MATISSE status report and science forecast

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ABSTRACT

MATISSE is the mid-infrared spectrograph and imager for the Very Large Telescope Interferometer (VLTI) at Paranal. This second generation interferometry instrument will open new avenues in the exploration of our Universe. Mid-infrared interferometry with MATISSE will allow significant advances in various fundamental research fields: studies of disks around young stellar objects where planets form and evolve, surface structures and mass loss of stars in late evolutionary stages, and the environments of black holes in active galactic nuclei. MATISSE is a unique instrument. As a first breakthrough it will enlarge the spectral domain used by optical interferometry by offering the L & M bands in addition to the N band, opening a wide wavelength domain, ranging from 2.8 to 13 μm on angular scales of 3 mas (L/M band) / 10 mas (N band). As a second breakthrough, it will allow mid-infrared imaging – closure-phase aperture-synthesis imaging – with up to four Unit Telescopes (UT) or Auxiliary Telescopes (AT) of the VLTI. MATISSE will offer various ranges of spectral resolution between R~30 to ~5000. In this article, we present some of the main science objectives that have driven the instrument design. We introduce the physical concept of MATISSE including a description of the signal on the detectors and an evaluation of the expected performance and discuss the project status. The operations concept will be detailed in a more specific future article, illustrating the observing templates operating the instrument, the data reduction and analysis, and the image reconstruction software.

Keywords: Interferometry, Spectroscopy, Mid-Infrared, VLTI

1. INTRODUCTION

In 2002 the two-telescope MIDI-VLTI instrument had its first light. At this time, the idea of an upgrade to an interferometric imager was born. A first prototype was studied and built, leading to a first concept called 'APreS-MIDI' (Aperture SynthesiS with MIDI), which was presented at the 2005 ESO Conference 'The Power of Optical/IR Interferometry: Recent Scientific Results and 2nd Generation VLTI Instrumentation'.
Following a recommendation by ESO, the MATISSE Consortium initialized the instrument conceptual design study in 2005. The official kick-off meeting took place in Nice in November 2008. After a lot of hard work and a change of the instrument concept, the Preliminary Design Review was held in December 2010 in Garching, and the Final Design Reviews occurred in September 2011, for cryogenics and optics, and in April 2012 for the whole instrument.
Currently, we are building the instrument, and the preliminary acceptance in Europe, planned for November 2015, will mark the end of the current integration and test period, with the first light at Paranal foreseen in 2016.
MATISSE is a long-term project - more than ten years of development to open two decades of innovative science. The project became possible thanks to the scientific research conducted in our laboratories in the field of interferometric concepts and observing methods. The experience acquired on AMBER and MIDI, the availability of several new key technological components, like the large detectors, the efficient cooling devices and the state of the art cryo-mechanisms allowing a highly automated instrument, have contributed to make MATISSE possible. The numerous interactions between people and institutes from different countries as well as the engineering challenges have made our project a pleasant human adventure that has generated a lot of creativity.

2. SCIENCE MOTIVATION

From the very beginning of the project, MATISSE was planned as an interferometric imager for a broad range of astrophysical targets. To achieve this goal, stringent requirements for the instrument were derived from most challenging science cases: Protoplanetary disks around progenitors to solar-type stars (T Tauri stars) and the dusty tori around Active Galactic Nuclei (AGN). The derived and realized instrument characteristics will also cover the study of the birth of massive stars, of the structure, dynamics, and chemistry of evolved stars, of the early evolution of the Solar system through studying its minor bodies, of exozodiacal dust disks, of properties of Pegasean planets, and of the immediate vicinity of the Galactic center. In the following, we give an overview about the key astrophysical questions for which a significant impact from observations with MATISSE is expected.
To illustrate the potential of MATISSE, a short review of the achievements of its main progenitors –MIDI and AMBER– appears useful. First and foremost, MIDI has demonstrated the feasibility of long-baseline interferometry at the VLT in the mid-infrared. The angular resolution reaching up to 10 mas was just right to spatially resolve warm reemission regions around various types of astrophysical objects, and the sensitivity was sufficient to observe a significant number of objects of each class. Moreover, the chemical composition of the dust could be investigated on interferometric scales.

