AMBER Optical Design

Romain Petrov, Sylvie Robbe-Dubois, Martin Vannier (UNSA)
Pierre Antonelli, Yves Bresson, Stéphane Lagarde (OCA)
Yves Rabbia, Sylvestre Rebattu (OCA)
Fabien Malbet, Pascal Puget, Karine Rousselet-Perraut (LAOG)
Debora Ferruzzi,Sandro Gennari, Franco Lisi (OAA)
Udo Beckmann, Albrecht Dress (MPIfR)

Abstract

The AMBER instrument is the Astronomical Multi BEam combineR of the VLT, covering the J, H, and K optical infrared bands (from 1.1 μm to 2.4 μm). It combines lights of up to 3 telescopes (UTs or ATs) working together, in order to enable the system to benefit from phase closure techniques.

This instrument developed by LAOG, MPIfR, OAA, OCA and UNSA is expected to reach K = 20 when a bright reference star is available, and K = 14 otherwise, in order to explore young stellar objects and AGN dust tori with a resolution up to 10 000.

AMBER fills a single table of around 4.2 m x 1.5 m. The major part of the optics of this table are working in the ambient air of 15 +- 1 degrees. This part (comprising also all AMBER alignment and calibration tools) is called the warm optics part.

This warm optics part is fed with 3 VLT beams of diameter = 18 mm and of separation = 240 mm.

After a reduction of this beam separation (to gain place on the table) those 3 warm beams are :

- polarised,
- subdivided in the 3 spectral channels (K, H and J),
- focussed in 9 singlemode polarisation maintaining fibres
  (for spatial filtering and optical path matching),
- collimated in 3 new VLT beams having differing beam separations
  (to get various fringes periods on the final 2D detector),
- anamorphosed (with an ellipticity of around 15),
- and focussed towards the imput slit of a cold spectrograph.

Then, the light enters in the nitrogen cooled part of AMBER, where all those beams are :

- collimated again together,
- partially filtered and dispersed on the appropriate grating
  (Resolution choice = 35, 1000 or 10000),
- and imaged on the 2 D detectors, creating 4 separate images :
  1 interferometric image (ombining the 2/3 of all the beams energy),
  and 3 photometric images (one for each VLT beam remaining energy).

We present today the design of this instrument, with an emphasis on the optical tolerancing strategy associated to the AMBER warm optics part.

DT = Division Technique de l'Inst. Nat. des Sc. de l'Univers(Meudon-France)
LAOG = Laboratoire d'Astrophysique, Observatoire de Grenoble (France)
MPIfR = Max-Planck Institut für Radioastronomie in Bonn (Germany)
OAA = Osservatorio Astrofisico di Arcetri in Firenze (Italy)
OCA = Observatoire de la Côte d'Azur (France).
UNSA = Universite de Nice Sophia Antipolis (France)

[1] e-mail=martinot@dt.insu.cnrs.fr, Fax=+33 (0) 1 45 07 51 40, Tel=+33 (0) 1 45 07 52 42

The FINITO project: a fringe tracker for VLTI

M. Gai[1], L. Corcione[1], D. Gardiol[1], A. Gennai[2], M. G. Lattanzi[1], D. Loreggia[1],
G. Massone[1], S. Menardi[2]

1 : Osservatorio Astronomico di Torino
2 : European Southern Observatory

Abstract

The interferometric group of the Torino Astronomical Observatory is involved in a collaboration with the ESO for the development of a Fringe Sensor Unit for the VLTI project, that is scheduled to start operations in a short time, in order to gain expertise and perform astronomical measurements on selected targets.

The goal of this project is to update and improve a Fringe Sensor Unit prototype, built by the Observatoire de la Côte d'Azur - Nice. This FSU will be used at the VLTI instrument during the initial period of activity, i.e. 2002 at least; it will operate in the H band, in close loop with the delay lines, allowing the others interferometric instruments to observe in integration mode, with a potential gain of several magnitudes in sensitivity.

Some key features are: OPD modulation using piezo-stretched optical fibers, compensation for atmospheric dispersion, coverage of a small field of view (~1") and the possibility of combining the beams from two or three different telescopes.

The completion is foreseen for the end of next year.

1. Introduction and objectives

The application of the interferometric techniques to the domain of optical astronomy is one of the most promising advances made possible by the new resources and developments in computing and metrology science. The control of the optical path within the required stability through the two (or more) arms of the interferometer is a challenging technical problem when the aim is to combine the light from collectors of the size of large modern telescopes.

