EUROPEAN SOUTHERN OBSERVATORY

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

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

Very Large Telescope

Paranal Science Operations

MATISSE Template Manual

Doc. No. ESO-255467

Issue 110, Date 06/07/2022

Th. Rivinius, C. Paladini, J. Woillez, A. Meilland
Prepared . . . .
Date Signature

S. Mieske
Approved . . . .
Date Signature

A. Kaufer
Released . . . .
Date Signature

This page was intentionally left blank

Change Record

Issue/Rev.	Date	Section/Parag. affected	Reason/Initiation/Documents/Remarks
P103	11.12.2018	all	First version for operation
P105	16.01.2020	Sect.1.4, 2.3, 2.5, 3.1.2, 3.1.3, 3.1.4, 3.2, 3.2.2, 3.3, 3.5	Update for P105 P2.
P106	26.03.2020	Addition of GRA4MAT capability	
P110	06.07.2022	Unify GRA4MAT templates	

This page was intentionally left blank

Contents

1 Introduction

1.1 Scope

This document describes the templates for MATISSE, the second generation VLTI mid-infrared instrument. As for all the VLT instruments, observations with MATISSE are carried out with observation blocks (OBs). The OBs must be defined by the user during Phase-2 preparation with p2 through either the web interface or the Application Programming Interface API. An OB consists of a constraint set and several templates that describe the target acquisition and the observation sequence. For some templates, the user has to indicate the values of keywords (parameters).

This Template Manual requires the user to have some basic understanding of the MATISSE instrument. If you are a first time user, we recommend reading the MATISSE User Manual and web pages that can be accessed from:

`http://www.eso.org/sci/facilities/paranal/instruments/matisse.html`

The OBs are prepared with the web application p2. The web interface is available at: `http://www.eso.org/p2`

Visiting observers at Paranal are also asked to prepare their observations with this web-based application. OBs created or changed through p2 will be directly recorded in ESO's database and immediately become available at the telescope on Paranal.

Finally, the VLTI manual provides all the information which is not instrument specfic (e.g. AT configuration, limiting magnitudes for the Auxiliary Telescopes etc.) that one needs to prepare VLTI observations: VLTI User Manual.

1.2 MATISSE brief description

MATISSE is a four-beam interferometric combiner that can operate in the L, M, and N bands simultaneously (i.e. from 3 to 13μm). It can work with either the four UTs or the four ATs. It is composed of three main parts: the warm optics table (WOP), the L&M-bands cryostat and the N band cryostat. After a dichroic located on the WOP, MATISSE can be seen as two separate instruments working simultaneously (and synchronised). The L&M and the N arms differ in a few points. The most important are:

Spectral resolutions:

- In the L&M bands: LOW (R=34), MED (R=506), HIGH (R=959) and HIGH+ (R$\sim$3666).
- In the N band: LOW (R=30) and HIGH (R=218).

Detectors:

- The L&M bands cryostat is equipped with a 2048 $\times$ 2048 pixels HAWAII-2RG detector (identical to the GRAVITY science detector).
- The N band cryostat is equiped with a 1024 $\times$ 1024 pixels AQUARIUS detector (identical to the VISIR detector).

After being spatially filtered by pinholes or slits (in service mode only one pinhole is offered), the light of the four beams is combined in the focal plane and spectrally dispersed. This produces the typical X-lambda fringe pattern, similar to AMBER. However, in order to efficiently remove background contamination and reduce cross-talk between the fringe peaks, an optical path difference (OPD) modulation is applied on the four beams during observation.

Before the combination, beam splitters can take a part of the flux and redirect it into photometric channels. As these devices are movable, each arm can operate in two different modes:

- SI-PHOT (SImulatenaous PHOTometry): with the beam splitters, the photometric calibration of the fringes is then done during fringe observation.
- HI-SENS (HIgh SENSitivity): In that mode, the beam splitters are removed and all photons are sent to the interferometric channel. Subsequent photometry exposures, closing the shutters one by one, are needed to evaluate the beams absolute photometry.

Currently MATISSE is only offered in a so-called HYBRID mode, where the L&M arm operates in SI-PHOT and the N band in HI-SENS.

1.3 Contact information

In case of questions or suggestions related to Phase-2 preparation, please contact the ESO User Support Department (usd-help@eso.org).

1.4 Period of validity of this manual

This manual is valid for observations with MATISSE during P106 and for the GRA4MAT science verification. In P106, MATISSE standalone is offered in LOW, MED, and HIGH spectral resolution L&M-band and in LOW and HIGH resolution N-band. Moreover, for the very first time, MATISSE is offered only on the ATs and without chopping with GRAVITY as a fringe tracker (GRA4MAT) in all L&M spectral resolutions with the addition of HIGH+.

1.5 ESO observation glossary

- **Constraint Set (CS)**
  List of requirements for the conditions of the observation that is given inside an OB. OBs are only executed if conditions meet or exceed these requirements.
- **Observation Block (OB)**
  An Observation Block is the smallest schedulable entity for the VLT. It consists of a sequence of Templates. Usually, one Observation Block includes one target acquisition template and one or several observation templates.
- **Observation Description (OD)**
  A sequence of templates used to specify the observing sequences within one or more OBs.

