Jean-Marie Mariotti Center for Interferometry

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ABSTRACT

The Jean-Marie Mariotti Center is a network of 11 French Institutes, Laboratories or Observatories, appointed by CNRS in 2000. It coordinates the efforts of the member institutes to offer all the potential users of interferometric facilities the best operational environment, providing software, academic formation and stimulating the prospective on new interferometric developments. At present, besides academic formation, the major effort is focused on the development of the software to prepare the observations, to reduce the data and tointerpret the results in terms of models or reconstructed images. In this contribution, we describe the achievements and the future plans of the Mariotti Center.

Keywords: Astronomical Interferometry – High angular resolution – Software – Signal Processing – Modeling – Image Reconstruction

1. INTRODUCTION

Since the 90's, the French interferometric community has promoted the creation of an interferometric center. In September 2000, the Jean-Marie Mariotti Center (JMMC, also known as Mariotti Center) was formally appointed by the French CNRS ("Centre National de la Recherche Scientifique"). The JMMC is a network of 11 French Institutes, Laboratories or Observatories which have interferometric expertise:

— Département d'Astrophysique (Université de Nice-Sophia Antipolis, UNSA)
— Département Fresnel (Observatoire de la Côte d'Azur, OCA)
— IAS (Institut d'Astrophysique Spatiale, Orsay)
— LAOG (Laboratoire d'Astrophysique de Grenoble)
— LAT (Observatoire de Midi-Pyrénées, Toulouse)
— LESIA (Observatoire de Paris-Meudon)
— LISE (Observatoire de Haute Provence)
— IRCOM (Université de Limoges)
— Observatoire de Bordeaux
— Observatoire de Lyon
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The Mariotti Center is meant to be a delocalized laboratory, formed by a network of experts and provided with a Center of Coordination located at the Laboratoire d'Astrophysique de Grenoble. It coordinates the efforts of the member institutes to offer all the potential users of interferometric facilities the best operational environment. The mission of the JMMC is threefold and consists on:

- to develop, produce, document and maintain the software necessary for the exploitation and the follow-up of new interferometric equipments, especially the VLTI;
- to stimulate and coordinate the academic formation of non specialists;
- to participate to the prospective around new interferometric instruments.

The main activity of the Mariotti Center, besides prospective and training, is software oriented system analysis and software development. These are meant to be a structural part of the instrument and, ideally, conceived right from the beginning of the instrument development. At present, the JMMC is formed by 25 researchers, who operate in working groups and via actions of formation (equivalent to 4 researchers full time), 5 PhD students and 2 engineers.

2. WHY A CENTER FOR INTERFEROMETRY?

An historical review will help to answer this question. Modern interferometry in the optical domain was born in France in the 70's[1]. However, two decades have been necessary for it to become perceived as a major observational technique by the astrophysical community. Besides the experimental complexity and the novelty of the technique for the optical community, this was likely due to the difficulty of controlling and hence of calibrating the signal, giving the impression of a not much reliable technique. The situation has radically changed in the last decade, thanks to two reasons: 1. the better reliability of adaptative optics techniques has allowed to concentrate a large part of the flux within the Airy disc and hence to boost upwards the limiting magnitudes of optical interferometers, making possible observations in sensitive astrophysical domains, like star formation, extra-solar planets or nucleus of active galaxies; 2. the introduction of single mode fibers has enabled to control the interferometric signal and hence to calibrate it (at least to the percent level) with automatic procedures transparent to the user, hence opening us the use of interferometric facilities to non specialists and to a larger number of investigators.

These two developments have been decisive in the choice of constructing today's large interferometric facilities: the Very Large Telescope Interferometer[2] and the Keck Interferometer[3]. However, the VLTI has a unique specificity: it is conceived as a service instrument[4]. Any astronomer will be able to ask for telescope time with the VLTI and to observe as a visitor astronomer, going back home with the software, developed by the consortia building the instruments (AMBER and MIDI), to reduce his/her data. Nevertheless, this is not sufficient to make the VLTI a real service instrument. Indeed, it is necessary to develop a bunch of software:

1. to prepare the observations (observing proposal), that is to say to investigate the feasibility with the prediction of errors on the pertinent astrophysical parameters;
2. to select calibrators, that is to say point sources (not resolved by the interferometer, unit visibility sources) or sources with known visibility;
3. to interpret the astrophysical observables in terms of astrophysical models;
4. to reconstruct the object spatial brightness distribution if the UV plane coverage allows it.