Some people of Torino Astronomical Observatory, with previous activities on both astrometry and technology fields, decided to start a collaboration to explore the possibilities of interferometry from the scientific and technical point of view. Among the several possible scientific objectives, we can quote the following as the ones of highest interest for Torino group:

- high resolution characterization of exo-planet candidates for space interferometric missions (SIM, GAIA, TPF) ;
- revision of the radius-mass relation (visual binaries) and stellar masses;
- distance calibration of double-lined spectroscopic binaries up to 2.5 kpc (single-lined with PRIMA) ;
- pulsation of Mira variables.

From the technical point of view, the collaboration to an outstanding interferometric project is a unique opportunity to gain expertise and experience on cophasing and interferometric measurement calibration. Therefore, the European Southern Observatory (ESO) and the Osservatorio Astronomico di Torino (OATo) agree on a joint program for fast implementation of a Fringe Sensor

Unit (FSU), based on the Prototype Fringe Sensor Unit (PFSU) from the Observatoire de la Côte d'Azur (OCA). The instrument is aimed at early set-up of the Very Large Telescope Interferometer (VLTI) and to improve the sensitivity of the VLTI instruments (AMBER, MIDI and VINCI) by providing them longer exposure time thanks to the correction of the optical path (OP) perturbations induced by atmospheric turbulence. *The increase in integration time from the order of few tens of milliseconds to several seconds (or tens of seconds) may improve the sensitivity by about 5 magnitudes, even in photon-limited regime.*

2. Instrument concept

The project, aimed at the implementation of a two or three beam fringe tracker for VLTI, based on the concept of the PFSU from OCA, is referred to below as FINITO, for Fringe-tracking Instrument of NIce and TOrino.

The FSU is fed by the beams from two-three telescopes, either the 40 cm siderostats, the 1.8 m auxiliary telescopes (AT), or the 8.2 m Unit Telescopes (UT). During the first phases, i.e. basically throughout 2002, the operations are supposed to be based primarily on the siderostats and ATs, since UTs will require a complete adaptive optics (AO) system to achieve an acceptable interferometric performance in the near IR.

The basic instrument function is *fringe tracking*, i.e. measurement of the position of zero Optical Path Difference (OPD), for correction in real time of the atmospheric perturbation resulting in fluctuations of the optical path of each beam. The atmospheric turbulence is assumed to have a bandwidth of a few tens Hz, in typical weather conditions, therefore it must be measured with a frequency of a few hundred Hz.

Parameter	Frequency [Hz]
Fringe tracking loop bandwidth	40
DL correction frequency bandwidth	120
FSU estimate cut-off frequency	100 - 500
Fringe modulation frequency	200 - 1000
Fringe sampling rate	4k
Metrology sampling rate	20k

Table 1 - Most relevant frequencies associated to the FSU operation.

FINITO operates in H band, i.e. in a wavelength range approximately between 1.5 and 1.8 μm; this appears as a reasonable compromise to avoid astrophysically interesting bands (J, K).

At the beginning of the operations, a phase of *fringe detection* explores a relevant optical path difference (OPD) range, in order to identify the appropriate operating region around the point of path balancing. Then the FSU switches to the normal operation mode, which evaluates the *zero OPD* (ZOPD) position by scanning a smaller OPD region, corresponding to a significant fraction of the *coherence length*, and applying a single-fringe *cophasing algorithm*: as the position of each fringe is related to the position of the central fringe, it is possible to deduce small discrepancies with respect to the current expected (nominal) value of OPD. Since infrequent *fringe jumps* are induced by occasional large noise events, it is necessary to operate on a comparably large interval, in order to apply a search for the envelope maximum, i.e. identification of the *central/white light fringe*. We assume that events inducing OPD jumps much larger than one fringe are beyond the nominal regime of FINITO: in such a case, as required at the beginning of the observation, a new phase of fringe detection must be performed.

3. Conceptual Optics and Detectors Layout

The overall concept is shown in Figure 1. The 18 mm beams reaching the VLTI lab instruments are picked up by dichroics, separating the H band used by the fringe tracker from the scientific beams.

