Perspective of Imaging in the mid-Infrared at the Very Large Telescope Interferometer

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ABSTRACT

MATISSE is a mid-infrared spectro-interferometer combining the beams of up to four Unit Telescopes or Auxiliary Telescopes of the Very Large Telescope Interferometer (VLTI) of the European Southern Observatory.
MATISSE will constitute an evolution of the two-beam interferometric instrument MIDI. New characteristics present in MATISSE will give access to the mapping and the distribution of the material, the gas and essentially the dust, in the circumstellar environments by using the mid-infrared band coverage extended to L, M and N spectral bands. The four beam combination of MATISSE provides an efficient uv-coverage: 6 visibility points are measured in one set and 4 closure phase relations which can provide aperture synthesis images in the mid-infrared spectral regime.
We give an overview of the instrument including the expected performances and a view of the Science Case. We present how the instrument would be operated. The project involves the collaborations of several agencies and institutes: the Observatoire de la Côte d'Azur of Nice and the INSU-CNRS in Paris, the Max Planck Institut für Astronomie of Heidelberg; the University of Leiden and the NOVA-ASTRON Institute of Dwingeloo, the Max Planck Institut für Radioastronomie of Bonn, the Institut für Theoretische Physik und Astrophysik of Kiel, the Vienna University and the Konkoly Observatory.

Keywords: High angular resolution, Long-baseline interferometry, Instrumentation

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1. INTRODUCTION

MATISSE is a second generation instrument of the European Southern Observatory Very Large Telescope Interferometer (VLTI), it is designed to be a mid-infrared spectro-interferometric instrument combining the beams of up to four telescopes (Unit Telescopes or Auxiliary Telescopes). This new instrument offers two major breakthroughs:

- Opening of two new observing windows at the VLTI, the L and M bands in addition to the N band,
- Measurements of closure phase relations and capability for image reconstruction in the mid-infrared domain.

No other instruments in the world will offer the same capabilities, thus placing the VLTI at the forefront of interferometry in the L, M, N mid-infrared bands.
By offering a sufficient sampling of the uv-plane and the reconstruction of model-independent images, MATISSE will allow to remove ambiguities in the model fitting and resulting interpretations and thus to consider more realistic astrophysical models. It will for the very first time allow image reconstruction of small-scale regions in the mid-infrared and will thus finally allow an investigation of these structures/regions based on an unprecedented level of constraints. MATISSE will offer various spectral resolutions currently chosen in the range of R ~ 30-1000, thus enabling measurements of visibilities, phase closures, differential phases and differential visibilities which will permit a study of wavelength-dependent characteristics of gas and dust grains and of complex geometries. MATISSE is designed to exploit fully both the sensitivity and the angular resolution potential of the VLTI. The existence of ATs which are repositionable on about 30 different stations will allow the inspection of the Fourier plane with up to 200m baseline length. Moreover the existence of the four large apertures of the VLT will permit to reach the sensitivity limits required by primary astrophysical programs like the study of formation and evolution of the planetary systems, and the study of Active Galactic Nuclei.

This article gives a general overview of the MATISSE instrument, which after its detailed design study enters now in its manufacturing phase. A view of the Science Case and the MATISSE characteristics and performances is given and different subsystems of MATISSE are presented here below. At this conference three complementary presentations were provided :

- MATISSE : concept, specifications, design and performance, Lagarde et al., this Conference [1],
- MATISSE cold optics : optomechanical design strategy, an iterative approach, N. Tromp et al., this Conf. [2],
- MATISSE selection mechanism development Jan W. Kragt et al., This Conference [3].

2. SCIENTIFIC GOALS AND MATISSE CHARACTERISTICS

2.1 Fields of research

Through the Science Case study we have mainly concentrated our attention on these two important astrophysical fields of research that we judge the most challenging for optical interferometry: the protoplanetary disks and the cores of Active Galaxies. The fields of astrophysical research which will benefit of MATISSE are of course much wider. Key science programs cover for example the birth of massive stars as well as the observation of the high-contrast environment of evolved stars.
The perspective of observations of protoplanetary disks in a spectral domain not so often used in optical interferometry and the perspective of image reconstruction will contribute to answer to a certain number of key questions like : what are the initial physical conditions in the inner astronomical unit regions of the young protoplanetary disks under which planets, and as we may expect, telluric planets, form ? And/or what are the interactions between the giant freshly formed planets with their disk and with the surrounding gas and dust ?
In order to tackle a sufficiently wide sample of sources, one of the necessary requirements is a sensitivity limit better than one Jansky. This requirement will allow observing a sample of several tens of Herbig and T Tauri sources. A second generation fringe tracker will at least double this sample and will allow an efficient use of the spectral capabilities of the instrument. In addition, it will improve the data accuracy by stabilizing the instrument transfer function. Another important requirement driven by the science case is indeed the visibility accuracy to be achieved to answer some identified important key questions. For instance, the study of dust mineralogy presenting some spectral signatures (silicates, Olivine, Forsterite, SiC, ..), in particular in the N band domain, ideally requires an accuracy of a few-percent level on the visibility or on the differential visibility to derive information down to the 10 percent level content for the crystalline material.

Important requirements are those concerning the necessary spectral resolution. Such requirements come for example from the gas lines and concern the measure of kinematic effects.
All the set of requirements defining the characteristics and motivating the performance of MATISSE are compiled in an document called the ‘Science Analysis Report’. From this document and the associated study, a certain number of desired improvements in the VLTI infrastructure is derived, together with their related specifications. This concerns in particular the second generation fringe tracker.

2.2 MATISSE and the other existing facilities

With the coming of MATISSE, ESO and our Consortium are contributing to the next generation of the mid-infrared instrumentation at the VLTI. This new generation of instrument offers a new view of our Universe and is a necessary complement to other instruments and observatories which will become available at a similar time. The MATISSE wavelength range is of strong scientific interest (see Figure 1). It is between the near-infrared domain to which instruments like AMBER are sensitive, and the sub-millimeter domain for which high angular resolution observations are foreseen with ALMA (the Atacama Large Millimeter Array). In term of instrument evolution, MATISSE can be seen as a successor of MIDI by providing imaging capabilities in the mid-infrared domain. The extension of MATISSE down to the atmospheric L and M bands as well as the generalization of the use of closure phases make it also an extension of AMBER. In terms of capability, MATISSE can be seen as a ground precursor of future interferometric space projects foreseen to be sensitive also to the mid-infrared spectral domain and aiming at characterizing high contrasted objects not easily observable from the ground level condition: exozodi disks and the atmosphere of extra-solar planets.

