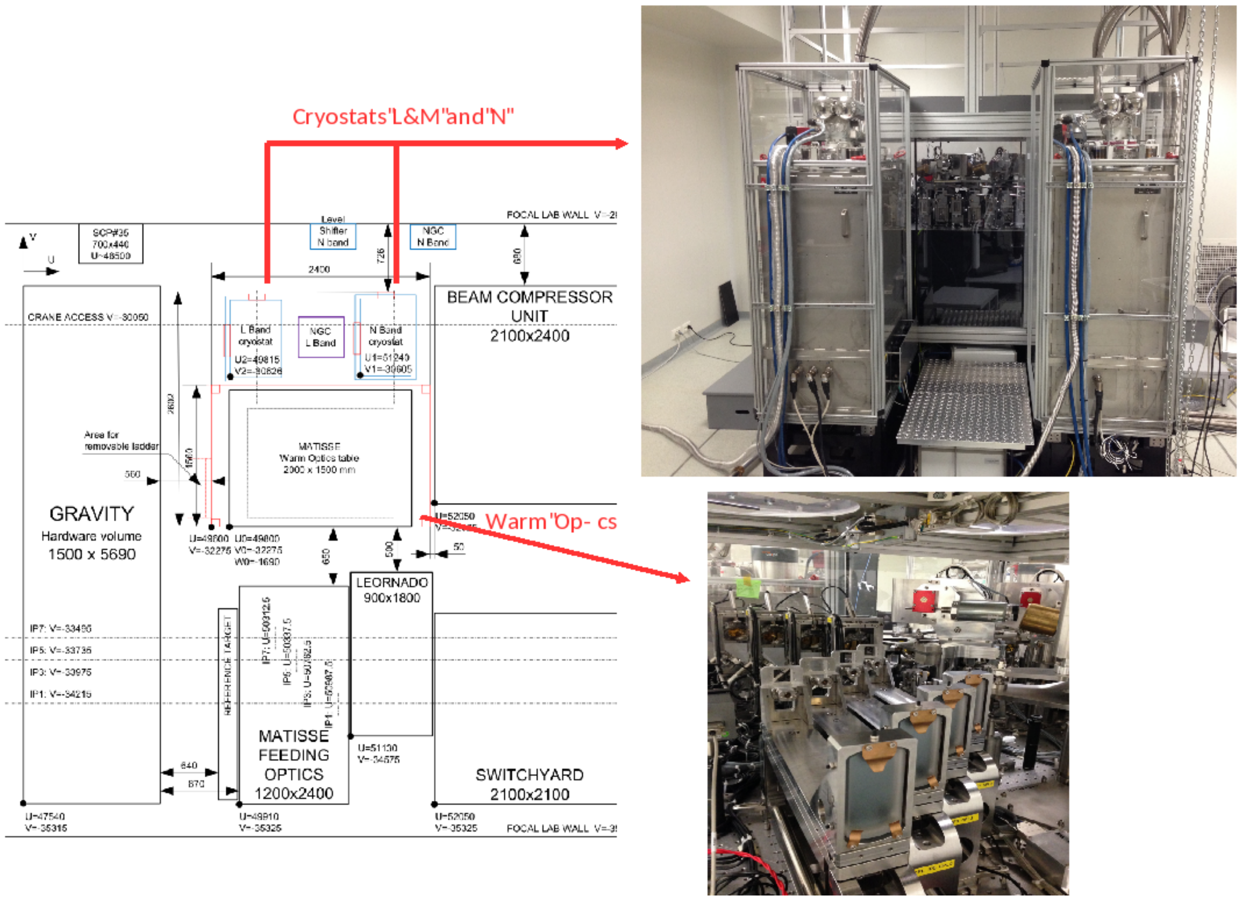

Figure 1: MATISSE during testing in Nice.

MATISSE will observe in three bands simultaneously: L, M and N. 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 with 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. Each BCD exchanges two input beams with each other, such that the instrument cold optics if fed by the inout 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.