These developments together with the organization of interferometric schools for the future users correspond to the minimum requirement necessary for the optimum use of the VLTI. They will need to be complemented on the mid and long term by the follow-up of the instruments in order to optimize the data reduction software provided by the consortia. All these are the goals of the JMMC.

In the following, we describe the development plans of the Mariotti Center. They can be divided into three types of actions: software developments, prospective, training and assistance to users.

3. RESEARCH AND ALGORITHMIC DEVELOPMENTS

The first goal of the Mariotti Center has been to fulfill the software needs described above with the creation of four groups of research and developments. Most of these software developments are meant to be transparent to the use of a given interferometer or instrument.

3.1. Preparation of observations: the ASPRO software

This software tool called ASPRO[5] allows to prepare interferometric observations with the instruments VINCI[6], AMBER[7] and MIDI[8] of the VLTI, and also with the GI2T[9]. It is provided with a modular structure which allows to incorporate any other interferometer (IOTA[10], CHARA/FLUOR[11 12], PTI[13], OHANA[14], KI, etc...) by updating 2 modules: the geometrical configuration of the *interferometer* and the signal to noise ratio calculator of the *instrument*. The other modules are transparent.

At present, ASPRO contains a set of pre-defined geometrical models (collection of point sources, Gaussian sources with or without envelopes, etc...) covering most of the needs. By fixing the observation and selecting a model, it can *predict* the error on the model parameters with visibility and/or phase closure constraints. In the near future, we will implement simple differential models (rotating stars and multiple sources with or without envelopes) using differential phase constraints. At that stage, ASPRO will be able to combine visibility, closure phase and differential phase information. If necessary, the user will be able to use in the future its own analytical model, and – why not – its own numerical model.

The first version of ASPRO has been delivered to the community in September 2001. The second version, provided with a Web interface and simplified procedures, will be delivered at the beginning of 2003. The next three modules described below will be interfaced with ASPRO.

3.2. Search of calibrators

The goal is to provide a tool that allows to select the reference stars required to calibrate the interferometric observations. This tool has to be as general as possible so that it can be used for observations with the VLTI, but also with any other interferometer. For this, it is necessary to develop an expert system which, from the physical parameters characterizing a given object, allows to conclude if it can be used or not as a calibrator. This means that the expert system has to be able to predict the visibility of the object at a given spatial frequency.

Given the difficulty to create a catalog of stars containing the useful informations to define a calibrator, it has been decided to develop a tool allowing the user to create, from an *on line* consultation of the CDS catalogs, a list of stars from which he/she will be able to select the reference stars most adapted to his/her scientific program. This approach is complementary to the ESO approach which consists to build a catalog of interferometric results: the CHARM catalog[15]. The list of possible calibrators provided by the expert system will be cross-checked with the CHARM catalog.

The first version of this calibrator selection tool will be delivered to the community at the beginning of 2003.

3.3. Modeling the interferometric observables

It is well known that the sparse *UV* plane coverage of an interferometer working with a small number of telescopes (let us say up to 5) does not allow in general to reconstruct the image of the observed object. In this case, it is necessary to model the interferometric observables. The analysis of the modeling problem can be summarized into two questions:

— what is the exact relationship between the interferometric observables and the object?

— what is the quantity (χ^2) to be minimized to estimate the astrophysical parameters?

The answer to the first question is instrument dependent. However in the case of the VLTI, for compact objects (smaller than the Airy disc) and even at low spectral resolution (a few tens), the problem of the exact relationship between the interferometric observables and the object arises only in the case of chromatic objects when looking for very high dynamics as for extra-solar planets detection. In most cases, we can consider that the interferometric observables are instrument independent. With respect to the second point, the main question is to know if we need to constrain the phases or complex quantities. If the visibilities are well calibrated (no systematic errors), it is preferable to work with the complex bispectrum. If this is not the case, we need to work with the closure phase in order to keep the advantage of the self-calibration. For differential measurements the use of the complex cross-spectrum in a well suited estimator is appropriate.