- **Observation Toolkit (OT)**
  Tool used to create queues of OBs for later scheduling and possible execution (service mode).

- **Proposal Preparation and Submission (Phase 1)**
  The Phase 1 begins right after the CfP (Call-for-Proposals) and ends at the deadline for CfP. During this period the potential users are invited to prepare and submit scientific proposals. For more information, see:
  http://www.eso.org/sci/observing/phase1.html

- **Observation Preparation (Phase 2)**
  Once proposals have been approved by the ESO Observation Program Committee (OPC) and scheduled, users are notified and the Phase 2 begins. In this phase, users are requested to prepare their accepted proposals in the form of OBs using the p2 web application. See:
  https://www.eso.org/sci/observing/phase2.html.

- **Service Mode (SM)**
  In service mode (in contrast to "Visitor-Mode"), the observations are carried out by the ESO Paranal Science-Operation staff (PSO) alone. Observations can be done at any time during the period, depending on the CS given by the user. OBs are put into a queue schedule in OT which later sends OBs to the instrument.

- **Template**
  A template is a sequence of operations to be executed by the instrument. The observation software of an instrument dispatches commands written in templates not only to instrument modules that control its motors and the detector, but also to the telescopes and VLTI sub-systems.

- **Template signature file (TSF)**
  File which contains template input parameters.

- **Visitor Mode (VM)**
  The classic observation mode. The user is on-site to supervise his/her program execution, to directly analyse the data and to take real-time decisions if necessary.

2 Observation Blocks composition

With the introduction of GRA4MAT, the number of templates available to assemble OBs has increased. They are summarized and organized in Table 1. They come in two flavours that cannot be mixed: standalone and with fringe tracker. As such, a standalone MATISSE OB will always contain one **MATISSE_img_acq** template followed by one **MATISSE_hyb_obs** template. Similarly, a GRA4MAT OB will contain one **MATISSE_img_acq_ft** template followed by one **MATISSE_hyb_obs_ft** template. In the current offering, chopping with UTs is not supported when operating MATISSE with the GRAVITY fringe tracker, and hence only the correlated flux can be measured for the N-band. If, with UTs, absolute visbilities are needed, it is necessary to obtain the flux thrpugh a non GRA4MAT OB, e.g., by concetanating it with the GRA4MAT OB, or using photometry from another source.

MATISSE use	Acquisition template	Observation template
Standalone	**MATISSE_img_acq**	**MATISSE_hyb_obs**
GRA4MAT	**MATISSE_img_acq_ft**	**MATISSE_hyb_obs_ft**

Table 1: Overview of the templates available to prepare MATISSE OBs, organized by MATISSE use (standalone or with GRA4MAT) and template phase (acquisition or observation).

3 Acquisition templates

The first template in an OB must be an acquisition template which contains the information to point the telescope at a source and set up the VLTI and instrument for observation. MATISSE only has two acquisition templates named **MATISSE_img_acq** for MATISSE standalone and **MATISSE_img_acq_ft** for GRA4MAT.

3.1 Template sequence

The sequence of the acquisition template is always the following:

- Telescopes are slewed to the target.
- Delay lines are preset to offer enough delay range for the interferometric observation.
- The adaptive optics loops are closed on the target.

What follows after the AO loop closure depends on whether MATISSE is operated by itself or with the GRAVITY fringe tracker.

3.1.1 MATISSE standalone acquisition

When the VLTI is ready, and the lab guiding loop is closed on IRIS, MATISSE can perform additional verifications which are optional:

- The target can be acquired by MATISSE to check the MATISSE-VLTI alignment. As alignment is very stable, this is currently only done once per night, on the first star acquired with the instrument. The night astronomer verifies the instrument, and, if needed (which rarely happens), changes the IRIS reference pixel to align it with MATISSE.
- Though the quality of the pupils in the VLTI lab are checked at the beginning of the night using IRIS, MATISSE also offers an option to verify its pupils internally. This feature is mainly used for technical troubleshooting and is not offered, neither in service nor in visitor mode.
- Finally, a fringe search can be done during the acquisition template. As the VLTI delay line model is now very stable and MATISSE offers a reasonable coherence length even in the L-band low resolution mode (i.e. of the order of 10μm) this step is usually only done once per night, during the first acquisition with MATISSE.

Performing MATISSE image acquisition, pupil check, and fringe search is the responsibility of the VLTI night astronomer and is not offered as a user parameter in service mode.

3.1.2 MATISSE with GRAVITY fringe tracker acquisition

When MATISSE is operated with the GRAVITY fringe tracker, IRIS is replaced by the acquisition camera of GRAVITY, and the sequence is as follows:

- First, the current acquisition procedure requires that MATISSE perform a target acquisition. This step is similar to the one for MATISSE standalone, but is mandatory in this case.
- Then, the GRAVITY acquisition camera takes over the control of the field and aligns itself on the MATISSE position, optimizing the coupling of the target into the fringe tracker fibres.
- Finally, the GRAVITY fringe tracker searches, finds, and stabilizes the fringes for MATISSE, which then takes the control back for observations.

The mandatory field acquisition on MATISSE, and the fringe acquisition on the GRAVITY fringe tracker, make the acquisition template duration a little longer than for MATISSE standalone.