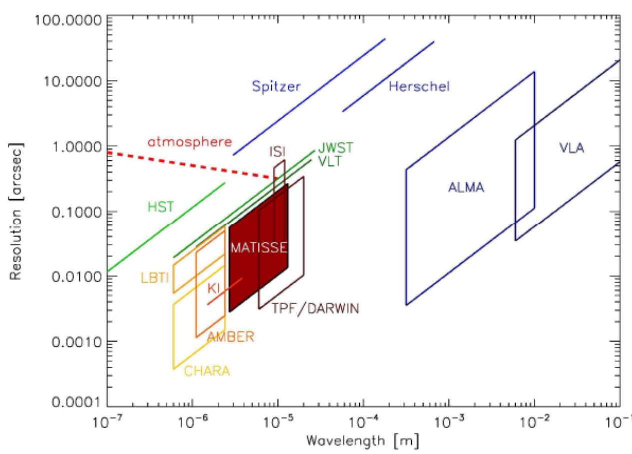

Figure 1: MATISSE in a Wavelength/Resolution diagram

With the extended wavelength coverage from the L to the N band, MATISSE will not only allow one to trace different spatial regions of the objects, but also different physical processes, and it will thus provide insights into previously unexplored areas, such as the investigation of the distribution of volatiles in addition to that of the dust.
There exist only two other 10µm ground based long-baseline interferometers, ISI 3 and Keck I. ISI 3 (the Infrared Stellar Interferometer) is equipped with three 1.6 m telescopes. This instrument allows imaging and operates in heterodyne mode compared to the direct recombination mode of the VLTI. The Keck Interferometer, on the other hand, possesses two large apertures. Its sensitivity is equivalent to that of the VLTI. However, its imaging capability is only based on the supersynthesis effect with an exploration of a limited range of spatial frequencies in the Fourier plane.
The main advantage of MATISSE over METIS, which will be an ELT mid-infrared instrument, is its significantly higher angular resolution. The sensitivity of MATISSE at the VLTI is such that a majority of key science cases can be performed with the ATs, thus achieving an angular resolution which is higher by a factor of 4 to 5 than that of METIS. MATISSE - as the successor of MIDI - will be the only ESO instrument providing this angular resolution in the mid-IR.
The imaging capability of MATISSE and the opening of L and M bands, rarely used in long baseline interferometry, will remain a breakthrough in the perspective of the E-ELT. E-ELT instrumentation, in particular METIS which will benefit of the large collecting area of the ELT, does appear as a complement to MATISSE and vice-versa. We evaluate that MATISSE will be completed approximately 10 years before METIS allowing to keep a momentum in the important research fields such as Young Stellar Objects and AGNs requiring High Angular Resolution observations.

2.3 MATISSE characteristics

The 'Phase A Science Case' study was conducted in 2006-2007. This study concluded on the interest for astrophysical research to develop a mid-infrared 4-beam instrument for the VLTI. The MATISSE project entered then in a phase of conceptual study leading to its Preliminary Design Review, PDR, in December 2011. The project is currently at the Final Design Review stage, meaning that the detailed study is completed and that the manufacturing starts.
Three high level documents defining the science case requirements, the instrument performances and the instrument specifications were produced at the PDR stage and in an updated version at the FDR stage. These documents are talking to each others because they are interdependent. The documents have driven the instrumental design study since they define the required instrumental characteristics and high level specifications.
The requirements imposed by the science cases such as the formation and evolution of the planetary systems, and the Active Galactic Nuclei, are as quoted above tackled in 'the Science Analysis Report'. More precisely these requirements have led to the definition of the desired spectral resolution, sensitivity and accuracy needed to answer a number of key astrophysical questions. 'The Performance Analysis Report' assesses the MATISSE performances considering the current VLTI characteristics and performances as a necessary input.
The high level instrument specifications are defined in the 'Instrument Specifications' and in the 'Technical Specifications' documents. These specifications drive the design study.

We remind here below the main instrument characteristics and performances.

MATISSE will have the following characteristics and performances:

a. Number of beams: four, two and three also possible.

b. Spectral coverage: L&M, N. The L and N bands can always be observed simultaneously, with two independent detector systems. The L and M can be observed simultaneously on the same detector system.

c. Spectral resolution :

   Instrument sensitivity, sampling and throughput are optimized for L and N. L band is specified from 3.2 to 3.9 μm and N band from 8.0 to 13.0 μm. MATISSE will operate also in M band, from 4.5 to 5.0 μm.

   i. Low: 20 <R<40 in L&M at 3.5 μm; 20<R<40 in N at 10.5 μm.

   ii. Medium: 350<R<550 in L&M at 3.5 μm; 150<R<250 in N at 10.5 μm.

   iii. High: 800<R<1000 in L at 3.5 μm

   The full simultaneous coverage of the L&M bands in low and medium resolutions, and the L band high spectral resolution require an external fringe tracker.

d. MATISSE will measure: visibilities, closure phases and differential phases. Differential visibilities can also be derived. These quantities will be measured as a function of the wavelength.

e. Imaging mode for field acquisition, and possibility of fringe coherencing.

f. Incoherent combination (flux measurements, non-interferometric imaging)

2.4 Observing modes

There are 2 observing modes called SiPhot for simultaneous photometry and HighSens for High sensitivity.
The "HighSens" mode has no photometry and all photons are collected in the interferometric beam. This maximizes the sensitivity and also the SNR on the differential and closure phases. Chopping is optional in this mode. The "SiPhot" mode uses photometry (2/3 of flux in the interferometric channel and 1/3 in the photometric ones) and chopping to measure the average source photometry and therefore to extract the visibility from the coherent flux (the chopping period is longer than the coherence time and hence the chopping has no influence on the limiting magnitude).

In the L band the changes of tip-tilt statistics combined with the Strehl ratio variations yield photometric fluctuations that is clearly the dominant cause for photometric imprecision and is not compatible with any correct calibration of visibilities and this imposes the SiPhot mode. The HighSens mode will be used only to boost the sensitivity limit on targets for which science observation is based on differential and closure phase measurements. Indeed, fringe detection, differential measures and closure phase are insensitive to global photometric variations. In the N band, the tip-tilt and Strehl variations will yield photometric fluctuations smaller than 2%, much smaller than the uncertainty due to the background fluctuations. Hence the HighSens mode is always usable in the N band with or without (if only phases are measured) sequential observations of photometry. However, for bright targets in N, the use of the SiPhot mode combined with chopping allows a gain in observing time since it avoids the sequential analysis of the photometry.