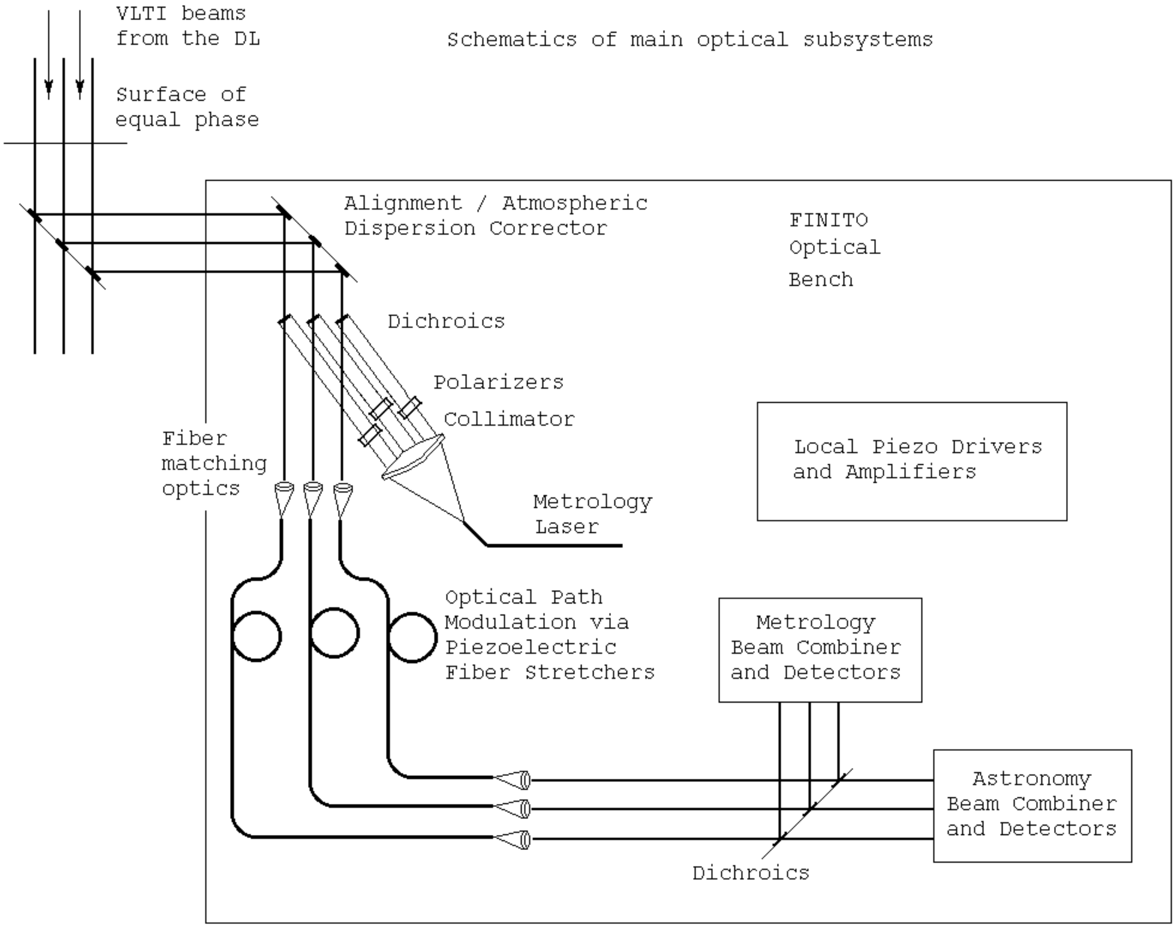


Figure 1- Schematic of the FINITO optical and mechanical functions

The H band beams are fed to the *alignment and correction optics*, which also has functions of differential fine tracking (i.e. Atmospheric Dispersion Correction, ADC) and of initial fringe detection. The beams from the alignment sub-system are assumed to be appropriately oriented and in the correct relative phase, corresponding to a common wavefront across a surface orthogonal to the propagation direction. This device will also make possible a differential tracking with a guide star, i.e. wherever the object sky distribution will permit, to select bright guide star in order to integrate with the scientific instruments over a faint astronomical source within +/- 1 arcsec VLTI field of view.

The following sub-system encountered by the H beams onto the FINITO bench is the set of dichroics used to superpose the metrology laser beam, operating at $\lambda = 1310$ nm wavelength. The laser beam is collimated and fed to a set of polarizers, in order to match one of the principal axes of the modulated fiber optics, so that avoiding inter-modulation associated to the fiber birefringent properties. Internal metrology is used to monitor and control the fiber modulation, measuring the interference between the laser beams and thus regulating the stretch of the optical fiber.

Next is the fiber modulator and its associated matching optics, a set of doublets used to inject and extract the astronomical and metrology beams into the fiber core. The size of the fiber core is such that only the central peak of the PSF is within the fiber core: therefore, the fiber acts as a *spatial filter*, selecting a small region of the 2 arcsec FOV of the VLTI beams and rejecting the aberrated side wings of the PSF. Since the fibers are mono-mode, the output beam is quasi-Gaussian, so that the residual aberrations within the central PSF lobe are regularized as well, providing below the collimating optics at the fiber output a nearly ideal flat wavefront. Residual error from adaptive optics is translated into beam intensity fluctuations by spatial filtering, as the current Strehl ratio defines the instantaneous power for each beam. On the siderostats, intensity fluctuations are due to *scintillation* and wave front error residuals.