In the specific case of circumstellar disks, MIDI and AMBER allowed, for the first time, to investigate the potential planet forming region around young stars in nearby star-forming regions. Global characteristics of these disks on scales of a few 100 AU could now be compared to the structure of the inner, AU-scale regions (e.g., Leinert et al. 2004, Schegerer et al. 2009). Differences found in the dust size and crystallinity provided valuable insights into the physics determining the disk mineralogy (van Boekel et al. 2004), and temporal variability of the reemission brightness on the scales of few AU shed light on the processes in young eruptive stars (Mosoni et al. 2013). MIDI opened infrared intererferometry for the investigation of AGNs and allowed the characterization of the hot inner component of these galaxies. AMBER was able to resolve the inner AU- and sub-AU-scale gas and dust regions of accretion disks and the launching areas of winds in the near-infrared continuum and in emission lines (e.g., Brackett Gamma). Furthermore, the high spectral resolution of R=12000 offered by AMBER allowed the study of kinematic properties of the inner disk and disk wind regions (e.g., Weigelt et al. 2011). Such studies are important to improve our understanding of the fundamental accretion-ejection process.

MATISSE will allow us to continue from here, but with even more ambitious goals. This bold statement is valid because of the new discovery potential of the instrument. At first, MATISSE will allow the direct detection of asymmetric structures which can be used as tracers for the disk physics as well as various processes related to the planet formation process. Second, the extension to the L and M bands will allow one to investigate different spatial regions of the targeted objects as well as different physical processes: N band observations are dominated by the thermal emission of warm and cool dust, while the L/M band flux is expected to consist of both emission and scattering of short-wavelength radiation. Third, MATISSE will offer various spectral resolutions in the range of R~30 to ~5000, providing the means to study spectral features of amorphous and crystalline dust and polycyclic aromatic hydrocarbons (R~30/200-500) as well as the distribution and kinematics of the gas. And fourth, the continuation of observations in the N band will allow one to investigate the temporal variability of the brightness distribution – and thus possible AU-sized structures – as suggested from planet formation and planet-disk interaction scenarios. In symbiosis with other high-angular resolution instruments/observatories operating at complementary wavelength ranges (e.g., ALMA), MATISSE will provide the means to study the planet-forming region in detail (see Figure 1).