2.5 MATISSE specifications and performances

The specifications for MATISSE in terms of sensitivity, visibility, differential visibility, differential phase and closure phase accuracies are given in the 'Technical Specifications' document. The expected performances of MATISSE taking into account the environmental conditions, the VLTI and MATISSE characteristics, are given in the "Performance Analysis Report". The following tables give the technical specifications and the expected ultimate performances.

Table 1: L band Limiting magnitude.

L band	Technical Specifications	Estimated Performances	
Sensitivity		Without FT	With FT (DIT=300ms)
AT	7.5 Jy (L=3.95)	2.95 Jy (L=5)	0.55 Jy (L=6.8)
UT	0.75 Jy (L=6.45)	0.26 Jy (L=7.6)	0.05 Jy (L=9.5)

Table 2: L band performances. They are estimated for a 20 Jy source at low spectral resolution as it is specified in the "Technical Specifications" The observing mode is "SiPhot" which is not the most powerful mode to obtain the best accuracies on phases.

L band		Technical Specifications	Estimated Performances
20 Jy Low resolution			(without FT)
Visibility	AT	≤ 7.5 %	≤ 1.6 %
	UT	≤ 7.5 %	≤ 2.3 %
Closure	AT	≤ 80 mrad	≤ 20.3 mrad
Phase	UT	≤ 40 mrad	≤ 20 mrad
Differential	AT	≤ 3 %	≤ 0.7 %
Visibility	UT	≤ 1.5 %	≤ 0.8 %
Differential	AT	≤ 60 mrad	≤ 19.3 mrad
Phase	UT	≤ 30 mrad	≤ 22.2 mrad

Table 3: N band Limiting magnitude.

L band	Technical Specifications	Estimated Performances	
Sensitivity		Without FT	With FT (OBS=10s)
AT	60 Jy (N=-0.55)	14.6 Jy (N=1)	2.1 Jy (N=3.1)
UT	4 Jy (N=2.4)	0.9 Jy (N=4)	0.12 Jy (N=6.25)

Table 4: N band performances. They are estimated for a 20 Jy source at low spectral resolution as it is specified in the "Technical Specifications" The observing mode is "SiPhot" which is not the most powerful mode to obtain the best accuracies on phases.

N band		Technical Specifications	Estimated Performances
20 Jy Low resolution			(without FT)
Visibility	AT	≤ 30 %	≤ 8.6 %
	UT	≤ 7.5 %	≤ 2.8 %
Closure	AT	≤ 80 mrad	≤ 28.2 mrad
Phase	UT	≤ 40 mrad	≤ 13.6 mrad
Differential	AT	≤ 30 %	≤ 8.4 %
Visibility	UT	≤ 5 %	≤ 1.5 %
Differential	AT	≤ 60 mrad	≤ 26.1 mrad
Phase	UT	≤ 30 mrad	≤ 24.9 mrad

In order to push the MATISSE performances in terms of sensitivity and accuracy, some important desired equipments on the VLTI infrastructure are identified. These equipments are the Fringe Tracking, the lateral pupil motion monitoring and the collection of data such as the OPD residuals from the fringe tracker, the tip-tilt residuals and the data from the pupil lateral motion monitoring.

3. IMAGE RECONSTRUCTION

The primary goal of MATISSE is the image reconstruction from UTs or ATs. The comparison between models and visibility points, and closure and differential phases in the Fourier plane is considered also as an important approach for the data interpretation.

There were two documents : the MATISSE Phase A Science Case (VLT-TRE-MAT615860-4325) and in particular the MATISSE Phase A Science Software design (VLT-TRE-MAT-15864-4333), which describe different situations for the image reconstruction. In these documents, 3-4 telescope configurations on 3-4 nights were considered. Our more recent work on image reconstruction with the necessary detailed explanations is presented in the Data Reduction Library Specifications document and in the Science Analysis Report (VLT-TRE-MAT-15860-9008). We refer to all these documents for discussing the operational requirements.

In the example below, which was also presented in the MATISSE Phase A Science Software Design (VLT-TRE-MAT-15864-4333), the long North-South baseline provides a better resolution in y compared to x. The reconstruction presented is obtained from the science case target ”YSO plus planet”. The uv coverage of the experiment corresponds to: DEC = -30°, 3×4ATs: B5-D0-G1-J3, A1-B5-D1-K0, A0-G2-I1-J6); intensity ratio between star and planet: 200/1.

A more recent work on image reconstruction with the necessary detailed explanations is presented in the Data Reduction Library Specifications document and in the Science Analysis Report (VLT-TRE-MAT-15860-9008).

In the Science Analysis Report, we were interested by over passing the incompleteness of the uv plane. This incompleteness is identified as the current major limitation affecting the image quality. In order to understand and check the effect on the reconstructed image of a good data quality set in terms of accuracy on visibilities and closure phases :
- the best possible MATISSE accuracies were assumed,
- a 7 night/configuration observation in order to not be dominated by an uncomplete uv coverage.

This simulation has shown that : a) as expected, a large number of uv points are indeed of importance for high-fidelity image reconstruction, b) the use of 7 configurations put us in the regime where the quality of image reconstruction is driven by the accuracy of the data. Thus, adding new possible configurations and use several of them (>3) depending of the science objective seems inescapable.

The operation requirement would be :

- 3-4 configurations provide an image quality driven by the incompleteness of the Fourier plane coverage,
- 7 configurations provide an image reconstruction quality driven by the accuracy of the visibilities and closure phases.

It is interesting to note also that the astrophysical objects like the protoplanetary disks, when observed at spatial scale less than one astronomical unit, tend to show temporal variations on the month time scale. Evolved class stars and binary class objects show also monthly scale variabilities.
Such results presenting temporal variability in the visibilities of protoplanetary disks are not yet widely diffused through publications but they were presented at the Conference '10 years of the VLTI' held in Garching ESO in September 2011.
We expect that a major science return of MATISSE will concern, for several classes of objects, the time variability of the stellar and circumstellar structures. Images reconstruction based on a set of data collected within one month should be foreseen.