The fibers are wound around piezoelectric drums, used to stretch the fibers under electric command by the Optical Path Modulator (OPM); the OPD is modulated over an interval of a few fringe periods around the ZOPD point, in order to get a measurement of the white (or central) fringe position. On output from the fibers, the beam is collimated by an optical doublet similar to the one used in the input optics, and sent to a combination assembly based on semi-reflective beam splitters. The metrology and astronomical beams are separated before combination, in order to optimize the structure of the two combiners.

The combined metrology output is sent to dedicated photo-diodes, and the metrology loop is closed by the OPM Local Control Unit. The piezoelectric drums are driven accordingly to the planned fiber stretching law, in order to generate a triangular modulation of the OP over a range of several wavelengths, the actual path variation is monitored by the laser combination, and the required correction signal is fed back to the actuator to achieve the nominal modulation, at any time, within a few nm.

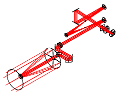
The astronomical output is sent to an integrating array detector of HAWAII type, served by a new release of the ESO IRACE electronics, able to make available the detector data with low latency. Since several spots must be focused on a ~2x2 cm^2 area, the adopted solution is similar to the one adopted for VINCI.

4. Implementation plan and conclusions

The implementation schedule of our fringe sensor is rather stringent, as the instrument should start activity before the end of 2001. After a preliminary phase of understanding and reviewing of the existing prototype, we are now completing a detailed technical analysis of the project. For some critical aspect we had to modify the original PSFU solutions, in order to gain in sensitivity, reliability and on criticity of the setup, whereas for some others we had just to adapt the specifications to the present VLTI standards.

We hope to conclude the bulk of the procurement plan for the optical and mechanical components within the next six months period, and in the meantime to start the test and assembling activities in the optical laboratory at the Torino Observatory. This phase will continue until Summer 2001, when the instrument will be formally delivered to ESO and sent to Paranal for its final collocation in the VLTI interferometric laboratory. From the procurement point of view, the most critical items are probably the fiber-piezo modulators and the detector with control electronic unit. For the first the collaboration with IRCOM (Limoges) is under negotiation, while for the second ESO should deliver a new release of the IRACE system used for other VLT instruments.

The active life of this instrument will start at the end of 2001, and it will continue for some years at least, as presently no other fringe sensor with three beam capability is foreseen.



Performance of Optical Path Length Modulators in MIDI

Peter Schuller and Christoph Leinert

Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

Contact: Peter Schuller <schuller@mpia-hd.mpg.de> Internet: http://www.mpia-hd.mpg.de/MIDI/

Introduction

MIDI – the *MID*-infrared *I*nterferometric instrument – is one of the interferometric instruments in the Very Large Telescope Interferometer (VLTI) project of the European Southern Observatory (ESO) on Mt. Paranal/Chile. It will work in the wavelength band around $\lambda_{MIDI} = 10\,\mu$m (8...13 μm) as a pupil plane interferometer with two incoming beams. Different spectroscopic and photometric options will be available.

To acquire the interferometric signal, it is necessary to modulate the Optical Path Difference (OPD) of the two beams over a wide range in order to find Zero OPD and then to sample the fringe pattern (see Fig. 1). These two tasks have to be performed by piezo translation stages within the coherence time T_{coh}, i.e. the time in which atmospheric changes of the OPD are small compared to the wavelength. At 10 μm, T_{coh} is typically 100 ms.

For signal acquisition, sampling, and interpretation of interferometry data, it is necessary to know the properties of the scanning piezos in respect to stability, repeatability, linearity, and speed. The introduced OPD errors should be less than 1 % of λ_{MIDI}. We are presenting results on various tests performed on the MIDI piezo stages.

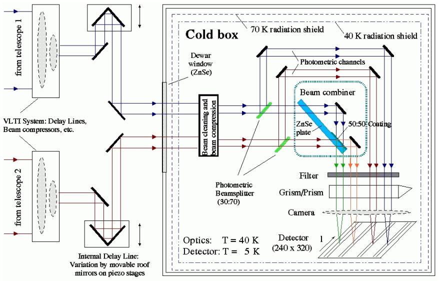


Fig. 1: *Scheme of MIDI.* Note the position of the piezo stages in the MIDI Internal Delay Line in front of the dewar.

Experimental Setup

As OPD modulators, we use two piezo translators by Physik Instrumente, Waldbronn/Germany (model P-780.20) with appropriate electronics to allow for compensation of hystheresis. The maximum mechanical stroke of one piezo is about 110 μm. To command the piezo, we applied an input voltage generated by a VME system to test the connection between the Instrument Control Electronics and the piezo control electronics.

For testing the piezo stages including the roof mirrors used in the Internal Delay Line (mass ≈ 18 g each), we used a commercial dual-frequency laser interferometer (model ZLM 500 by JENAer Meßtechnik, Jena/Germany) with a resolution of 2.5 nm (see Fig. 2).