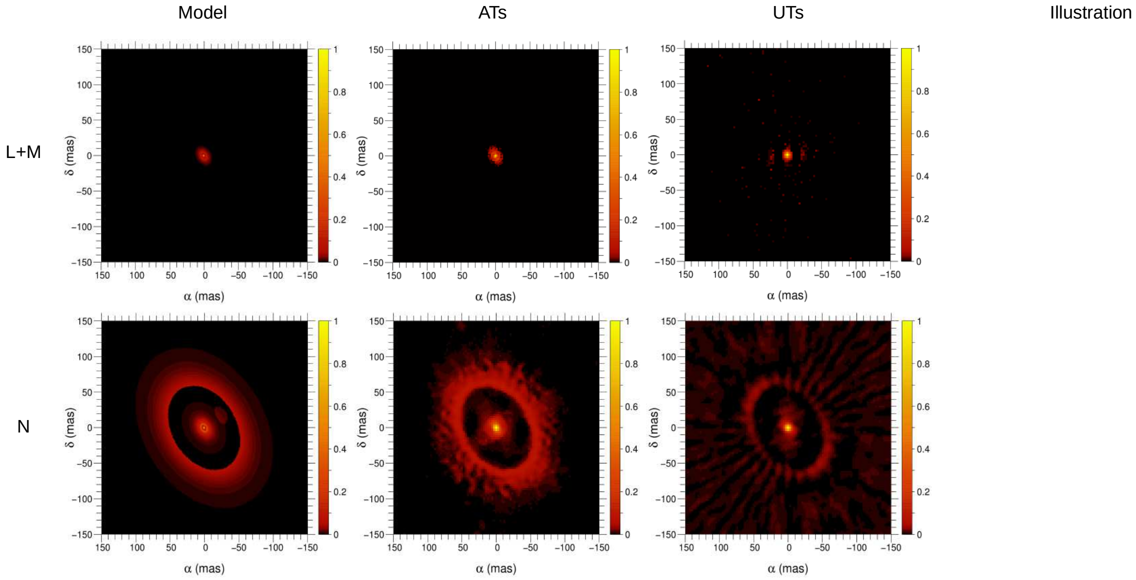

Figure 1. Illustration of the imaging capabilities of MATISSE in L+M and N bands. We simulated a realistic scene representing the appearance of the HD 100546 system, fed it into a MATISSE simulator producing 3 nights (ATs) or 1 night (UTs) of data, and reconstructed images using the MIRA software (Thiébaut et 2010). The right illustration is based on Crida et al (2008).

Specific key topics and questions concern the complexity of disk structures in the planet forming zone of circumstellar disks at various stages of their evolution, the status of inner disk clearing in transitional disks, constraints on properties, growth, and sedimentation of dust grains, tracers for giant protoplanets, properties of circumbinary vs. circumstellar disks, the nature of outbursting young stellar objects, the status of the Solar System minor bodies, the dust production as an outcome of planetesimal collisions and exo-comets evaporation, the spatial distribution of the gas (carbon monoxide and hydrogen) and dust (silicates/graphite, CO ice) in the typically complex and distant high-mass star-forming regions, the link between low and high-mass star formation and the search and characterization of accretion disks around young massive (proto)stars. Table 1 gives a series of components owning a spectral signature in the wavelength domain of MATISSE.

Table 1. Components and corresponding wavelengths of excepted spectral signature.

Components	**Wavelengths**
H_2O (ice)	3.14µm
H_2O (gas)	2.8 – 4.0µm
H recombination lines	4.05µm (Brα), 4.65µm (Pfβ)
Polycyclic Aromatic Hydrocarbons	3.3 – 3.4 µm
Nano-diamonds	3.52 µm
CO fundamental transition series	4.6 – 4.78 µm
CO (ice)	4.6 – 4.7 µm
Amorphous silicates, Crystalline silicates (olivines and pyroxenes), PAHs, fine structure lines (e.g. [NeII])	8 – 13 µm

The other major topic concerns the study of *Active Galactic Nuclei*. The wavelength and baseline configurations provided by the VLTI allow to investigate gas and dust in the temperature range 300-1500 K in the 0.1-5 parsecs core region of the nearest AGNs. The astrophysical problems that can be addressed with observations in the mid-infrared spectral domain concern the morphology, chemistry and physical state of the circumnuclear dusty structures. Where does this dust come from? How does it lose its angular momentum? What portion is accreted inwards, what portion sublimates and what portion is blown out by winds? What supports the thickness of the dust torus? What determines its inner edge? How does it affect the energy balance of the accreting material and the AGN as a whole? How does the jet interact with dust clouds? How does its optical extinction affect our perception of the inner regions of the AGN? Does the Type I/TypeII dichotomy arise from an inclination effect, or are there fundamental morphological differences? How do the dusty regions relate to the inner ionized Broad Line Regions?
The results achieved within a) individual, many uv-point studies of nearby bright AGNs with MIDI, AMBER and the Keck interferometer, and b) a homogeneous Large Program Survey of 25 Seyfert galaxies with MIDI have shown that warm (300-1500 K) nuclear dust disks indeed exist, but that they are physically smaller than expected (~1 pc) in the N band, sometimes misaligned relative to the jets, and show indications of clumpiness. The spectrum of the silicate absorption does not resemble that in star-forming regions. These results are interpreted as showing that the disks are comprised of dense clumps, optically thick even in the mid-infrared. The radio galaxy Centaurus A show a complicated mixture of thermal and synchrotron emission. MATISSE will allow one, for the first time, to reconstruct infrared aperture synthesis images of NGC 1068, Circinus, and Cen A. Their mid-IR dust emission in the circumnuclear region was too complex for MIDI to disentangle. The structural relations between the components could not be established unambiguously and true mapping with closure phases is needed. MATISSE will allow us to probe the relative astrometry of features over its broad wavelength range (3-13µm), and may allow, if plans for a dual beam second Generation Fringe Tracker (2GFT) are realized, absolute astrometry related to a reference star in the field.
However, to make full use of the potential of MATISSE and thus to fully achieve the above goals, improvements on the VLTI infrastructure are mandatory. In particular, these concern the decrease of the vibration level of the UTs, adaptive optics on the ATs, and, most importantly, the availability of a second-generation fringe tracker (2GFT) for MATISSE. The 2GFT will improve sensitivity, accuracy and spectroscopic capability of MATISSE and will thus have a direct strong impact on the scientific potential of the instrument:

