Publ. Astron. Obs. Belgrade No. 91 (2012), 129 - 139 *Invited lecture*

PERSPECTIVE OF THE INTERFEROMETRIC MATISSE INSTRUMENT AT THE VLTI

B. LOPEZ

UMR Lagrange 7239, UNS, CNRS, OCA, BP 4229, 06304 Nice Cedex 4, France
E–mail: lopez@oca.eu

Abstract. MATISSE is a mid-infrared interferometric instrument that will operate at the VLTI in 2016 as one of the second generation instruments. One of the science case is to contribute to a better understanding of the conditions under which the planets form and evolve. Our approach consists in investigating through observation, theory and modeling the physics of proto-planetary disks by taking advantage of this new scheduled observing tool : MATISSE, that we are developing and have optimized for this scientific objective. Despite the recent advances in the observations of protoplanetary disks and in their interpretation, open questions remain in relation with the physical initial conditions giving birth to planets. The current infrared interferometers MIDI and AMBER are already used for such observations, and soon the improved spectral and imaging capabilities of the future MATISSE instrument will provide a new insight on the disc inner regions, revealing information and details about for instance the fine structures predicted by models in disks and in their inner regions (shape and size of the inner rim, curvature of the inner rim, truncature of the disk). I will present, the principle, the expected performances and the status of the MATISSE project and will give some illustrations of what kind of astrophysics is expected to be achieved.

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 $\sim$ 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.

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.

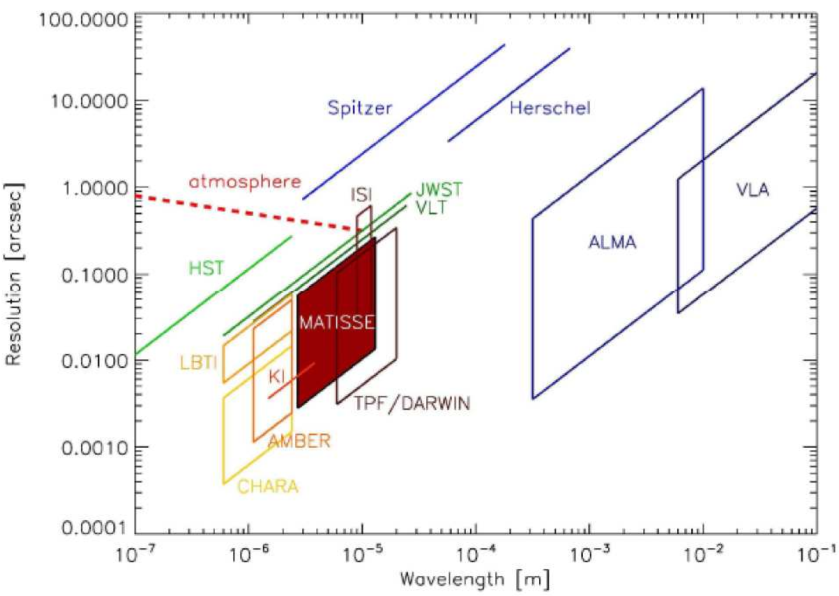

Figure 1: MATISSE in a Wavelength/Resolution diagram.

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

Table 3: N band Limiting magnitude.

L band Sensitivity	Technical Specifications	Estimated Performances Without FT	Estimated Performances 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 20 Jy Low resolution		Technical Specifications	Estimated Performances (without FT)
Visibility	AT	≤ 30 %	≤ 8.6 %
	UT	≤ 7.5 %	≤ 2.8 %
Closure Phase	AT	≤ 80 mrad	≤ 28.2 mrad
	UT	≤ 40 mrad	≤ 13.6 mrad
Differential Visibility	AT	≤ 30 %	≤ 8.4 %
	UT	≤ 5 %	≤ 1.5 %
Differential Phase	AT	≤ 60 mrad	≤ 26.1 mrad
	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^o, 3x4ATs: 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.