In order to investigate the piezos on their tip-tilt behaviour, a flat mirror was mounted on the stages to reflect a laser beam over a long distance. Moving the piezos, the deviation of the laser beam was detected by a CCD camera.

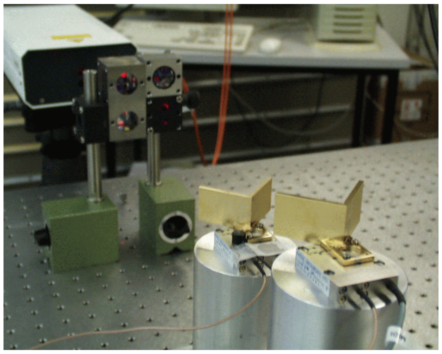


Fig. 2: *Interferometric test setup for piezo stages*

Results (Selection)

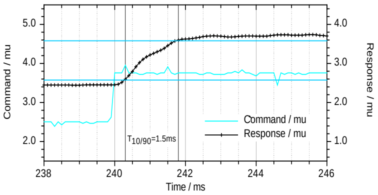


Fig. 3: *Step response of the piezo (mechanical)*

Testing one of the planned internal OPD scanning modes, we applied a stepping function as command signal setting the piezo in *optical* steps of $\lambda_{MIDI}/4 = 2.5\,\mu$m and a step duration of 20 ms. Both command and response signal are shown in Fig. 3. The time it takes the piezo to move from 10% to 90% of the average step height is $T_{10/90} = 1.5$ ms.

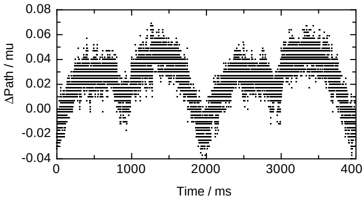


Fig. 4: *Residual path difference (mechanical)*

Applying the same command signal on both piezo stages, one expects a constant signal, since changes performed simultaneously on both interferometric channels should cancel each other. Figure 4 shows that there is a remaining signal due to non-linear behaviour which is not the same in both stages. These properties need to be adjusted.

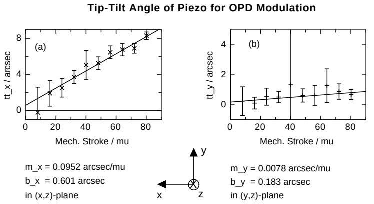


Fig. 5: *Tip-tilt angle of OPD piezos parallel and perpendicular to the beam plane (x,z)*

The piezo stage was moving in the (x,z)-plane parallel to the table surface. The tip-tilt angle in the (x,z)-plane is compensated by the corner mirror mounted on the piezo stages. The angle in the (y,z)-plane is 12 times smaller and thus uncritical to 10 μm interferometry. The different values of these two angles can be understood from the piezo stage mechanics.

Conclusion

The results of the tests on the OPD modulators show promissing properties. Noise (≈ 10 nm, not shown here) and tip-tilt deviation are well within acceptable limits, the speed fullfills also the requirements. Further investigation has to be done in the non-linear behaviour, which can be dealt with by changing parameters in the piezo control.

Peter Schuller, MPIA Heidelberg Summer School Interferometry 2000 September 18 - 22, 2000, Leiden/The Netherlands

Alexis Brandeker and René Liseau, Stockholm Observatory

2000-09-16

Pushing the spatial resolution of adaptive optics systems with post processing techniques

Abstract

In our search for circumbinary disks around young T Tauri stars, we have come across a technique of post processing data from adaptive optics systems. This poster is an overview of the technique and the way we put it into use.

Introduction

The spatial resolution of ground based observations are most often limited by the atmosphere to about 1 arcsecond. This obstacle can be partially overcome by the use of *adaptive optics* (AO), a real time technique to reduce the wave front errors introduced by the atmosphere. Under ideal atmospheric conditions, the diffraction-limited resolution may be reached. The real world is unfortunately seldom ideal. This is where the post processing comes into view.

Pushing the resolution

Even with AO, the point spread function (PSF) is not the ideal circular symmetric PSF with the squared Besselian radial profile expected from the theory of a circular aperture. The PSF is not even constant in time, but varies from frame to frame. It looks like a mess. Ideally we would like to de-convolve our observations with the PSF, but this is not possible with PSFs like that. Instead we proceed as follows:

1) Observe a *number* of frames of the object of interest. This is necessary in any case if we want high signal to noise ratio and don't want to saturate the detector.
2) Observe a reference star with similar spectral properties to the object (i.e. same spectral class), and which is assumed to be singular.

Since the reference star isn't observed simultaneously with the object, we cannot use it directly as a PSF to de-convolve our object frames. Instead we make use of an algorithm called IDAC developed by J. Cristou, S. Jefferies, K. Hege and M. Chesalka.