- The *Sensitivity* achieved with a 2GFT is mandatory for the study of AGNs and the disks around young low-mass stars. Furthermore, longer baselines can be used to establish the connections between the high surface brightness inner disks and the asymmetric larger components in the protoplanetary disks or in the AGN tori. This will also be helpful for image synthesis.
- The higher *Accuracy*, on the other hand, is important for L/M band observations of disks around young stars, providing constraint for the radial and vertical temperature gradient and opacity structure in the disk.
- Finally, medium and high resolution *spectroscopy* will become feasible for a statistically large sample of circumstellar disks.

3. CONCEPT AND PERFORMANCES

MATISSE uses an all in one multi-axial combination scheme. Following seven years of preparatory conceptual research, we concluded that this type of combination is the most adequate for an interferometric instrument with more than two apertures operating in the mid-infrared.

Initially, based on the efficiency of the two telescope MIDI recombination scheme, a pairwise co-axial concept was considered. The advantage of this scheme is to get simultaneously two interferometric signals per baseline, phase shifted by π. The correlated flux is obtained by subtracting the two signals. In this way, the thermal background level and its associated temporal fluctuations are directly eliminated, nevertheless not the related thermal photon noise. However, in spite of a good expected efficiency in terms of Signal-to-Noise-Ratio (SNR), this scheme opens many issues when extended from two to four telescopes: a possible weakness for the stability of the closure phase measurements and a high instrumental complexity due to numerous opto-mechanical elements required in the cold. These issues led us to consider the multi-axial global combination as the more robust and simpler scheme. Yet, the method for thermal background subtraction, ensuring a good SNR, had to be re-visited.The multi-axial global combination scheme means that the four beams are combined simultaneously on the detector. The interferometric signal and the four individual photometric signals receive respectively 2/3 and 1/3 of the incoming flux. The signals are dispersed orthogonal to the fringes. MATISSE will observe in three bands simultaneously: L, M and N. Two spectral resolutions are provided in N band, R = 30 and 220, and four in L&M bands, R = 30, 500, 1000, and 3500. The spatial size of the interferometric channel is larger than the photometric channels in order to optimize the sampling of the six different spatial fringe periods. The beam combination is made by the camera optics. At this level, the beam configuration is non redundant in order to produce different spatial fringe periods, and thus to avoid crosstalk between the fringe peaks in Fourier space. The separation B_{ij} between beams i and j *is* respectively equal to 3D, 9D and 6D, where D is the beam diameter.

Measuring the coherent flux from which all the interferometric observable quantities are derived, such as the color differential visibility, the color differential phase, and the closure phase, requires – in Fourier space - the subtraction, for each individual fringe peak, of all cross talks. The most critical contamination of the fringe peak due to the signal windowing is the one from low frequency, containing the background from thermal optics and atmosphere.

Because the thermal background at the longest wavelengths is variable and far exceeds the target coherent flux, it is important to limit the cross-talk between the low frequency peak and the high frequency peaks at a level below the thermal background photon noise limit. Two methods are used in MATISSE to ensure this result, in order to estimate the coherent flux with a good accuracy: spatial modulation, like in the VLTI near-infrared spectrometer AMBER, combined with temporal modulation like in MIDI by varying at high frequency the optical path difference between the beams.