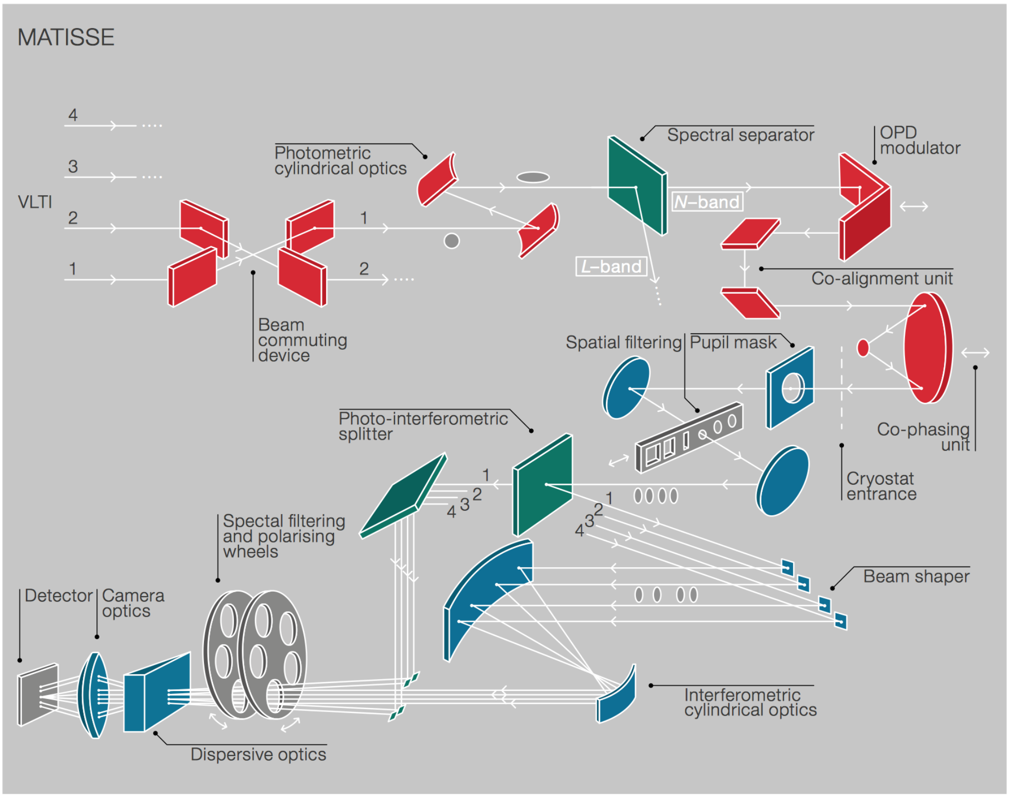

Figure 2: Schematics of the MATISSE optical path. The red components represent optical elements located on the warm optics table at ambient temperature. The blue components represent optical elements of the Cold Optics located in the cryostats. Acknowledgements to J. R. Walsh and A. C. da Fonte Martins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

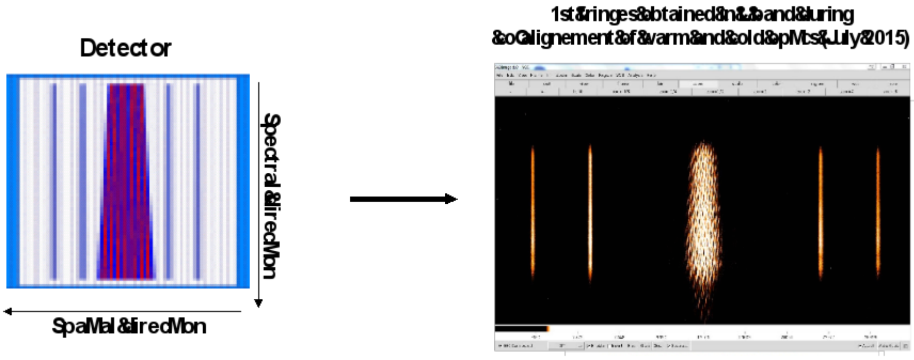

Figure 3: Left, layout of the interferometric pattern (central detector blocks, dispersion direction is vertical) and the four photometric signals on one of the two MATISSE detector, in SiPhot mode. Right: first fringes obtained in laboratory in July 2015.

2.2.3 Dispersive Elements

MATISSE has four dispersive elements for the L&M bads, and two for the N band. For the L&M band, four dispersive elements providing five resolutions are available, for the N-band two dispersive elements are available.