IDAC

The underlying assumption in IDAC is that the object is static on the time scale of the observations, while it is the PSF that changes. Assume we have *n* frames observations of the same object. The idea is then simple and works like this:

1) Make an initial guess of how the diffraction-limited object image might look like, and make an educated guess of what the PSF looks like for each of the *n* frames.
2) For each observed frame, convolve the current guess of the diffraction-limited object image with the current PSF guess corresponding to the observed frame, and compare the result with the observed frame.
3) From the result of the comparisons in 2), compute a correction to the guess of the diffraction-limited object image and the PSF guess for each frame. Start over from 2) with the new guesses.

A conjugate gradient search method is applied in step 3) to compute the corrections of the guesses. The error function used to evaluate the correctness of the guesses in step 2) is defined as

$$\varepsilon = \sum_{k}\sum_{\vec{r}\in R}\left[i_k(\vec{r}) - \hat{o}(\vec{r}) * \hat{p}_k(\vec{r})\right]^2 + \\ + \sum_{k}\sum_{\vec{f}}\left|\hat{P}(\vec{f})\right|^2 B(\vec{f})$$

where $\hat{o}$ is the current guess of the diffraction-limited object image, $\hat{p}_k$ is the current PSF guess corresponding to the *k*:th observed frame, i_k is the *k*:th observed frame, $\hat{P}_k$ is the Fourier transform of $\hat{p}_k$, B is a band limiting function to punish use of too high spatial frequencies, and $*$ denotes a convolution integral.

A real world example

In March this year we used the adaptive optics near infrared system (ADONIS) at the ESO 3.6m telescope at La Silla to observe binary T Tauri stars. Since we wanted to try post-processing techniques, time was taken to observe reference stars for each science object. The pixel scales in the images below are 0.035 arcseconds per pixel, and the part of the field shown corresponds to approximately 2 arcseconds. The example below is the VW Cha system, a 0.7" wide binary where the secondary was found to be a 0.15" wide binary in itself.

The observations consist of a series of 10 frames in J-band (λ=1.25µm) with 30 second exposures. SAO 256804 was observed as a reference star to obtain a good initial estimate of the PSF. A series of 60 observations was also obtained in a similar manner in K-band (λ=2.20µm), with a similar result (not displayed here).

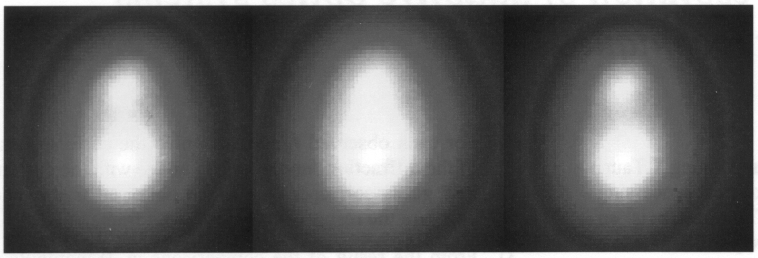
Further reading

http://www.ls.eso.org/lasilla/Telescopes/360cat/adonis/

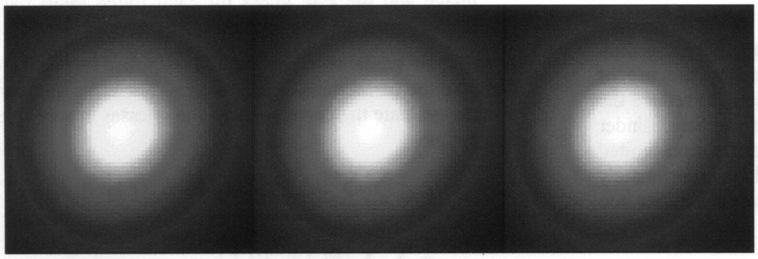
Contact: alexis@astro.su.se

Alexis Brandeker and René Liseau, Stockholm Observatory ***2000-09-16***

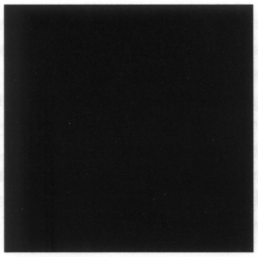
Frame 2, 6 and 10 respectively of the AO corrected observations.



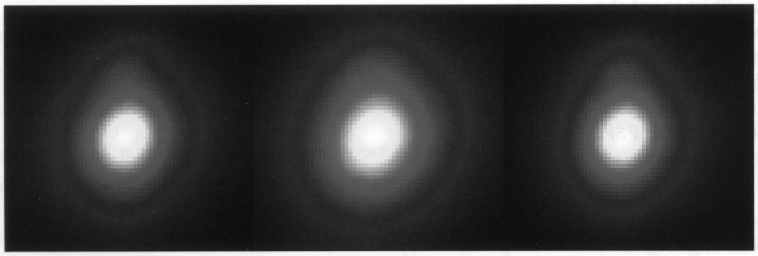
The PSF initial guesses for frame 2, 6 and 10. Initially, they are identical.