We are developing a modeling software to ajust the interferometric observables with the geometrical/differential models defined in the ASPRO software and if necessary with user models. The first version of this modeling software will be delivered to the community during the second semester of 2003.

3.4. Image reconstruction

The possibility of reconstructing the images from interferometric measurements is of prime importance in order to identify and to interpret the environment of the observed objects with milliarcsecond spatial resolutions. However, the irregular and sparse coverage of the UV plane makes the reconstruction difficult. In radioastronomy, this problem has been largely covered and image reconstruction algorithms have been developed (CLEAN, Maximum of Entropy, WIPE). Nonetheless, whereas radio interferometers measure the complex visibility, optical interferometers measure the modulus of the complex visibility and not directly the phase, but phase closure relations. Due to these differences, the image reconstruction methods developed in radioastronomy are not directly applicable to the case of optical interferometry. Hence, it is necessary to develop image reconstruction methods dedicated and adapted to the nature of the observables produced in optical interferometry. Our objectives are the following:

- to develop and provide algorithms of image reconstruction from the observables of optical interferometers. These algorithms will produce an image, but also an estimate of the image quality (error bar on the intensity distribution, effective spatial resolution, reconstructed field, etc...);
- to develop an expertise on the optimization of the telescopes configuration in the phase of preparation of the observations. This expertise will be acquired by processing simulated data or real data provided by the interferometers. In due time, this expertise will allow to optimize the telescope time required to perform the desired observations.

A first version of the image reconstruction software from optical interferometric observables has already be written[16]. A user friendly version will be delivered to the community in 2004.

3.5. Expert tool for instrumental follow-up

In optical interferometry, there is a long way between the acquisition of raw data and the production of astrophysical observables. The calibration problems are highly relaxed when using single mode spatial filters and the interferometric instruments (like AMBER for example) are likely to achieve their specifications. But how close they can achieve their most ambitious goals will be known after quite some actual observations. Hence, the software packages delivered to the users together with the instruments might not be perfectly optimized.

The achievement of the ultimate performances of the VLTI will require a long term follow-up and analysis of the instrument behavior in correlation with its environment in order to identify and to quantify the long list of instrumental, atmospheric and astrophysical biases. In this context, some of the software tools to model marginal instrument errors from environmental or technical information still have to be developed. This is unavoidable to be able to observe very faint sources and to reach the high image dynamics required for example for the detection of extra-solar planets.

Besides the development of standards algorithmic tools, the fine analysis of the interferometric signal in a long term perspective to reach the ultimate performances of the instruments is one of the goals of the Mariotti Center.

4. PROSPECTIVE

In this section, we make some prospective analysis of the software needs which will be required to optimize future interferometric developments.

4.1. Nulling and high dynamics interferometry: DARWIN/GENIE

Nulling interferometry is a technique which combines high angular resolution and high dynamics[17]. Its consists to cancel with destructive interferences the light coming from a star to enhance with constructive interferences an object (stellar or planetary companion, disc) in its vicinity. This technique allows to study the source in a large spectral domain, and combining the informations at each wavelength, to produce image maps of the observed region. To improve the performances and the sensitivity of the technique, it is necessary to modulate the signal of the source. This implies a complex processing of the data resulting from the observations in order to extract the pertinent spectral and spatial scientific information. The DARWIN spatial mission of ESA[18], to be launched in 2014, is based on the nulling concept.

To date, only very simple algorithmic approaches have been developed to estimate the performances of the instrument. In order to prepare the DARWIN mission, it will be necessary:

— to propose optimized algorithms for processing the data from nulling interferometers, which take into account the spectral information and all possible sources of modulation (internal modulation of the interferometer response, full rotation of the interferometer, etc...). These algorithms will have to be capable to extract the signal of the object to observe from the residual signal of the central star, the signal of the zodiacal environment of this star, and the other sources of noise related to the instrument itself;

— to study different geometrical configurations of the interferometer in order to define an optimal configuration.