3.2 Execution time

MATISSE standalone acquisition template execution times range between 4 min if only the VLTI preset is done, to about 15 min if pupil check with IRIS and image acquisition and fringe search with MATISSE are performed. When operating MATISSE with GRAVITY, the acquisition is always longer at about 15 min. In p2 the execution time is set to 10 min.

3.3 NAOMI and MACAO guiding

On the Unit Telescopes (UTs), the adaptive optics correction is provided either by MACAO in the optical or by CIAO in the infrared, both located in the coudé focus of the telescopes. However, MATISSE is currently not offered with CIAO so that only MACAO can be used on the UTs. Details on MACAO and CIAO can be found in the VLTI User Manual.

MACAO (Multi-Application Curvature Adaptive Optics) is a 60-elements curvature adaptive optic system working in the visible. It has the following requirements:
(i) The guide star must be fainter than V= 1 mag and brighter than V= 15 mag. Note that the Strehl starts dropping significantly when the coudé guide star becomes fainter than the V $= 13 \sim 14$ mag.
(ii) The guide star must be within a radius of 57.5 arcsec from a point 10 arcsec to the East of the science target, see Fig. 4 of the VLTI User Manual.

The Auxiliary Telescopes (ATs) guide by means of the New Adaptive Optics Module for Interferometry (NAOMI). NAOMI is a low-order Shack-Hartman system operating in the visible which replaces the previous STRAP tip-tilt guiding. Installation and commissioning of 4 NAOMI modules took place between September and November 2018. The sensitivity limit of NAOMI on the ATs is G= 12.5 mag in service mode. For fainter guide stars, only allowed in visitor mode, the Strehl delivered by NAOMI degrades to $\sim 10\%$ for G= 15 mag in median seeing conditions. A description of NAOMI and of the limiting magnitudes for the ATs can be found in the VLTI User Manual.

For both UT and AT, the visual magnitude (faintest, for variable stars) of the coudé guide star should be given in the keyword **"GS mag"** of the acquisition template. The details on how to set such keyword are described in Sect. 3.4.

As MACAO and NAOMI are the default guiding system for the UTs and ATs respectively, the **"Guiding Type"** should be be set to DEFAULT. Note that it is also equivalent to ADAPT_OPT for MATISSE.

3.4 List of user parameters

MATISSE acquisition template contains only three parameters in addition of the standard VLT/VLTI parameters.

L band flux in Jy

The object estimated L band flux in Jansky. The users can find such flux, for instance, in the Wide-field Infrared Survey Explorer (WISE) all sky catalog. This parameter is used by the observation template to set-up the real-time fringe coherencing parameters.

N band flux in Jy

The object estimated N band flux in Jansky. The users can find such flux, for instance, in the WISE all sky catalog or in the IRAS catalog. This parameter is used by the observation template to set-up the real-time fringe coherencing parameters.

K band magnitude

The object estimated K band magnitude. This is used by the IRIS lab-guiding system when operating with MATISSE standalone (**MATISSE_img_acq**), or by the GRAVITY fringe tracker with GRA4MAT (**MATISSE_img_acq_ft**).

H band magnitude

The object estimated H band magnitude. This is only used in GRA4MAT operation (**MATISSE_img_acq_ft**), by the GRAVITY acquisition camera, performing the same function as the IRIS lab-guiding system.

Differential tracking in RA

Differential tracking in RA in arcsecs per second. This keyword should be used if the object is moving on the sky with a large differential motion i.e. an asteroid or a comet.

Differential tracking in DEC

Differential tracking in DEC in arcsecs per second. This keyword should be used if the object is moving on the sky with a large differential motion i.e. an asteroid or a comet.

RA of guide star if COU guide star is SETUPFILE

Right Ascension of the coudé guide star. This keyword should only be specified if the keyword **COU guide star** is set to SETUPFILE.

DEC of guide star if COU guide star is SETUPFILE

Declination of the coudé guide star. This keyword should only be specified if the keyword **COU guide star** is set to SETUPFILE.

Epoch

Epoch of the coordinates of the coudé guide star if it is different from the science target. Usually 2000.

Equinox

Equinox of the coordinates of the coudé guide star if it is different from the science target. Usually 2000.

COU guide star

This keyword is used to tell the system which source shall be used for coudé guiding, either: SCIENCE if the target is used for the guiding, or SETUPFILE if an off-axis star will be used. In that case, the coudé guide star coordinates need to be specified.

Off-axis Coude Proper motion Alpha

Alpha coordinate of the proper motion of the coudé guide star in arcsec/year. This should only be specified if the keyword **COU guide star** is set to SETUPFILE.

Off-axis Coude Proper motion Delta

Delta coordinate of the proper motion of the coudé guide star in arcsec/year. This should only be specified if the keyword **COU guide star** is set to SETUPFILE.

Guiding Type

This keyword defines the type of coudé guiding to be used. The default setting (i.e. DEFAULT) , implies that, for the ATs, NAOMI or, for the UTs, MACAO will be used. Is it equivalent to ADAPT-OPT. MATISSE is currently not offered with CIAO, the infrared adaptive optic system installed on the UTs.