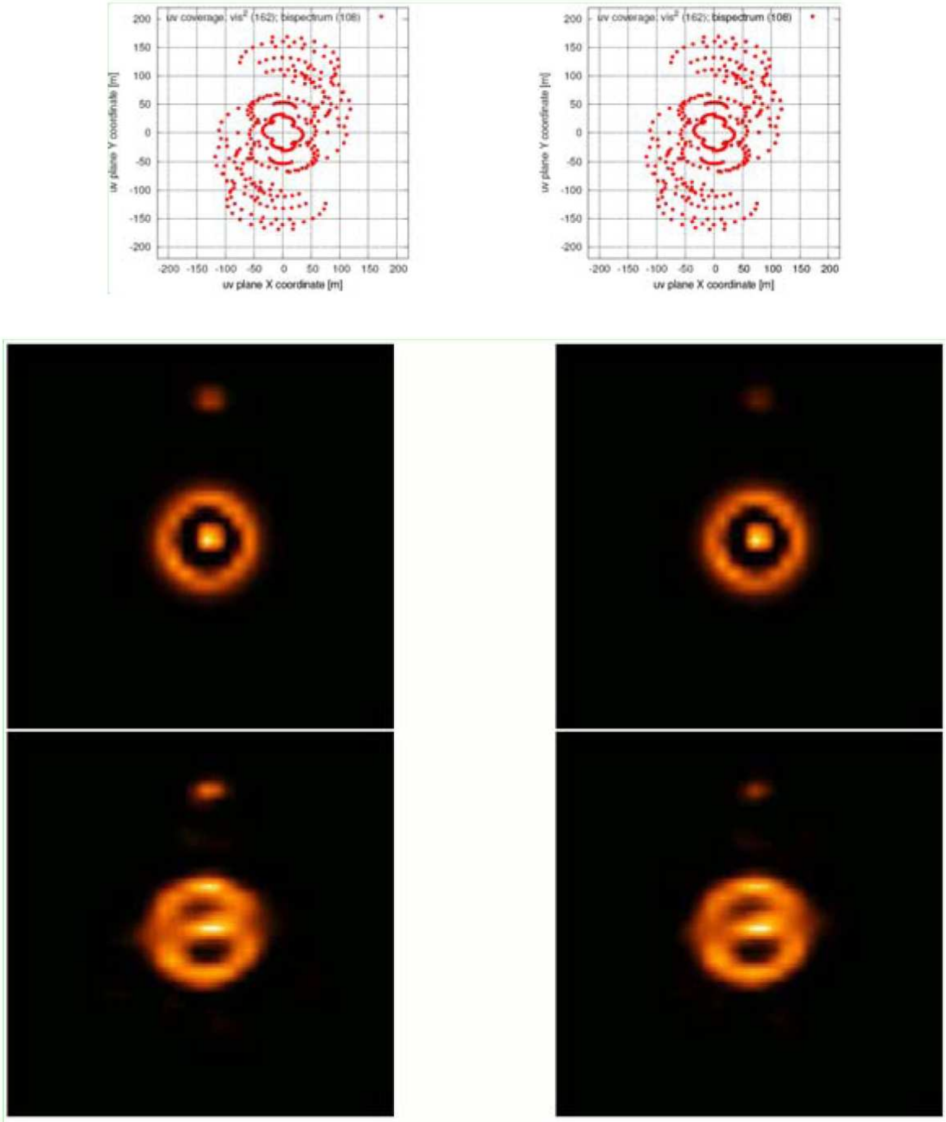

Figure 2: Reconstructed N band images (3x4ATs; 150 m) of a protoplanetary disk with an embedded bright planet. Left: Brighter planet: intensity ratio star/planet = 100/1; Right: Fainter planet: intensity ratio star / planet=200/1. First row: uv coverages. Second and third row: originals and reconstructions, respectively. The images are not convolved (super resolution). Simulation parameter: modeled YSO with planet (declination -30^{o}; 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.

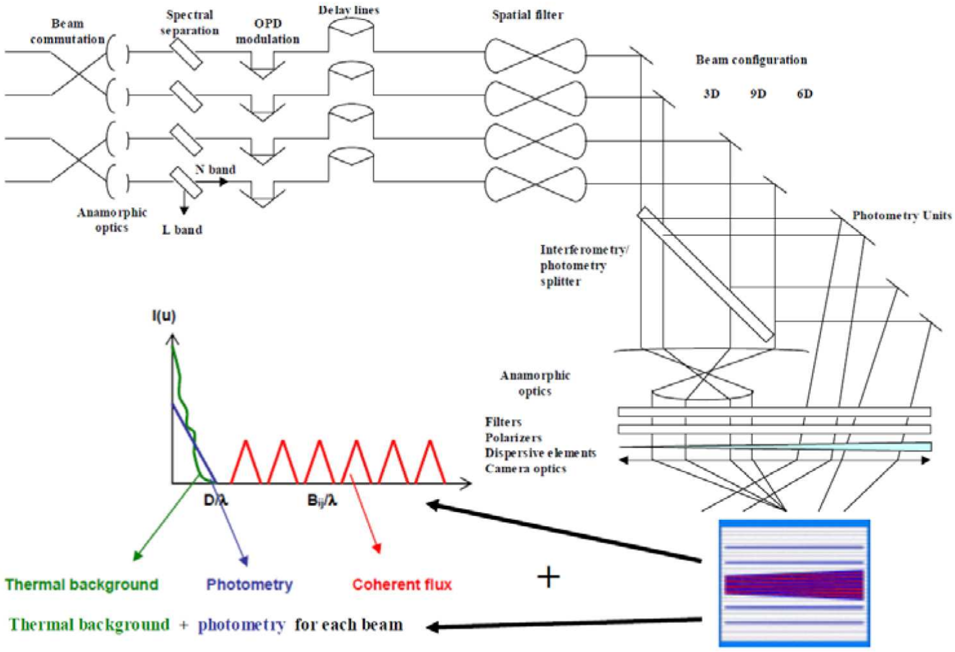

Figure 3: MATISSE concept.

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.

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.

$$I\left(u\right) = M_b\left(u\right).\sum_{i=1}^{4} n_{bi}^{I} + M\left(u\right).\sum_{i=1}^{4} n_i^{I} + \sum_{i=1}^{4} \sum_{\substack{j=2 \\ j>i}}^{4} M\left(u-u_{ij}\right).\sqrt{n_i^I.n_j^I}V_{ij} \quad (1)$$

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

$$P_i(u) = M_b(u)n_{bi}^P + M(u)n_i^P \quad (2)$$

i and j are the index of beams, n_{bi}^I and n_{bj}^I are the numbers of photons produced by the thermal background for each beam in the interferometric channel. n_{bi}^P and n_{bj}^P are the numbers of photons produced by the thermal background for each beam in the photometric channels. n_i^I and n_j^I are the numbers of photons produced by the observed object for each beam in the interferometric channel. n_i^P and n_j^P 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:

$$I_S(u) = M_b(u)\sum_{i=1}^{4} n_{bi}^I \quad (3)$$

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

$$S_i(u) = M_b(u)n_{bi}^P \quad (4)$$

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. 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. 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.

Bibliography

Lopez, B., Lagarde, S., Antonelli, P., Jaffe, W., Petrov, R., Venema, L., Robbe-Dubois, Sylvie, et al.: 2012, "Perspective of imaging in the mid-infrared at the Very Large Telescope Interferometer," *Proc. SPIE*, **8445**, 0RL.