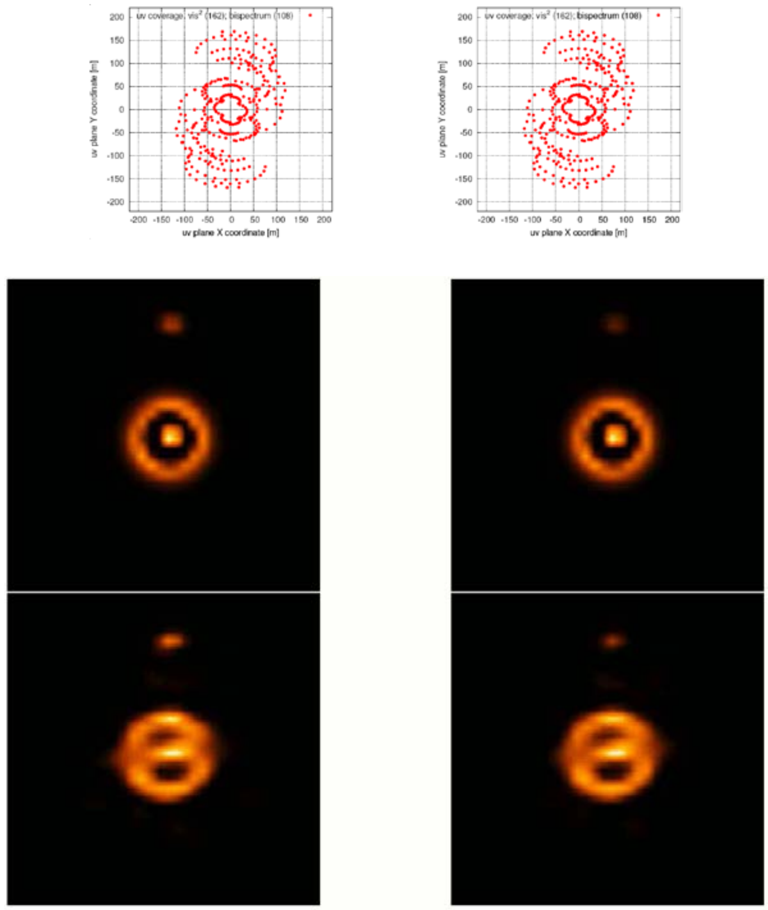

Figure 2: Reconstructed N band images (3x4ATs; ~150 m) of a protoplanetary disk with an embedded bright planet. Left: Brighter planet: intensity ratio star/planet=100/1; Right: Fainter planet: intensity ratio star / planet=200/1. First row: uv coverages. Second and third row: originals and reconstructions, respectively. The images are not convolved (2_super resolution). Simulation parameter: modeled YSO with planet (declination -30_; observing wavelength 9.5 µm; FOV =104 mas; 1000 simulated interferograms per snapshot considering photon and 10 µm sky background noise; average SNR of visibilities: 20). See Doc. 'MATISSE Phase A Science Software Design, VLT-TRE-MAT-15864-4333' for details.

4. CONCEPT AND SIGNAL

4.1 Concept

MATISSE is a four-beam experiment with a multi-axial global combination (Figure 3). It means that the four beams are combined simultaneously at the detector level. The signal is dispersed with different spectral resolutions. The interferometric image contains 6 dispersed fringe patterns encoded with different frequencies. There are two different cryostat+detector assemblies: one for the L&M band (2.8-5µm) and one for the N band (8-13µm). The design of MATISSE is based on the use of spatial filters, including image and pupil stops.

To measure the coherent fluxes and all the derived interferometric measures such as the differential visibility and phase and the closure phase, the key problem is to eliminate the cross talks between the low frequency peak and all other peaks that introduce sensitivity of the fringe peaks to variations of the thermal background. Two methods are used in MATISSE to ensure this result with a large margin: a spatial modulation like in AMBER combined with a temporal modulation like in MIDI.

In order to measure closure and differential phases with a good accuracy, a beam commutation can be made in order to reduce the effect of the instrumental defects.

In addition, a beam splitting can be used in order to monitor the photometry. To measure the absolute visibility we have also to find the true source photometry, which needs separating the stellar flux from the sky background, using chopping.

Some devices such as artificial sources, hot screen, lenses for flat field or pupil visualization, special material for spectral calibration are implemented in the instrument in order to perform alignment, test, maintenance, calibration and acquisition operations.

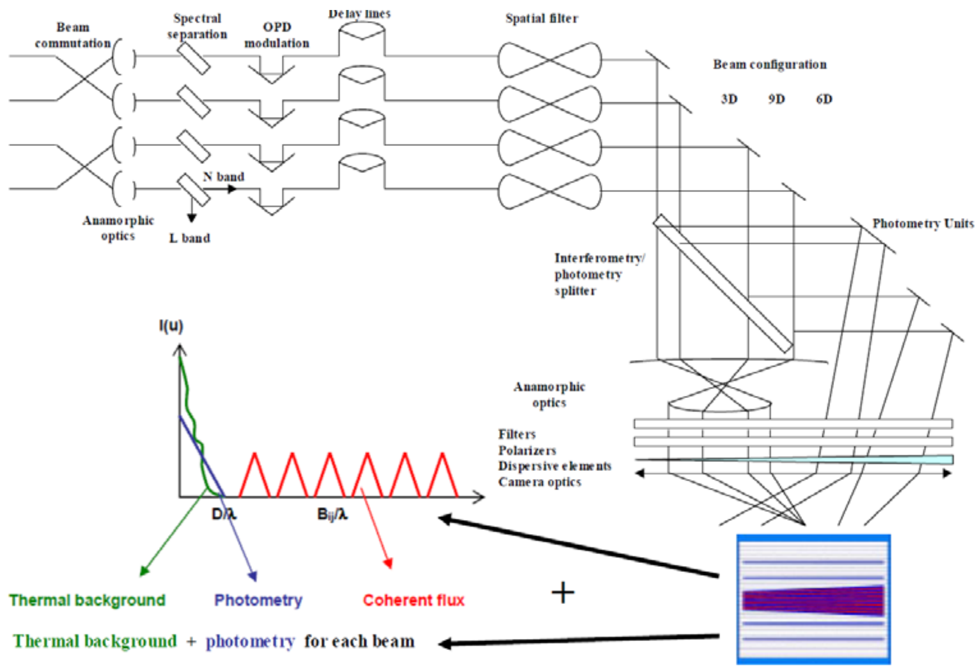

Figure 3: MATISSE concept.

4.2 Signal

The interferometric beam and the photometric beams receive respectively 2/3 and 1/3 of the incoming flux (SiPhot mode). It leads to have 5 images (4 photometric channel and the interferometric one) on the detector (Figure 3).
During observations with 4 telescopes, the interferogram contains 6 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 (anamorphic factor of 24). The spatial sampling of the photometric channel is 12 pixels per λ/D with the same spectral sampling than the interferometric one.
The beam combination is made by the camera optics. The beam configuration is non redundant (separation B between beams equal to 3D, 9D and 6D where D is the spatial diameter of the beam) in order to avoid crosstalk between fringe peaks in the Fourier space. In the spatial direction, the sampling of the narrowest fringes is 4 pixels; the sampling of the widest fringes is 24 pixels at the lowest wavelength.
The Fourier transform of each spectral column of the interferometric image is thus composed by 6 fringes peaks at different frequencies Bij/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 4 telescopes. Assuming a detector window of 4λ/D, we have a frequency step f_0=D/4λ and hence 8 frequency points per fringe peak.