GS mag

Coudé guide star visual magnitude. This should always be specified. In the case of a variable star the faintest magnitude should be given. For the ATs the users are encouraged to use guide-star magnitudes obtained in the Gaia G filter when possible. If nor G nor R magnitude are available, V-band magnitude is also possible. When using the UTs, V-band magnitude should be provided (see VLTI User Manual).

Interferometry Array
As of P105 for all VLTI instruments, including MATISSE, users will have to specify the interferometric array using generic names instead of specific baselines. The possibilities for MATISSE on the ATs are *small, medium, large*, or a combination of them. For the UTs the only choice is *UTs*.

Type of interferometry observation
As of P105 for all VLTI instruments, including MATISSE, users will have to specify the type of interferometric observations. The possibilities are *snapshot, imaging, or time-series*. For details, see the VLTI configuration page and Sect. 7.2 of the VLTI User Manual.

4 Observation templates

Following the acquisition template, the user has to include in the OB one or more observation templates. For **P110** , MATISSE offers two main observation templates: the HYBRID observation template for MATISSE standalone **MATISSE_hyb_obs**, and the HYBRID observation template with Fringe Tracker **MATISSE_hyb_obs_ft**.

These templates define an observation in HYBRID mode, where the L&M-band arm observes with the beam splitter in SI-PHOT mode and the N-band arm without the beam splitter in HI-SENS mode.

In the following subsection we describe the different observing configurations (instrumental and detector setting).

4.1 Observing configurations

Table 2 summarizes MATISSE instrumental and detector configurations available for observation. Note that not all values are offered in service mode and that some are even unavailable in **P110** in visitor mode.

4.1.1 Spatial filtering

In each cryostat, spatial filtering is done by pinholes or slits mounted on a motorized wheel. The pinholes diameters and slit widths varies from 1.0 to 2.0 λ/D in L&M and 1.5 to 2.5 λ/D in N. All slits have a length of 5 λ/D. The possible settings are given in Table 2 where we highlight also the service mode configurations.

4.1.2 Beam splitter: the HI-SENS and SI-PHOT modes

Thanks to movable beam splitters installed in each cryostat, each arm of MATISSE can record simultaneous photometry or not. The modes with and without this photometry are respectively named SI-PHOT (SImultaneous-PHOTometry) and HI-SENS (HIgh SENSitivity).

Device	Possible values L&M bands	N band	comments
Spatial Filter	1, **1.5**, 2.0 λ/D 1x5, 1.5x5, 2.0x5 λ/D	1.5,**2.0**, 2.5 λ/D 1.5x5, 2.0x5, 2.5x5 λ/D	Holes or Slits. Fixed to bold value in service
Beam Splitter	HI-SENS (Out) **SI-PHOT** (In)	**HI-SENS** (Out) SI-PHOT (In)	Fixed to bold value in service
Spectral Filter	LM, L, and M	OPEN	LM bands automatically set depending on central wavelength λ_0
Spectral Disp.	LOW (R=34) MED (R=506) HIGH (R=959) HIGH+ (R=3666)	LOW (R=30) HIGH (R=218)	Set by users
Frame Mode	SCI-FAST-SPEED SCI-SLOW-SPEED	SCI-HIGH-GAIN	For L&M band depends on the target brightness
DIT [s]	0.02, 0.075, 0.111 1.0, 1.3, 3.0, 10.0	0.02 / 0.075	See section 4.1.5

Table 2: MATISSE instrumental and detector configurations available for observation. Note: Elements in blue are only offered with GRA4MAT.

MATISSE is currently only offered in a so-called HYBRID mode where the L&M band arm operates in SI-PHOT mode and the N-band in HI-SENS.

4.1.3 Frame rate modes in L&M band

Unlike the AQUARIUS detector used for the N-band which is offered only in HIGH-GAIN frame mode (Table 3), the L&M-bands HAWAII-2RG detector is offered in two frame-modes for science observations:

- SCI-SLOW-SPEED: Full frame detector readout in 1.38s (shorter when windowed)
- SCI-FAST-SPEED: Full frame detector readout in only 0.078s (shorter when windowed)

The major difference between the two modes is the detector read-out noise which is 6 times higher in the SCI-FAST-SPEED mode. For that reason, most objects should be observed in SCI-SLOW-SPEED. The SCI-FAST-SPEED mode is only offered for the brightest targets (limits are listed in Table 4), and should only be used for targets that would saturate the detector using the minimum DITs offered in SCI-SLOW-SPEED. For example, in LOW spectral resolution, the windows including the full L&M bands can be read in 0.020s in SCI-FAST-SPEED mode and 0.111s in SCI-SLOW-SPEED mode. Using the SCI-FAST-SPEED mode allows to observe stars 10 times brighter than the saturation limit in SCI-SLOW-SPEED mode. The saturation limits for all offered modes are given in Table 4 (i.e. column Max Flux). Note that the science target and the calibrators must be observed with the same frame-mode and DIT, so that faint calibrators should be avoided for very bright science targets that require observation in SCI-FAST-SPEED mode.