For each of the six explored baselines and in each of the spectral channels, MATISSE will provide the following observable quantities:

1. the photometry of the source in each beam, and hence the source spectrum,
2. the coherent flux of the source,
3. the absolute visibility derived from the photometry and the coherent flux measurements,
4. the color differential visibility (change of visibility with wavelength),
5. the color differential phase (change of phase with wavelength),
6. the closure phase from the triplets of coherent fluxes.

In order to measure the visibility, we also need to extract the source photometry by separating the stellar flux from the sky background, using sky chopping. The problem with chopping is that the observation of the sky and that of the target are not simultaneous. The thermal background fluctuations will be the most important contribution to the visibility error. Fortunately, chopping is not necessary for measuring coherent flux, color differential phase, and closure phase.

MATISSE has two standard operating modes. The “HighSens” mode does not provide photometry and all photons are collected in the interferometric beam. This maximizes the sensitivity on the color differential and closure phases. It is still possible to take photometric observations sequentially after the interferometric observations. In “SiPhot” mode, 2/3 of the flux goes into the interferometric channel and 1/3 into the photometric channels. Chopping is used to measure the average source photometry and therefore extract the visibility from the coherent flux. These modes can also be mixed, e.g. the HighSens mode in N band and the SiPhot in L band. In SiPhot mode, five images (four photometric and one interferometric) form on the detector (see Figure 2). During observations with four telescopes, the interferogram contains six dispersed fringe patterns. The sampling of this interferometric channel is 72 pixels per λ/D in the spatial direction and 3 pixels per λ/D in the spectral direction, i.e. an anamorphic factor of 24. The spatial sampling of the photometric channels is 12 pixels per λ/D with the same spectral sampling as in the interferometric channel.

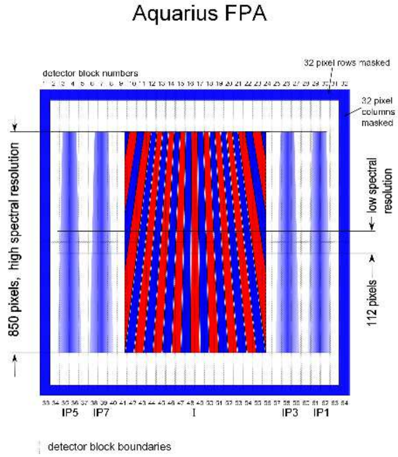

Figure 2. Layout of the MATISSE beams on the Aquarius detector. In the middle, interferometric fringes are encoded in horizontal direction. The four photometric channels are located pairwise at the left and right of the detector. Spectral dispersion is in the vertical direction.

Beam combination is made by the camera optics. The beam configuration is non redundant (separation B between the beams is equal to 3D, 9D and 6D, where D is the spatial diameter of the beam) in order to avoid crosstalk between fringe peaks in Fourier space from the spatial modulation principle. In the spatial direction, the sampling of the narrowest fringes is 4 pixels, while it is 24 pixels for the widest fringes at the shortest wavelength. The Fourier transform of each spectral column of the interferometric image is thus composed by six fringe peaks at different frequencies B_{ij}/λ (3 D/λ, 6 D/λ, 9 D/λ, 12 D/λ, 15 D/λ, 18 D/λ) and a low frequency peak containing the object photometry and the thermal background coming from the four telescopes. Assuming a detector window of $4\lambda/D$, we have a frequency step $f_0=D/4\lambda$ and hence 8 frequency points per fringe peak.
The tables 2 and 3 give the expected performance of MATISSE. They take into account all characteristics of the VLTI (e.g., optical transmission, adaptive optics performance, tip-tilt, focal lab) and are the result of a full calibration procedure (calibration plus object).
The expected ultimate performance in terms of sensitivity and accuracy requires some important evolution of the VLTI infrastructure: external fringe tracking, collecting data such as OPD and tip-tilt residuals, and lateral pupil motion monitoring or even active correction.