The equation of the Fourier transform of the interferometric channel is:

$$I(u) = M_b(u).\sum_{i=1}^{4} n^I{}_{bi} + M(u).\sum_{i=1}^{4} n^I{}_i + \sum_{i=1}^{4}\sum_{\substack{j=2\\ j>i}}^{4} M(u-u_{ij}).\sqrt{n^I{}_i.n^I{}_j}\,V_{ij} \qquad (1)$$

The equation of the Fourier transform of each photometric channel is:

$$P_i(u) = [M_b(u).n^P{}_{bi} + M(u).n^P{}_i] \qquad (2)$$

i and j are the index of beams. $n^I{}_{bi}$ and $n^I{}_{bj}$ are the numbers of photons produced by the thermal background for each beam in the interferometric channel. $n^P{}_{bi}$ and $n^P{}_{bj}$ are the numbers of photons produced by the thermal background for each beam in the photometric channels. $n^I{}_i$ and $n^I{}_j$ are the numbers of photons produced by the observed object for each beam in the interferometric channel. $n^P{}_i$ and $n^P{}_j$ are the numbers of photons produced by the observed object for each beam in the photometric channels. V_{ij} is the complex visibility.
$M_b(u)$ is the background function in the Fourier space, $M(u)$ is the low frequency peak of the interferometer transfer function, $M(u-u_{ij})$ is the fringe peak of the interferometer transfer function at the spatial frequency u_{ij} ($u_{ij} = B_{ij}/\lambda$ where B_{ij} is the separation between the beams). $M(0)=M_b(0)=1$.
During an observation on the sky only, using the chopping for example, only the thermal background photons are recorded on the detector and the equation of the Fourier transform of the interferometric channel becomes:

$$I_S(u) = M_b(u).\sum_{i=1}^{4} n^I{}_{bi} \qquad (3)$$

The equation of the Fourier transform of each photometric channel becomes:

$$S_i(u) = M_b(u).n^P{}_{bi} \qquad (4)$$

To eliminate the cross talks between the low frequency peak and all other peaks we have to consider integration and background variation over duration of the calibration cycle. Two methods are used in MATISSE: spatial modulation like in AMBER combined with temporal modulation like in MIDI. The performances of these methods are exposed in the Performance Analysis Report and in Lagarde et al. [1].
In addition, to measure the absolute visibility we have also to find the true source photometry, which needs separating the stellar flux from the sky background, using chopping. Chopping is the only way in MATISSE to extract the source photometry from the background level using the photometric beams. Chopping is not necessary for measuring coherent flux, differential phase and closure phase.

5. HARDWARE DESIGN

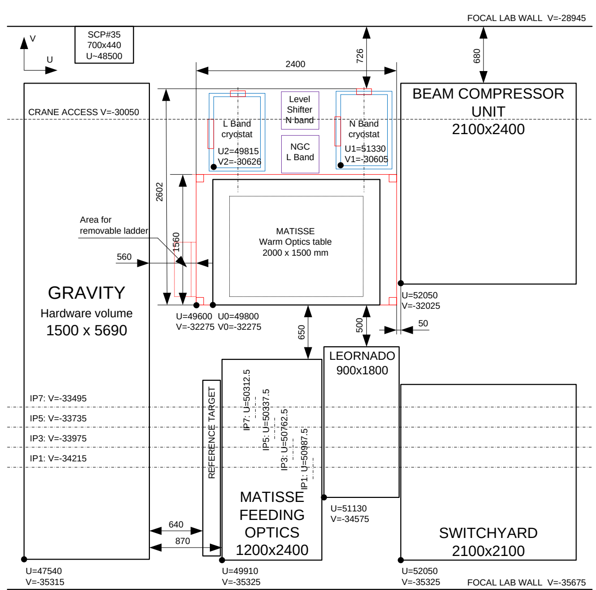

Figure 4: MATISSE, its Warm optics and the two cryostats housing the Colds Optics in the VLT interferometric laboratory.

MATISSE instrument is composed of:

- the Warm Optics
- the two Cold Optics benches housed in two cryostats.

For the N band, MATISSE will use the Raytheon Aquarius detector and, for the LM band, the Teledyne HAWAII-2RG detector. The implementation of the instrument in the VLT interferometric laboratory is illustrated in Figure 4.

5.1 The Warm Optics

The WOP (Warm Optics) receives four beams (thanks to feeding optics) coming from either Unit Telescopes (UTs) or Auxiliary Telescopes (ATs). These four beams enter first into the Beam Commuting Devices (commuting of beams IP7 and IP 5 and commuting of beams IP3 and IP1).
Then the beams are individually anamorphosed with a ratio 1:4 thanks to cylindrical optics.
The beams are then 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 which is used for the co-alignment (image and pupil),
- the second one is a delay line which will deliver the pupil plane at the correct position into the cold optics and will equalize the optical path differences between the beams and in particular the differential optical path between the L&M band and the N band.

In addition, the warm optics contains the OPD modulation function and contains the internal optical sources (one visible for alignment, one IR for calibration purpose). These internal optical sources deliver four identical beams and are injected into the instrument thanks to Source Selector module. The warm optics rests on a 2m x 1.5m optical table.

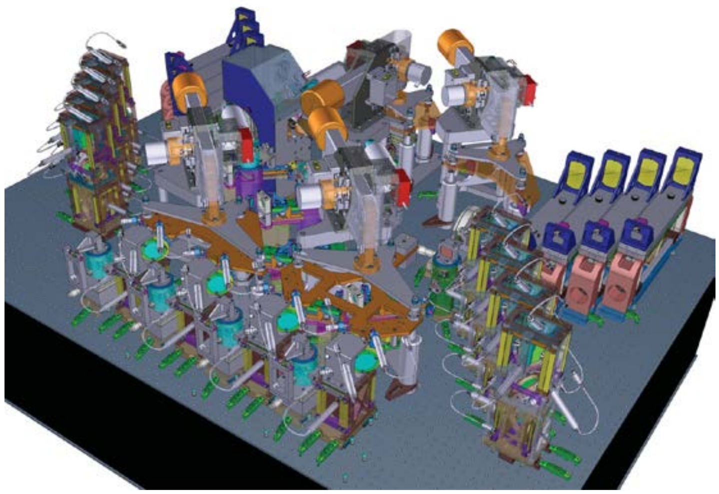

Figure 5: The Warm Optics and its modules on the optical table.