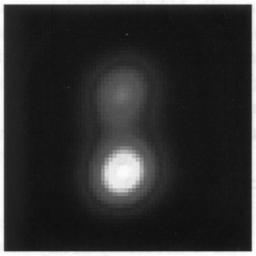
The initial guess of the object is flat.



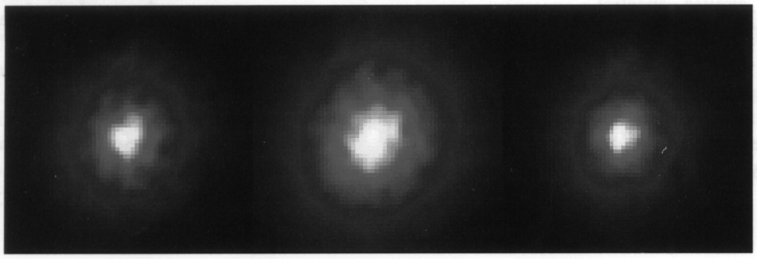
The PSF guesses for frame 2, 6 and 10 after 10 iterations. Already now the PSFs start to diverge.



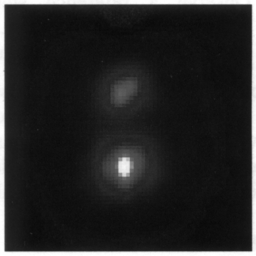
The object guess after 10 iterations.



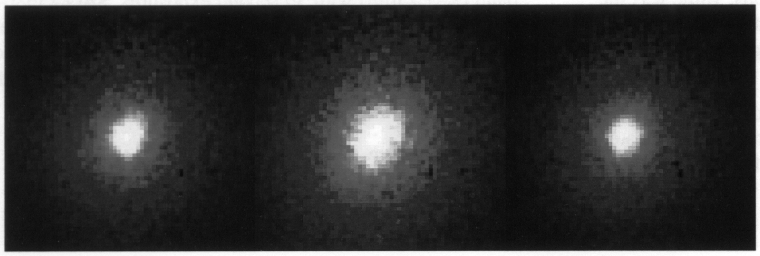
The PSF guesses for frame 2, 6 and 10 after 100 iterations. Details in the PSF become apparent.



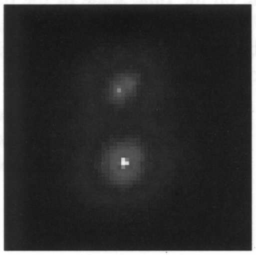
The object guess after 100 iterations.



The final PSF estimate for frame 2, 6 and 10 after 358 iterations.



The final object after 358 iterations.



Contact: alexis@astro.su.se

The Magdalena Ridge Observatory

Gary C. Loos[a,b], David J. Westpfahl[b,a]

[a]U.S. Air Force Research Laboratory (AFRL/DEBS),
3550 Aberdeen SE, Kirtland Air Force Base, New Mexico, 87117, USA

[b]New Mexico Institute of Mining and Technology, Physics Department
Socorro, New Mexico 87801, USA

ABSTRACT

The Magdalena Ridge Observatory is a cooperative effort between the US Department of Defense as represented by the US Army Space and Missile Defense Command and a consortium of four universities; New Mexico Institute of Mining and Technology, New Mexico State University, New Mexico Highlands University, and the University of Puerto Rico. We plan to build a three-telescope visible/near-infrared interferometer consisting of two fixed 2.4m AO-compensated telescopes and a third 2.4m AO equipped telescope which will be mounted on a transporter. The first two telescopes will be fully instrumented for traditional focal plane operation but will also be provided with coude feeds to enable afocal beam combination with the third telescope.

Keywords: interferometry, adaptive optics, observatory

1. INTRODUCTION

The Magdalena Ridge Observatory (MRO) collaboration has received first-year funding to complete planning and environmental assessment. The project is a joint venture between four universities comprising the Magdalena Ridge Research Consortium and the Department of Defense. The partricipating universities are New Mexico State University, New Mexico Highlands University, the University of Puerto Rico, and the New Mexico Institute of Mining and Technology (New Mexico Tech). The Department of Defense agencies are the U.S. Army Space and Missile Defense Command, which is the DOD lead agency and MRO program executing agent, the U.S. Air Force Research Laboratory, and the U.S. Naval Research Laboratory. Funding will come from the U.S. Department of Defense (DOD). The DOD will use the observatory for missile tracking over White Sands Missile Range during the day and the universities will use the observatory for research in astronomy and for development of astronomical instruments at night. The observatory site is in close proximity to the Very Large Array (VLA) radio telescope, and joint observations are anticipated.