Table 2. L and N band limiting fluxes, with and without fringe tracking (FT).

	L band sensitivity		N band sensitivity	
	Without FT	With FT (DIT=300ms)	Without FT	With FT (Obs.=10s)
AT	2.95Jy (L=5)	0.55Jy (L=6.8)	14.6Jy (N=1)	2.1Jy (N=3.1)
UT	0.26Jy (L=7.6)	0.05Jy (L=9.5)	0.9Jy (N=4)	0.12Jy (N=6.25)

Table 3. L and N band performance. These are estimated for a 20 Jy source at low spectral resolution in SIPhot mode and without the use of a Fringe Tracker.

		L band	
Visibility	AT	≤ 1.6 %	≤ 8.6 %
	UT	≤ 2.3 %	≤ 2.8 %
Closure phase	AT	≤ 20.3 mrad	≤ 28.2 mrad
	UT	≤ 20 mrad	≤ 13.6 mrad
Differential Visibility	AT	≤ 0.7 %	≤ 8.4 %
	UT	≤ 0.8 %	≤ 1.5 %
Differential Phase	AT	≤ 19.3 mrad	≤ 26.1 mrad
	UT	≤ 22.2 mrad	≤ 24.9 mrad

4. DESIGN

MATISSE is composed of the Warm OPtics (WOP), and two Cold Optics Benches (COB) together with two Mid-InfraRed detectors housed in two cryostats. The location of the different parts of the instrument inside the VLTI Laboratory is illustrated in Figure 3.