In the Figure 5 you can identify:

- On the right side and at the bottom, the four delay lines for the L&M band. On the opposite side you have the ones for the N band.
- On the right side and in the foreground we can see the four periscopes for the L&M band. On the oppsotie side you have the ones for the N band.
- In the foreground and in the middle we can see the fixed part of the BCDs and behind its movable part.
- At the bottom part of the figure in the middle we can see the two SOS modules which are similar to the BCD.
- At the bottom and on the left side we can see a tower supporting the optical sources (one side is in blue).

5.2 The Cold Optics

The two cryostats L&M and N bands are similar. The Figure 6 gives a view of the layout of the cold optics. Only the recombination of the 4 beams through the camera onto the detector is represented in this view. This recombination produces the so-called interferometric channel.
Light enters the entrance windows of the cryostat from the upper left with an anamorphic factor of 4, passing the cold stops and the off axis optics and spatial filtering module (slit) of the re-imager unit until it reaches the beamsplitter. The light is split into the interferometric channels and the photometric channels. The anamorphism of the interferometric channels is further increased with a factor 6, to a total of 24 by the anamorphic optics. Finally after passing the filter, polarizer and dipersion wheels light will reach the detector via the camera.

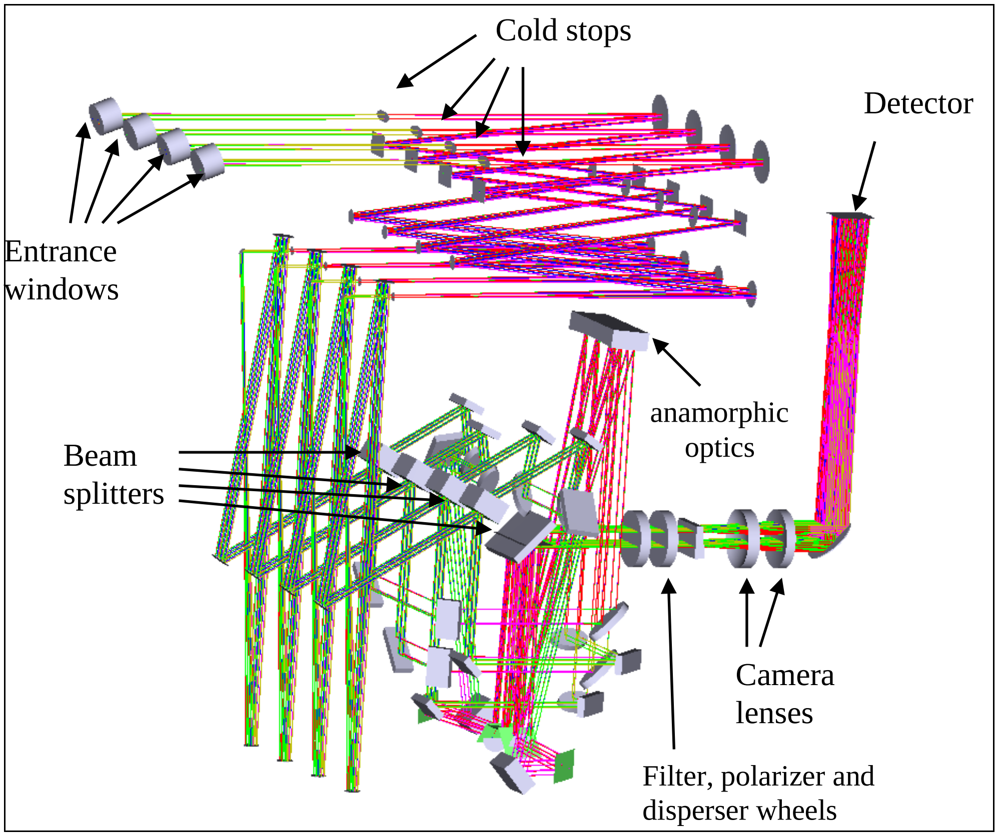

Figure 6: Layout of the interferometric light path

5.3 The Cryostats

The Figure 7 shows the cryostat completely assembled with its components and the interior of the cryostat.

The operating temperature of the cold optics is 40°K.
The operating temperature of the N band detector is 6 - 10°K.
The operating temperature of the L&M band detector is 40°K.
The vacuum (<1*10-5 mbar) is realized by a turbomolecular pump fixed on the top of the cryostat.
The operating temperatures are realized thanks to Pulse Tube Cooler fixed on the top of the cryostat. The Pulse Tube Cooler has two stages:

- the first stage cools down the cold optics,
- the second stage cools down the detector.

At the bottom of the cryostat a LN2 vessel cools down the radiation shield.

5.4 The detectors

In “SiPhot” mode, 5 images (1 interferometric image with 6 dispersed fringe patterns and 4 photometric images) are produced on each detector as it is shown on Figure 8. In spatial direction, the size of the interferometric is about 468 pixels (corresponding to field of 4λ/D) and the photometric channels one is about 78 pixels. The size in the spectral direction depends of course of the spectral resolution. It varies from 100 pixels for LM band at low resolution (150 pixels for the N band at low resolution) to the full detector for the medium and high resolution.