The Very High or High+ grism can be used in two orders in the L&M bands and will provide a resolution of a few thousand. Precise values for the grism are currently being characterized.

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 behaviour (hence the Hybrid mode as standard observing mode), the typical atmospheric

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

Spectral Bands	L&M	N
Resolving power	Low: 34	Low: 30
	Medium: 506	
	High: 959 (L only)	High: 218
	High+: $\sim$ 5200 at 4.05 μm	
	High+: $\sim$ 3900 at 4.7 μm	

Table 4: Detector integration times

Spectral Bands	L&M	N
Resolving power	Low: 75 ms	Low: 20 ms
	Medium: 111 ms	
	High: 111 ms	High: 75 ms

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.

In L-band the chosen DIT limits the size of the window in high resolution to about $\Delta\lambda = 0.1\,\mu$m and to $0.2\,\mu$m in medium resolution, respectively. In low resolution the DIT enables to observe one complete band, i.e., either L or M.

2.4 Dealing with the background radiation

Since the so-called thermal background level in the mid-infrared can exceed 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 difference (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 multiaxial 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 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. However, the observation of the sky and the target are never simultaneous during chopping. Therefore, 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, observable quantities, and modes

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 wavelenth 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.

Table 5: Characteristics and observable quantities.

Spectral Bands	L&M	N
Number of beams	4	
Modes	HiSens, SiPhot, Hybrid	
Spectral coverage	2.8–5.0 μm	8.0–13.0 μm

2.5.2 MATISSE observing modes

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 require 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). Obtaining data in the L&M bands does not require chopping. 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 interferoemtric 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 xposures, in which beam shutters 1 to 4 are opened, respectively. This observing mode is called HiSens.

A standard MATSSE observation is obtained in Hybrid mode, employing SciPhot in L&M bands and HighSens in N-band. In case the target is faint in N-band, so hat no useful data is expected in any case, or only (relative) coherent flux measurements are needed, the photometry exposures in N-band can be skipped to save time.

2.5.3 MATISSE limits and performances

For instrumental perfomance, operational limits and execution time estimates see http://www.eso.org/sci/facilities/paranal/instruments/matisse/inst.html

For the performance of the VLTI systems see the VLTI manual linked from http://www.eso.org/sci/facilities/paranal/instruments/matisse/doc.html

3 Observing with MATISSE

3.1 Creating Observing Blocks and Concatenations

All observing at ESO telescopes is defined through OBs. ESO has published a phase 2 tool with which OBs can be created (https://www.eso.org/sci/observing/phase2/p2intro.html).

The individual OBs follow an identical scheme, except a keyword identfying 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 SCI-CAL-SCI mode is the standard observing sequence. Experienced users of mid-IR interferometry might consider to use a CAL-SCI sequence only, but it should be noted that a proper calibration is much less straightforward with such a sequence and requires expertise.

For calibrator selection and calibration strategy see http://www.eso.org/sci/facilities/paranal/instruments/matisse/inst.html.

3.2 N-band photometry

The acquisition of N-band photometry for the purpose of visibility calibration is optional. In can be skipped in case of a target with an N-band magnitude below the sensitivity limits, or when the user intends to use only coherent N-band fluxes, not absolute visbilites. 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 visbilities.

For an observation without N-band photometry, the duration of each individual OB is shorter by 10 minutes. For details and numbers see http://www.eso.org/sci/facilities/paranal/instruments/matisse/inst.html

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 P103

MATISSE is offered in period 103 based on early commissioning results. Hence only a subset of functions and modes will be available to the user, and the inital limiting magnitudes and conditions will very likely be revised for later periods and be made availble through the instrument webpages.

Hybrid is the only observing mode offered.

L-band observations are offered with low, medium, and high, but not very high resolution in P103.

M-band observations are not offered in P103.

N-band observations are offered with low resolution only in P103.

Execution time is fixed per setup, see http://www.eso.org/sci/facilities/paranal/instruments/matisse/inst.html

Limiting magnitudes and observing conditions see http://www.eso.org/sci/facilities/paranal/instruments/matisse/inst.html