4.1.4 Spectral resolution and wavelength coverage in L&M bands

When operating in the more sensitive SCI-SLOW-SPEED detector mode, short DITs limit the detector readout window size. This has an implication on the L&M band spectral coverage for a given spectral resolution. The parameter controlling the windowing is the central wavelength (`SEQ.DIL.WL0`). In service mode the wavelength is selected through the **predefined central wavelengths for L&M bands** list[1] which is also available on the MATISSE instrument webpage. The two values of `WL0 (or` λ_0`)` allowed in low spectral resolution are:
– 3.5 μm for observations with DIT 0.075s, allowing to cover the L-band;
– 4.1 μm for observations with DIT 0.111s, allowing to cover the full LM coverage.

Table 4 provides a summary of the DITs offered and the corresponding wavelength coverage.

To observe several spectral windows in either MED and HIGH resolution, the user can concatenate several observation templates with various values of λ_0 in the same OB (visitor mode only). In visitor mode the user is free to choose any central wavelength by filling the **user central wavelength** field in p2. This is allowed because depending on the source some spectral features might be red-shifted. The free choice of λ_0 by the user has a consequence in terms of automatic calibration of the data during the night: it is very likely that visitors will not see their data automatically reduced by the "quick-look MATISSE pipeline" running in Paranal. The pipeline needs in fact a set of standard master calibrations to run, and the master calibrations are usually updated once a year. Master calibrations include only the files for standard modes offered in service mode. The number of non-standard setups for which we prepare (on best effort basis) the pipeline for automatic processing during the night is limited to 2. If 2 visiting astronomers are sharing nights, only 1 setup per astronomer will be reduced. The visiting astronomers have to provide their setup information on the day of their arrival on Paranal. The calibration files needed to reduce the non standard setup are triggered at the end of the night, and will be always available the day after the observations in the ESO archive.

GRA4MAT, by stabilizing the MATISSE fringes, allows much longer DITs and significantly help with the wavelength coverage.

4.1.5 Summary of offered modes in P110

The Tables 3 and 4 summarize MATISSE offered modes for **P110** (both for visitor and service mode observations). It is advisable when preparing phase 1 and phase 2 of the observations to always double check the instrument webpage News section for last minute information.

For N band, the user only needs to set the spectral resolution parameter and the other parameters will be computed by the template accordingly.

For the L&M-bands arm, the user needs to provide: the spectral resolution, the detector frame-mode, the DIT, and the central wavelength of observation λ_0.

[1]Users interested in observing specific features missing from the service mode current central wavelength list are encouraged to contact the instrument scientist. The list of offered wavelengths can be updated from one observing period to the other.

Spectral mode	Frame-mode	DIT (s)	Spectral band (μm)	Offered in Service
LOW	SCI-HIGH-GAIN	0.020	8 - 13$^{(a)}$	**Yes**
HIGH	SCI-HIGH-GAIN	0.075	8 - 13	**Yes**

Table 3: N-band offered configurations for **P110** in service and visitor mode. (a) The low spectral resolution data are rather noisy longward than 11 μm. Users interested in data with low spectral resolution at such wavelength range may consider to apply for high spectral mode using DIT 0.075, and rebin a posteriori the data to low. This applies only for sources brighter than 35 Jy in N-band.

Spectral mode	Frame mode	DIT [s]	Coverage [μm]	Min/Max flux limits [Jy] ATs	UTs	Offered in Service
MATISSE Stand-alone mode (**MATISSE_hyb_obs**)						
LOW	SCI-FAST-SPEED	0.020	2.85 - 5.0	100 / 8000	20 / 400	**Yes**
	SCI-SLOW-SPEED	0.111	2.85 - 5.0$^{(a)}$	5 / 2000	1 / 100	**Yes**
	SCI-SLOW-SPEED	0.075	2.85 - 4.2$^{(b)}$	1 / 1600	0.15 / 80	**Yes**
	SCI-SLOW-SPEED	0.075	4.00 - 5.0	5 / 2000	1 / 100	No
MED	SCI-FAST-SPEED	0.075	2.85 - 5.0	150 / -	15 / 5000	**Yes**
	SCI-SLOW-SPEED	0.111	$\lambda_0 \pm 0.08$	$\star$ / -	$\star$ / 3000	**Yes**
HIGH	SCI-FAST-SPEED	0.075	2.85 - 4.2	500 / -	50 / 10000	**Yes**
	SCI-SLOW-SPEED	0.111	$\lambda_0 \pm 0.04$	75 / -	8 / 6000	**Yes**
MATISSE GRA4MAT mode (**MATISSE_hyb_obs_ft**)						
LOW	SCI-SLOW-SPEED	0.6	2.85 - 5.0	0.2 / 300	0.02/0.07/0.1 (L/M/N)	Yes
MED	SCI-SLOW-SPEED	10.0	2.85 - 5.0	1 / -	0.3/1/NA (L/M/N)	Yes
HIGH	SCI-SLOW-SPEED	10.0	2.85 - 5.0	2 / -	0.7/NA/0.5 (L/M/N)	Yes
HIGH+	SCI-SLOW-SPEED	10.0	2.85 - 5.0	20 / -	6/6/NA(L/M/N)	Yes

Table 4: L&M-bands arm offered configurations for **P110** in service and visitor mode. (a) This wavelength coverage is obtained by setting $\lambda_0 = 4.1$ in p2. See also Sect. 4.1.4. (b) This wavelength coverage is obtained by setting $\lambda_0 = 3.5$ in p2. See also Sect. 4.1.4. ($\star$) The minimum flux depends on the band of observation. See the table with the absolute and relative measurements limits in the MATISSE instrument webpage. The saturation limits are intended as L band.