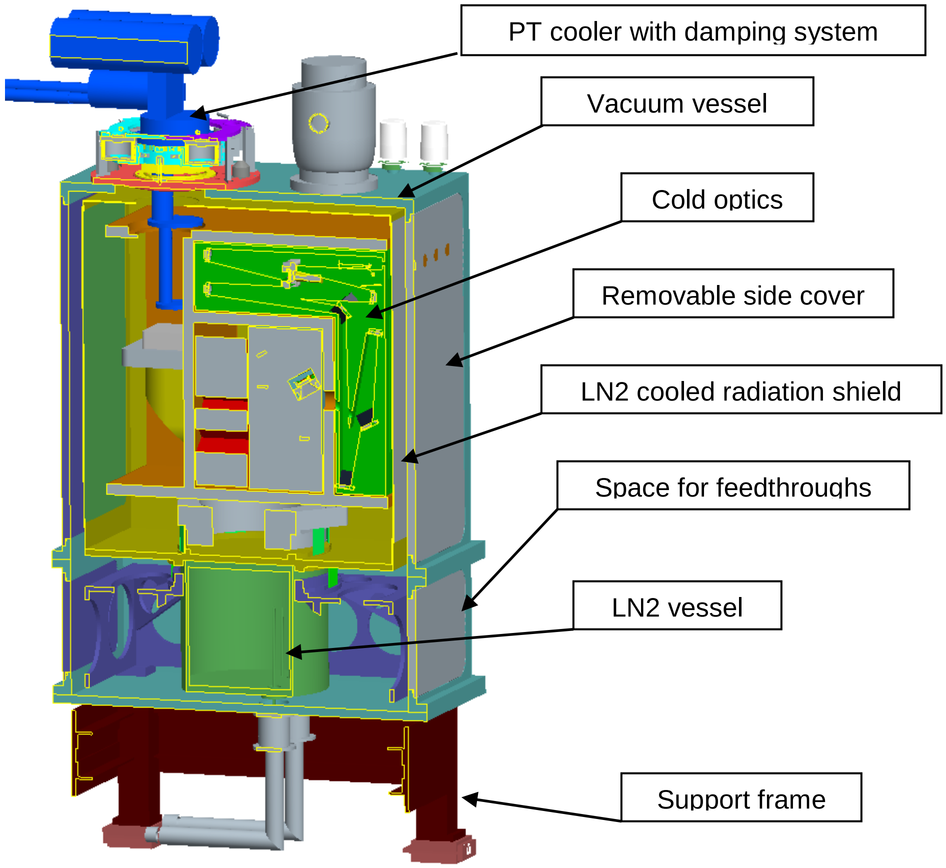

Figure 7: cross section through one MATISSE cryostat

The MATISSE L&M band detector will be a **Teledyne HAWAII-2RG FPA**. The basic specifications are:

Format:	2048 x 2048 pixels, grouped in 32 blocks of 64 x 2048 pixels
Pixel size:	18 µm
Q.E.:	> 60 % in L band
Full well capacity:	100,000 e^-
Readout noise:	<10 e^- CDS @ 100 kHz, ≥70 e^- @ 1 MHz
Number of outputs:	32 analog outputs
Operating temp.:	< 40 K
Power dissipation:	80 mW slow outputs, 150 mW fast outputs

For the MATISSE N band detector we will use the **Raytheon Aquarius FPA**. The detector basic specifications are:

Format:	1024 x 1024 pixels, grouped in 2 x 32 blocks of 32 x 512 pixels
Pixel size:	30 µm
Number of outputs:	64 analog outputs
Selectable gain:	low gain for high flux, high gain for low RON
QE:	> 50 % from 7 to 25 µm
Frame rate:	max. 150 /s
Data rate:	1 MHz (max. 3 MHz) pixel clock
Read noise @ 1 MHz CDS:	low gain: 1000 e^- / high gain: 300 e^-, goal is 100 e^-
Well capacity:	low gain: $0.6{\cdot}10^7$ e^- / high gain: $0.6{\cdot}10^6$ e^-
Operating temperature:	8 – 10 K
Power dissipation:	100 mW (64 output mode)

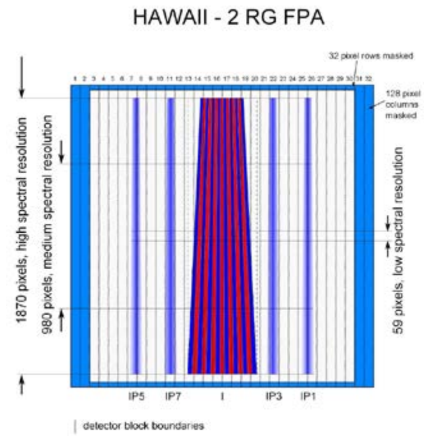

Figure 8: Interferometric and photometric beam configuration of the L band for R=500, and R=950.

6. SOFTWARE DESIGN

6.1 Instrument software

The diagram on Figure 9 shows the architecture of the instrument software and the data flow between its components**.** The software architecture is described in the 'Instrument Software Functional Specification' document. In the case of MATISSE, 4 devices could be synchronized: the OPD modulation, the chopping device and the 2 detector readings.

A typical day and night of observations with MATISSE will consist in the following sequence:

- **During daytime**

The frequency of the following actions will depend on the tests made during MAIT. Some of actions could be performed only at the beginning of an observing run and not before each MATISSE observing night.

Maintenance activities:

- Check of the detector remanence:

This detector characterization measures the remanence of both detectors. The procedure consists to a continuous frame acquisition with a sequence of all shutters (BSL, BSN) closed, all shutter opened, all shutters closed.

- Check of the MATISSE alignment and co-alignment:

This template allows the check of the instrument alignment. This check is made using the internal source and the instrument in image mode (without dispersion) to control the angular alignment then in pupil mode (visualization of the pupils) to control the lateral beam positioning alignment. This template will be performed in two modes:

- *Control Mode*: In this mode, the template checks the positions of images and pupils for each beam. No action on motors is made even if a misalignment is detected.
- *Correction Mode*: In this mode, the template compensates a possible misalignment by acting on dedicated motors (CUL, CUN).

- Check of the MATISSE co-phasing:

This template allows the check of the instrument phasing. This check is made using the internal sources and the instrument in fringe dispersed mode to control the internal OPD. This template will be performed in two modes:

- *Control Mode*: In this mode, the template checks the OPD for each baseline. No action on motors is made even if the OPD is not correct.
- *Correction Mode*: In this mode, the template compensates possible OPDs by acting on dedicated motors.