The algorithms defined for DARWIN will be tested with the GENIE instrument[19]. GENIE is an ESA/ESO instrument which, if built according the present schedule, will see its first light on the VLTI in 2006. It will combine several telescopes (UT and/or AT) of the VLT, and provide a full scale demonstration of what DARWIN can perform. The extra difficulty of an observation from the ground (atmospheric turbulence, sky emission, etc...) will require to adapt the algorithms defined for DARWIN to the GENIE case.

4.2. Optical astrometry and phase reference imaging: PRIMA

PRIMA (Phase-Referenced Imaging and Micro-arcsecond Astrometry)[20] is an instrument which will use the dual-beam capability of the VLTI by observing simultaneously two distinct fields: (i) to perform high precision differential astrometry and (ii) to observe very faint objects with phase reference. The main astrometric objectives of PRIMA concern the characterization of extra-solar planetary systems by observing the reflex motion of the central star, the study of the mass distribution towards the galactic center, the resolution of events like gravitational lensing, etc... The main goal of phase reference is the interferometric observation of very faint objects by controlling the atmospheric piston on an object of the dual field sufficiently bright for it. To prepare the PRIMA experiment, it will be necessary to model completely the instrument in order to perform a precise metrology between the two fields and to propose optimized algorithms to extract the differential signal.

4.3. Second generation of VLTI instruments

After more than ten years of developments, the VLTI has progressively reached its full capacity with the commissioning in 2003 of its main elements: the 10 μm recombiner instrument MIDI, the 3 telescopes near infrared recombiner AMBER, 3 auxiliary telescopes, adaptative optics modules for the 8m telescopes and fringe sensing units.

During the workshop in June 2001 on the second generation instruments, ESO has considered two priorities for the VLTI: the development of a 6 to 8 channels recombiner instrument and an extension to shorter wavelengths. These developments, that are often considered in terms of hardware development, call for an associated effort in software development which is fundamental to optimize the scientific return of the instruments. In the coming years, we will need:

— to optimize the geometrical configuration of the interferometer for the problem under study;

— to design simulators to specify the second generation of imaging instruments;

— to elaborate precise methods to calibrate the useful signal;

— to propose optimized algorithms to extract the pertinent information.

4.4. Participation to ASHRA prospective

One of the mandates of the ASHRA ("Action Spécifique de Haute Résolution Angulaire"), french council having in charge the prospective, is to define a mid and long term development strategy for optical interferometry[21]. For this purpose, a strategy group piloted by ASHRA and transverse to ASHRA and JMMC, has been formed. The working plan of this group is the following:

— definition of the interferometric field in terms of resolution, extent and dynamics;

— definition of observational strategies in terms of frequency coverage;

— definition of image quality criteria adapted to optical interferometry;

— simulation software tools.

5. TRAINING AND ASSISTANCE TO USERS

Interferometry opens up a new era in optical astronomy. The instruments installed on the VLTI will allow to push the limits of the present studies based on multiple systems, determination of stellar diameters and observation of circumstellar environments of late type stars, towards new fields such as stellar formation, extra-solar planets and, for the first time, the immense field of galaxies[22].

The VLTI infrastructure has been the fruit of a collaboration between ESO and the European Institutes. The performances of the VLTI and its instruments are unique in terms of sensitivity and of angular resolution thanks to the large collecting area of the 8m telescopes and to the numerous available baselines via the auxiliary telescopes, up to 200 m. These performances open new possibilities never reached before and require the European community to be prepared to the specificities of interferometric observations. It is then necessary for the interferometrists participating to the different instruments to transmit their knowledge to the whole astrophysical community. It is with this aims that the Mariotti Center has already begun to train French and European astronomers during a workshop (Nice, October 2001) and a European school (Les Houches, February 2002). To optimize the exploitation of the VLTI and interferometers in general, it is of prime importance:

— to provide interferometers and instruments conceived to be accessible also to non specialists;

— to provide simple tools allowing astronomers to investigate the "mysteries" of interferometry (simulators, signal to noise ratio calculators, etc...);

— to pursue the efforts to develop imaging techniques;

— to provide schools for training to the observations, preparation of observations, data reduction techniques, etc...;

— to organize permanent assistance teams for each VLTI instrument and the relevant software.