4.2 Template sequence

Here we describe the MATISSE observing sequence for the HYBRID mode, which is the only mode offered for **P110** . The fringe acquisition is similar for MATISSE standalone and for GRA4MAT.

The Beam Commuting Devices (BCDs) are the first devices in MATISSE. They are two identical devices allowing to commute the beams two by two. BCD1 commutes beams 3&4, and BCD2 beams 1&2. They each have two positions: OUT where the beams are not commuted, and IN where beams are commuted. Commuting the beams allows to remove most instrumental effects, and significantly improves the closure and differential phase measurements.

The MATISSE observation starts with two 30s sky exposures: one recorded with both BCDs in OUT position and a second one with both in IN position. The sky offsets α and δ are users parameters that should be modified only for very extended object. The sky exposures are recorded simultaneously on both detectors.

The instrument then records a series of fringe exposures simultaneously on both detectors. Each exposure lasts 60s and the total number of exposures is 4 times the **Number of exposure cycles** specified in the template by the user. The default exposure cycle is 1. This can be increased to 2 keeping in mind that the concatenation should not last longer than 1h for a CAL-SCI sequence, and 1.5h in the CAL-SCI-CAL. Each cycle consists on 4 exposures taken with different BCDs positions: IN-IN, OUT-IN, IN-OUT, OUT-OUT. In service mode, the standard number of cycles is 1 in **LOW, MED, and HIGH resolution.**

After the fringe sequence, the template can perform a photometry sequence if the template parameter **Do photometry sequence** is set to "T". This sequence is necessary to compute visibilities in the N-band, moreover commissioning results showed that the photometry step is crucial to properly calibrate M-band data, and also L-band for sources with L fluxes less than 25 Jy on the ATs and 1.5 Jy on the UTs (see also Sect. 4.2.1 and the MATISSE User Manual). The photometry sequence consists of a four-shutter sequence performed twice, with two BCDs positions (IN-IN and OUT-OUT). Each of the 8 exposure is 60s. The photometry sequence is performed using chopping. The chopping parameters are fixed in service mode (chopping frequency is 1 Hz and stroke is 4.0ïn the North-South direction). During the N-band photometry sequence the L&M-band detector records a chopped fringe exposure, that will be treated by the pipeline to provide additional L&M-band data.

For **P110** , the chopped photometry sequence is not available when operating with GRA4MAT with UTs, and is forcibly turned off by the **MATISSE_hyb_obs_ft** template. This prevents the measurement of absolute visibilities except for the brightest objects (see 4.2.1) with UTs. If correlated flux is not sufficient, an non-GRA4MAT OB can be added as a second observation. Since there is a maximum amount of time allowed for service mode concatenations with a fixed structure (1h CAL-SCI, 1.5h CAL-SCI-CAL), this has to be done in visitor mode.

4.2.1 Should I perform a photometry sequence?

The photometry is needed to compute visibility in the N-band. Moreover, commissioning results have shown that only chopped interferograms can be used for targets fainter than L = 25 Jy on the ATs, fainter than L = 1.5 Jy on the UTs, and for M-band visibilities. As a consequence it is strongly recommended to always include the N-band photometry step in MATISSE standalone, with the **MATISSE_hyb_obs** template. The N-band photometry can be skipped only in three cases:

- scientific interest is limited to the N-band, and the target is too faint to acquire N-band photometry (i.e. only N-band correlated flux is required);
- 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);
- only (relative) correlated flux measurements are needed.

Experience with VLTI/MIDI showed that for faint objects (for example AGNs), the photometry is the major source of noise and most users prefer to work with correlated flux only.

The up-to-date sensitivity limits for correlated flux and visibility measurements are given on the MATISSE instrument webpage.

4.2.2 What if I really need absolute visibilities with GRA4MAT?

When the target is too faint to yield absolute visibilities without chopping[2], only correlated flux can be measured with GRA4MAT. Since the reconfiguration of the VLTI between differemt modes is very short and automatic, this can be circumvented by taking a non-GRA4MAT OB immediately after. However, since there are constraints in service mode operations w.r.t. the structure and length of an observation, this has to be done in visitor mode.

4.2.3 About MATISSE coherencing

Only one of the two bands (L or N) is used for coherencing during the fringe exposures. It is set by the "**Master band for the coherencing**" user parameter.

In most cases, the L-band should be chosen as the master band, because:

- The L-band sensitivity is higher than the N-band one. There is a factor of about 10 in the fringe detection in L compared to N for the same flux.
- The stellar flux is usually higher in L. For stars there's typically a factor 8 in flux between the bands.

However, the N band might be chosen as master band if:

- the object is over resolved in the L-band (V<0.01)
- the object is highly reddened or has a very strong infrared excess (flux in N 10 times higher than flux in L).

If the user is not sure which band to use, L band should be selected and a note might be added as OB comment and in the README file to let the operator decide when acquiring the target.

If N-band is chosen as the master-band, the chopped fringes acquired in the L&M bands during the N-band photometry sequence will be coherenced using the L-band.