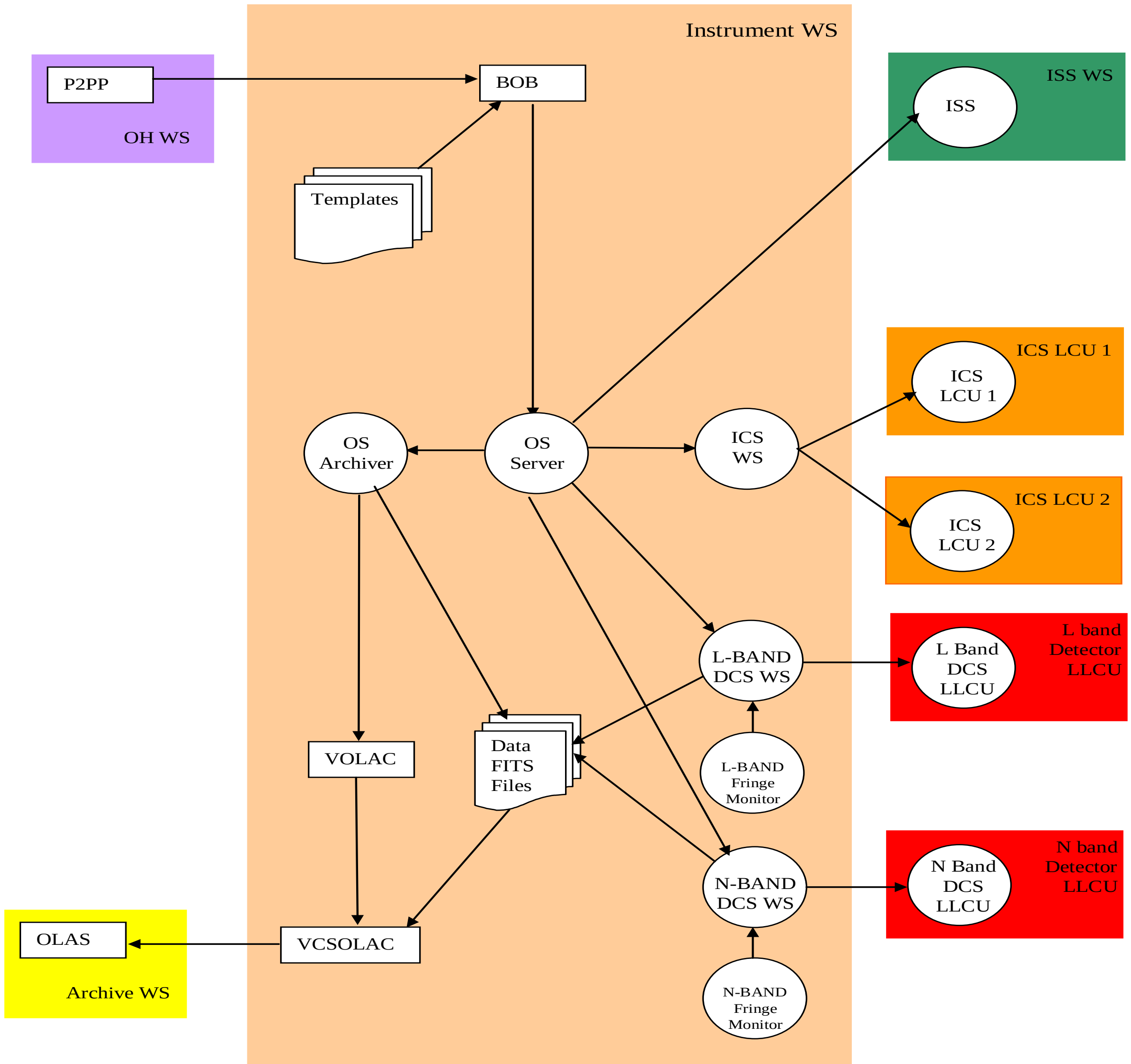

Figure 9: Software architecture

Calibration activities:

- Detector checks, bias and flat measurements:

This template measures the characteristics of the L and N detectors: gain table, bad pixel map, bias by performing flat-fields and darks for different DIT values.

- Checks of wavelengths calibration and distortion:

This template consists in recording sequentially images of 3 pinholes (located at 3 different positions in the field) and monitoring the spectral features of the plastic foils in order to estimate the distortion map of both detectors, derive the dispersive laws and measure a possible spectral shift.

- Kappa Matrix measurements with internal sources:

By using the internal source, this template provides a “laboratory” measurement of the flux ratio between the beams, the so-called Kappa Matrix. The template performs measurements of the flux coming from one beam by sequentially opening one shutter.

- **During an observing night**

For each source:

- Source acquisition: The goal of this template is to guarantee an optimum injection of the light into MATISSE up to the detector. This template consists in:
    - VLTI preset and acquisition: Preset telescope and delay lines, telescope acquisition, MACAO setup, IRIS pupil and image acquisition …
    - Optional pupil check (for the first object of the night) with MATISSE in pupil visualization mode. If check failed, corrections by sending command (lateral shift) to VLTI.
    - 2D image acquisition with MATISSE in 2D imaging mode (no dispersion and large diaphragm) in one band. If check failed, corrections by command (tip/tilt offset) to VLT.
        - In “SiPhot” mode with faint object or in “HighSens” mode, the acquisition is made sequentially in the interferometric channel by closing the shutters one by one.
        - In “SiPhot” mode with bright object, the acquisition is made simultaneously for the 4 beams in the photometric channels.
    - Verification of the image acquisition in the other band. If necessary, (for example, for object far from the zenith): tip/tilt adjustment with the internal periscope.
    - Instrument Setup (depending of the mode –“HighSens” or “SiPhot” –, the spectral resolution, the number of telescope and the filters chosen by the observer)
- Kappa Matrix measurements with sky sources:

This template provides a “sky” measurement of the flux ratio between the beams, the so-called Kappa Matrix. The template performs measurements of the flux coming from one beam by sequentially opening one shutter.

- Fringe search and optimization:

The goal of this template is to detect the fringes for each of the baselines. Consequently, the fringes search is performed in parallel for each baseline by moving the VLTI delay lines.

- Fringe record:

Two modes are foreseen for the MATISSE observations the HighSens and the SiPhot mode”. For the “HighSens” mode, an optional photometric measurement can be made after the interferometric observation, by using sequentially the cold shutters and chopping as it is made for MIDI. This operation is used for very faint objects.
In parallel L (or N) band coherencing: a corrective action of the VLTI delay lines can be given by MATISSE every 1-10 seconds when MATISSE is used without external fringe tracker.

6.2 Data reduction software

The data analysis of MATISSE is divided in two main parts:

- A) General data reduction process leading to the estimations of the interferometric signals through the measurements of the squared visibility, phase closure, differential phase and differential visibility,
- B) Image reconstruction process that could take place when the uv plane is covered by a sufficient number of measurements taken with different baseline lengths and orientations.

Calibration measurements during operation: a typical MATISSE Observation is accompanied by a set of calibration frames that may be taken directly before or after the science exposure or during daytime. Calibration frames represents all the frames characterizing the instrumental and sky signatures. The following Calibration files are created:

- The detector calibration maps: the flat field map, the dark and the bad pixel map derived from specialized frames.
- The k-matrix. The k-matrix is generated beam per beam by shuttering 3 of the 4 input beams. The matrix represents, for each spectral channel, the product of the instrument transmission by the detector pixel response.
- The background maps aiming at sky subtraction (including instrumental and sky background). A chopping cycle between the object and the sky is performed. The thermal background can be measured/mapped. Subtraction of the sky measurements to the on-source measurements allows the extraction of the source photometric signal.

7. CONCLUSION

The first light of MATISSE is expected beginning of 2016.

The second generation fringe tracker of ESO is on strong importance for allowing the full use of the MATISSE potential: sensitivity, accuracy and spectroscopic capability.

We hope that all the future observers will enjoy using this new generation instrument and will take advantage of the mid-infrared domain, not so often used in optical interferometry, for accompanying or driving their research.

A warm thank goes to all the MATISSE friends and to the ESO colleagues, for the involvement and work of everyone.

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