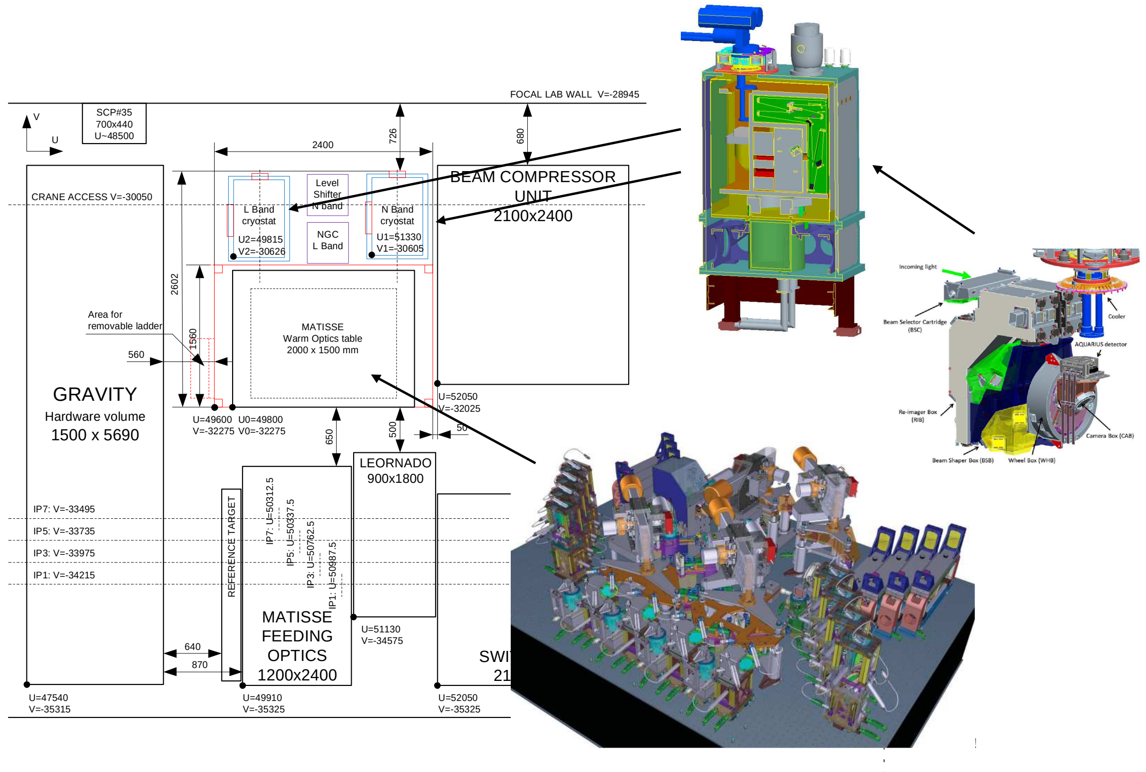

Figure 3. Future location of MATISSE in the VLTI laboratory. One can see the Warm OPtics table and the two cryostats above. This location is currently used by MIDI. a) The MATISSE Warm OPtics table with its optical components. b) One of the two MATISSE cryostats, which holds the Cold Optics Bench and the detector. c) The MATISSE Cold Optics Bench with its subsystems.

The WOP rests on a 2m x 1.5m optical table. The WOP (Warm OPtics) receives four beams - IP7/5/3/1 - through the feeding optics, coming from either Unit Telescopes (UTs) or Auxiliary Telescopes (ATs). These four beams enter first into the Beam Commuting Devices, which allow the commutation of beams IP7 and IP5 and beams IP3 and IP1. The beams are then individually anamorphosed with a ratio of 1:4 by the cylindrical optics. The beams are spectrally separated with individual dichroïcs in order to form the L&M band and the N band beams. Before entering into the cryostats, each beam passes through two modules. The first one is a periscope that is used for the co-alignment of image and pupil. The second module is a delay line that delivers the pupil plane at the correct position into the cold optics and equalizes the optical path differences between the beams and in particular the differential optical path between the L&M band and the N band.

The WOP also contains the OPD modulation function, which is part of the spectral separator. In addition, the WOP accommodates two internal optical sources in the Sources tower. One visible source for alignment purposes (a fibered laser diode) and one infrared source for calibration purposes (a ceramic with thermal insulation housing). These internal optical sources deliver four identical beams and are injected into the instrument through the SOurce Selector module (SOS). Figure 3 gives a 3D view of the WOP.

MATISSE has two separate cryostat/detector assemblies: one for the L&M band (2.8−5µm) and another one for the N band (8−13µm). The two cryostats and Cold Optics Benches for the L&M and N bands are similar.

The Cold Optics Benches are made of several modules (see Figure 3). The beam selector cartridge holds four shutters. The re-imager box supports the cold stop in the pupil plane, curved optics and the spatial filters in the image plane with its pinhole and slit slider. The beam shaper box contains the beam splitters with a slider, several folding mirrors, the

anamorphic optics and the photometric re-injection mirrors. The wheel box includes the filter wheel, the polarizing wheel and the dispersive wheel. The camera box carries the two camera lenses, a folding mirror and the detector mount.
Light enters the entrance windows of the cryostats from the upper left with an anamorphic factor of 4, passing the cold stops and the off axis optics and spatial filtering module of the re-imager unit, until it reaches the beam splitter. The light is split into the interferometric channel and the photometric channels. The anamorphism of the interferometric channel is further increased by a factor of 6, to a total of 24 by the anamorphic optics. Finally, after passing the filter, polarizer, and dipersion wheels, the light will reach the detector via the camera.
In "SiPhot" mode, five images (one interferometric fringe pattern and four photometric patterns) are produced on each detector in the L&M and N bands, as illustrated in Figure 2. In spatial direction, the interferometric field is about 468 pixels (corresponding to a field of 4λ/D) and the photometric field is about 78 pixels. The size in spectral direction depends on the spectral resolution. It varies from 100 pixels for L&M band at low resolution (150 pixels for the N band at low resolution) to the full detector for medium and high resolution.
MATISSE uses two detectors. The MATISSE L&M band detector is a *Teledyne HAWAII-2RG* of 2048 x 2048 pixels, grouped in 32 blocks of 64 x 2048 pixels. For the MATISSE N band detector, we use *the Raytheon Aquarius*, which has a format of 1024 x 1024 pixels, grouped in 2 x 32 blocks of 32 x 512 pixels.