4.3 Sensitivity

The target flux limits for MATISSE Stand-alone **can be found on the MATISSE ESO webpage.** They are defined in such a way that the typical errors for:

- Low resolution observations will be better than 5 degrees on closure phase data and better than 10% on absolute visibilities
- Medium resolution observation will be better than 10 degrees for closure phase data and better than 20% on absolute visibilities
- Attempting to obtain absolute calibrated quantities with high resolution is not recommended unless the targets are very bright.

[2]As of Period **P110** chopping is not offered for UTs, therefore this applies to all GRA4MAT observations with UTs

- The uncertainties of medium and high resolution observations will be about 1 degree on differential phases, and better than 10% on differential visibilities.

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.
The user should refer to MATISSE ESO webpages for the sensitivity definitions of GRA4MAT.

4.4 Execution time

The total execution times of standard observation OBs are the following:

- 20 min with L&M-band in LOW or MED without photometry sequence
- 25 min with L&M-band in HIGH without photometry sequence

The photometry sequence lasts 10 additional minutes.

4.5 List of user parameters

Integration time for the L&M detector
The detector integration time (DIT) in seconds for the Hawaii detector use in the L and M bands. The possible DITs depends on the detector frame mode. **For MATISSE standalone, DITs of 0.020s, 0.075s and 0.111s are currently possible; in addition, DITs of 1s, 1.3s, 3s and 10s are possible with GRA4MAT.**

Frame mode for the L&M detector
Either SCI-FAST-SPEED or SCI-SLOW-SPEED (see section 4.1.3 for more information).

Central wavelength for the L&M bands
This parameter is used only in SCI-SLOW-SPEED mode where the whole detector cannot be read during one DIT. It specifies the central wavelength of the observing window. In LOW spectral resolution it is only used to specify whether the user wants to observe in the L or M band. In MED resolution, the spectral window for the standard DIT of 0.111s is of the order of 0.16μm and in HIGH of 0.08μm. (See also Sect. 4.1.4). In Service Mode the user must choose the central wavelength from the predefined list. In visitor mode the user can enter the central wavelength in the user central wavelength entry of p2.

Number of exposure cycles
This parameter determines the number of fringe exposures cycles. One exposure is one minute and a full cycle is made of 4 exposures. We advice to increase the number of cycles to increase the precision of the measurements in cases where no photometry sequence (i.e. no absolute visibility) is required. The user should keep in mind that the total length of the concatenation should be within a maximum of 1 hour for CAL-SCI and 1.5 hours for CAL-SCI-CAL. Longer concatenations are not allowed in service mode.

Do photometry sequence (T or F)
If set to "T", a chopped shutter sequence is performed after the fringes exposures in the N-band. During this eight-exposures sequence (4 exposures each in BCD IN-IN and OUT-OUT), the L-band arm records chopped fringe exposures. Note that this photometric exposure is mandatory to obtain visibilities in the N band. If set to "F" the MATISSE pipeline will only be able to deliver correlated flux in the N band. The photometry step is crucial to properly calibrate M-band data and also L-band data for sources fainter than 25 Jy on the ATs and 1.5 Jy on the UTs (See Sect. 4.2.1 for more information). Since GRA4MAT does not support chopping with UTs, this option is not available and turned off by default in the **MATISSE_hyb_obs_ft** template.

Sky offset, right-ascension
Right ascension offset for the sky in arcseconds. Default is set to 1". This should only be modified in case of very extended object.

Sky offset, declination
Declination offset for the sky in arcseconds. Default is set to 15". This should only be modified in case of very extended object.

Master band for the coherencing (L or N)
Spectral band that will be used to perform the fringe coherencing. Possible values are "L" or "N". The default is L band as the SNR is usually higher on this band. This parameter can be changed at runtime by the night astronomer if coherencing can be better performed in the other band. When operating with GRA4MAT, this option should be kept to L. (See section 4.2.3 for more information).

Spectral mode for the L&M bands
MATISSE offers four spectral resolutions in the L&M bands: LOW (R=34), MED (R=506), HIGH (R=959) and HIGH+ (R=3666). The HIGH+ mode is only offered with GRA4MAT.

Spectral mode for the N band
MATISSE offers two spectral resolution in the N band: LOW (R=30) and HIGH (R=218).

Observation type
SCIENCE for the science target and CALIB for the interferometric calibrators.

A Comphrensive list of template parameters

A.1 Acquisition templates

All the template parameters, including those that cannot be defined by the user in p2 but can be modified at the time of observation, are listed in Table 5.