6. SUMMARY

The Jean-Marie Mariotti Center, appointed by french CNRS in 2000, is a newborn expertise center that coordinates the efforts of the member institutes to offer all future users of interferometric facilities the best operational environment, providing software, academic formation and stimulating the prospective on new interferometric developments. Its first goals have been to fulfill the software needs to prepare the observations, to select calibrators and to interpret the interferometric observables in terms of models or reconstructed images. In parallel, it has already organized two schools to educate the European astronomers to the "mysteries" of interferometry and started a network team of specialists for permanent assistance around each VLTI instrument and relevant software. In the next years, it will pursue this task and develop software for the next generation of VLTI instruments. The Jean-Marie Mariotti Center actively supports the creation of the future European Network for Interferometry.

REFERENCES

[1] A. Labeyrie: 1975, Interference fringes obtained on VEGA with two optical telescopes, *Astrophysical Journal* **196**, L71

[2] A. Glindemann et al.: 2002, Very Large Telescope Interferometer: a status report, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 11

[3] M. Colavita, P.L. Wizinowich: 2002, Keck Interferometer update, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 10

[4] M. Schoeller et al.: 2002, Commissioning the VLT Interferometer: from first fringes towards a genral user facility, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 153

[5] G. Duvert, P. Berio, F. Malbet: 2002, ASPRO, a software to prepare observations with optical interferometers, Proc. SPIE **4844** *Observatory Operations to Optimize Scientific Return III*, paper 60

[6] P. Kervella et al.: 2002, VINCI, the VLTI commissioning instrument: status after one year of operations, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 152

[7] R.G. Petrov et al.: 2002, Using AMBER: the near infrared VLTI focal instrument, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 158

[8] C. Leinert, U. Graser, R. Waters, G. Perrin, W. Jaffe, B. Lopez, F. Przygodda, O. Chesneau: 2002, Ten-micron instrument MIDI getting ready for observations on the VLTI, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 155

[9] D. Mourard, D. Bonneau, P. Stee, A. blazit, A. Domiciano, L. Abe: 2002, Status report on the GI2T interferometer, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 2

[10] W.A. Traub: 2002, Recent progress at IOTA with 3 telescopes, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 6

[11] T.A. ten Brummelaar: 2002, Update on the CHARA array, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 9

[12] V. Coudé du Foresto, H.A. MacAlister, G. Perrin, S.T. Ridgway, T.A. ten Brummelaar: 2002, Combining very high angular resolution with high dynamic range: the FLUOR instrument at the CHARA array, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 73

[13] B.F. Lane, PTI status report, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 8

[14] G. Perrin et al.: 2002, OHANA: the Optical Hawaiian Array for nanoradian astronomy on top of Mauna Kea, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 15

[15] A. Richichi, I. Percheron: 2002, *Astronomy and Astrophysics* **386**, 492

[16] E. Thiebaut: 2002, Imaging with the AMBER-VLTI: the case of microjets, *WS VLTI - The Very Large Telescope Interferometer Challenges for the Future*, JENAM 2002, 2-7 september, Porto (Portugal)

[17] E. Serabyn: 2002, Nulling interferometry, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 125

[18] P. Gondoin, C. Fridlund, A. Karlsson, S. Zodnid, S. Volonte: 2002, Darwin infrared space interferometer, Proc. SPIE **4852** *Interferometry in Space*, paper 72

[19] Gondoin et al.: 2002, Darwin Ground Based European Nulling Interferometer Experiment (GENIE), Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 143

[20] F. Paresce, F. Delplancke, F. Derie, A. Glindemann, A. Richichi, M. Tarenghi: 2002, Scientific objectives of ESO's PRIMA facility, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 113

[21] L. Arnold: 2002, High angular resolution in 2010-2020: a comparison between possible post VLT/VLTI instruments, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 18

[22] F. Malbet et al.: 2002, Astrophysical potential of the AMBER/VLTI instrument, Proc. SPIE **4838** *Interferometry for Optical Astronomy II*, paper 157