5. STATUS OF THE PROJECT

5.1 Current situation

The different MATISSE subsystems are integrated and tested at the NOVA-ASTRON Institute in Dwingeloo, at the Max-Planck-Institut für Astronomie in Heidelberg, at the Max-Planck-Institut für Radioastronomie in Bonn, at the detector department of ESO in Garching and at the Observatoire de la Côte d'Azur in Nice.
In a first step of integration and testing, the two COBs and the detectors are integrated at Heidelberg into their cryostats. Together with the electronics these systems are tested in the cold to make them ready for the installation and the final combination with the warm optics at Nice, where the global integration and tests will take place.
The integration of the MATISSE N-band cold optics bench was completed in October 2013 and delivered from ASTRON to MPIA (see figure 4). This was a major milestone for the MATISSE project after years of concept creation, technology development, detailed design, fabrication, integration, and tests. In February 2014, the Aquarius detector was installed in the N band Cold Optics and its cryostat, and the first functional tests with the related software took place. Figure 4 shows the first fringes on the Aquarius detector. A mid-infrared laser beam was feeding three of the four MATISSE beams.
In April 2014, a first part of the electronics and of the instrument software was delivered from MPIA to OCA, where the alignment, tests, and integration of the Warm Optics are performed. The delivery of the N band Cold Optics, its cryostat, the electronics and the Aquarius detector to Nice will follow in July 2014 (see Figure 4). Eventually also the L&M band system which includes the COB, the cryostat, the Hawaii detector and the electronics, will be sent from MPIA to Nice and installed there in the OCA lab in November 2014.

5.2 Future of the project

First light on the VLTI and the subsequent start of the MATISSE Commissioning are expected for 2016. As a general user instrument, MATISSE will allow many researchers in the international community to consolidate their research, offering unique observational capabilities. It is the combination of opening new observing spectral windows at the VLTI and measurements of closure phase relations, allowing image reconstruction in the mid-infrared domain that provides the instrument its originality.
The observations of young stellar objects where planets form and evolve, of surface structures and mass loss of stars in late evolutionary stages, and, of the environments of black holes in active galactic nuclei, taking advantage of both the properties of the mid-infrared spectral domain, and, allowing the image reconstruction, will contribute to answer several fundamental questions and will lead, we hope, to some unexpected discoveries.
We hope that all future observers will enjoy using MATISSE as a new generation VLTI instrument and will take advantage of the mid-infrared domain, rarely available on other optical interferometers, to accompany or drive their research.

Figure 4. Impressions from the integration in the laboratory at the MPIA in Heidelberg (top) and OCA (bottom right). Zoom on the computer screen during the first fringe event (bottom left). Dispersion is in the vertical direction. On the left and right one can see the photometric channels. The photometric laser spots show nicely their diffraction rings. The interferometric beams interfere and produce their very first fringes, which can also be seen in the horizontal cut displayed in the lower right.

ACKNOWLEDGMENT

The instrument was made possible through funding provided by ESO, th Max Planck Society, the INSU-CNRS Agency, the NOVA Agency, the OCA Institute and the “Conseil Général des Alpes-Maritimes”, the Vienna University, the Konkoly Observatory, the Cologne University.

A warm thank you goes to all the MATISSE friends, for their deep involvement and work and also to A. Moorwood, E. Thiebaut, K. Demick, Ph. Mathias, A. Russell, J. Walsh, W. Boland, J.-M. Hameury, J. Colin, L. Pasquini, D. Mourard, A.C. da Fonte Martins, A. Roussel, Th. Parra, F. Teste.

A special thought goes to Olivier Chesneau and Alan Moorwood. Both of them left us too early. Olivier was deeply involved in MATISSE. Alan was putting a lot of efforts to have the project starting in best conditions. Our colleagues were believing in what we are doing. Their fingerprint remains present in our day to day work.

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