Name	description	range	default
DET1.READ.CURNAME	Frame mode for L detector	SCI-FAST-SPEED SCI-SLOW-SPEED	SCI-SLOW-SPEED
SEQ.ACQ.ST	Do image acquisition	T F	F
SEQ.FLUX.L	L band flux in Jy	-	-
SEQ.FLUX.N	N band flux in Jy	-	-
SEQ.MAG.K	K-band magnitude	-	-
SEQ.FS.DET1.DIT	Integration time for fringe-search, L-band	-	0.111
SEQ.FS.INS.DIL.NAME	Dispersive element for fringe-search, L-band	HIGH+ HIGH MED LOW	MED
SEQ.FS.INS.DIN.NAME	Dispersive element for fringe-search, N-band	LOW HIGH	LOW
SEQ.FS.INS.SFL.NAME	Spatial filter for fringe-search, L-band	1.00 1.50 2.00 0.66x5.5 1.50x5.5 2.50x5.5	1.5
SEQ.FS.INS.SFN.NAME	Spatial filter for fringe-search, N-band	1.50 2.00 2.50 1.00x5 1.50x5 2.00x5	2.0
SEQ.FS.SKY.DURATION	Duration of sky exposure for fringe-search	1..60	15
SEQ.FS.ST	Do fringe-search	T F	F
SEQ.OSF.AUTO	Automatic execution of OSF scripts?	T F	T
SEQ.PRESET.ST	Preset VLTI ?	T F	T
SEQ.SKY.OFFS.ALPHA	sky offset, right-ascension	-	1
SEQ.SKY.OFFS.DELTA	sky offset, declination	-	15
SEQ.TRACK.BAND	Master-band controlling the VLTI delay-lines	L N	L
SEQ.CHOP.ST	Use telescope chopping	F T	T
TEL.TARG.ALPHA	Target RA	ra	0
TEL.TARG.DELTA	Target DEC	dec	0
TEL.TARG.EQUINOX	Target Equinox	-2000..3000	2000
TEL.TARG.ADDVELALPHA	Differential tracking in RA	-15..15	0
TEL.TARG.ADDVELDELTA	Differential tracking in DEC	-15..15	0
TEL.TARG.PMA	Proper motion in RA (”yr)	-500..500	0
TEL.TARG.PMD	Proper motion in DEC (”/yr)	-500..500	0
TEL.GS1.ALPHA	RA of guide star	ra	0
TEL.GS1.DELTA	DEC of guide star	dec	0
TEL.GS1.MAG	Magnitude of guide star	0..25	0
TEL.CHOP.FREQ	Chopping frequency (Hz)	-	0.5
TEL.CHOP.POSANG	Azimuth angle of chopping	0..360	0
TEL.CHOP.PVRATIO	Star/sky dwell ratio	1	1
TEL.CHOP.THROW	Amplitude angle of chopping	0..4.5	4.5
COU.AG.ALPHA	RA of guide star if COU guide star is SETUPFILE	ra	0
COU.AG.DELTA	DEC of guide star if COU guide star is SETUPFILE	dec	0
COU.AG.EPOCH	Epoch	-2000..3000	2000
COU.AG.EQUINOX	Equinox	-2000..3000	2000
COU.AG.GSSOURCE	COU guide star	NONE SETUPFILE SCIENCE	SCIENCE
COU.AG.PMA	Off-axis coude Proper Motion Alpha	-10..10	0
COU.AG.PMD	Off-axis coude Proper Motion Delta	-10..10	0
COU.AG.TYPE	Guiding Type	DEFAULT NONE ADAPT_OPT	DEFAULT
COU.GS.MAG	GS mag in V	0..25	0
DEL.FT.SENSOR	Fringe tracker sensor	MATISSE NONE	MATISSE

Table 5: Comprehensive list of template parameters accessible during observation.

A.2 Observation templates

Here we list all template parameters including those that cannot be defined by the user in p2, but can be modified at the time of observation.

Name	description	range	default
DET1.READ.CURNAME	Frame mode for L detector	SCI-FAST-SPEED SCI-SLOW-SPEED AUTO	SCI-SLOW-SPEED
DET1.DIT	Integration time for L-band	-	0.075/0.6⋆
INS.DIL.NAME	Dispersive element in L-band	HIGH+ HIGH MED LOW	LOW
INS.DIN.NAME	Dispersive element in N-band	LOW HIGH	LOW
INS.SFL.NAME	Spatial filter in L-band	1.00 1.50 2.00 0.66x5.5 1.50x5.5 2.50x5.5	1.5
INS.SFN.NAME	Spatial filter in N-band	1.50 2.00 2.50 1.00x5 1.50x5 2.00x5	2.0
SEQ.DIL.WL0	Central wavelength of LM-band spectra	2.85 -5	3.5
SEQ.FRINGES.NCYCLES	Number fringe exposure cycles	-	1
SEQ.FRINGES.BCD.SEQ	BCD sequence	2STEPS 4STEPS	4STEPS
SEQ.OSF.AUTO	Automatic execution of OSF scripts?	T F	T
SEQ.SKY.OFFS.ALPHA	sky offset, right-ascension	-	1
SEQ.SKY.OFFS.DELTA	sky offset, declination	-	15
SEQ.CHOP.ST	Use telescope chopping	F T	T
SEQ.PHOTO.ST	Do photometry sequence	T F	T
SEQ.TRACK.BAND	Master-band controlling the VLTI delay-lines	L N	L
SEQ.TRACK.ST	SEQ.TRACK.ST	T F	T
TEL.CHOP.FREQ	Chopping frequency (Hz)	-	0.5
TEL.CHOP.POSANG	Azimuth angle of chopping	0..360	0
TEL.CHOP.PVRATIO	Star/sky dwell ratio	1	1
TEL.CHOP.THROW	Amplitude angle of chopping	0..4.5	4.5
DPR.CATG	Observation type	SCIENCE CALIB	CALIB

Table 6: Comphrensive list of template parameters accessible during observation. (⋆) 0.075 s for MATISSE, 0.6 s for GRA4MAT