The observatory will be located in the Magdalena Mountains of New Mexico, about one kilometer south of South Baldy Peak, at an elevation of 3230 meters. This site is south of the town of Magdalena and west of the city of Socorro. It is about 140-km south-southwest of the city of Albuquerque and within the Magdalena Ranger District of the Cibola National Forest.

The site is in the 12,500 hectare Langmuir Research Area that was set aside for research in atmospheric physics and astronomy by the U.S. Congress in Public Law 96-550. New Mexico Tech has run research programs in the Langmuir Research Site since 1960 and operated astronomical telescopes there since 1973. The site is one of the darkest existing observatory sites in North America. The survey by Garstang[1] predicts very little threat from growing light pollution and what little there is comes from the small towns near the base of the ridge rather than from large cities. An unpublished cloud-cover study performed by the U.S. Air Force showed that the MRO site is competitive with any in the American southwest for number of clear nights per year.

The Langmuir Research Area was a candidate site for the Millimeter Array proposed by the National Radio Astronomy Observatory (NRAO) and its university partners. Extensive environmental work was done by the NRAO. That project found a more suitable site in Chile and is now the Atacama Large Millimeter Array (ALMA), so the NRAO kindly released its environmental findings to the MRO collaboration. That, and the reservation of the Langmuir Research Area for research by Public Law 96-550, has provided a good start on the environmental assessment of the site.

2. OBSERVATORY PLAN

The first priority of MRO is to meet DOD requirements, most of which can be met using the telescopes individually. The current plan for the observatory includes three 2.4-m telescopes. Two will have fast-tracking, alt-az mounts to meet the DOD requirements for observing missile tests. Accelerations as high as 10 degrees per second squared will be required for target acquisition. The observatory site overlooks the White Sands Missile Range and its northern extension. It also has an unobstructed view toward Fort Wingate in northwestern New Mexico, an additional launch facility. It has a clear line of sight to North Oscura Peak on the Missile Range and to the Starfire Optical Range on Kirtland Air Force Base in Albuquerque. The telescopes will be capable of pointing and tracking below the horizon to accommodate low-altitude tests over the range. Infrared tracking cameras for this work will be located at the coude foci.

The proposed location of MRO is a knoll on the main ridge of the Magdalena Mountains. The ridge runs nearly north south and at the MRO site it falls steeply to the west and gently to the east. The maximum east-west separation of the fixed telescopes that the geometry of the ridge can support is about 75 meters without building on high towers. Owing to the gentle slope to the east and the prevailing winds from the southwest, the control room, labs, shops, and dormitory facilities will be to the east of the telescopes so that their waste heat is not carried in front of the telescopes.

The top of Magdalena Ridge is nearly flat and can support telescope baselines of more than 100 meters. Given the advantages of having many baselines for interferometric imaging and the high cost of having many telescopes, we are investigating the possibility of having a movable third telescope. An ideal movable telescope would work in concert with a beam-combining facility that could keep the telescopes phased so fringes could be maintained as the telescope is moved. This is too much to ask initially given the current state of knowledge of movable telescopes. Initially the third telescope may need to sit on fixed stations and be moved only for experimentation. An ideal movable telescope would be very light in weight, so that it could be easily moved, and very stiff. This may require building the telescope of composite materials.

Owing to the DOD requirements, the initial university science will come from individual use of the telescopes. The universities require access to the Nasmyth foci as well as coude, and plan Nasmyth instruments that can be quickly changed. The observatory will also be a test bed for new instruments and sensors.

The site has been developed for many years, so a road, electrical power, and water are already in place. The infrastructure may need to be upgraded to support the dormitory and shop spaces of the new facility.

Many years of astronomical seeing measurements by Colgate[2] have shown that images as small as 0.7 arc second were common from the 30-inch telescope at the Digitized Astronomy Observatory. This was likely the seeing disk of the telescope, not the site. Seeing and turbulence testing specifically for the MRO project have been going on at the proposed MRO site for 16 months and will continue for at least another year.

3. SINGLE-TELESCOPE SCIENCE

The two fast-tracking telescopes will be optimized for different functions. The one placed just to the east of the ridge will be optimized for use in the infrared and will do most of the missile tracking. The one placed to the west will be optimized for the visible; it will be a backup telescope for missile tracking and the primary telescope of the universities. Each will have a camera and a spectrometer. The third telescope may be highly optimized for interferometry. This might include an afocal secondary mirror, in which case instruments would not be mounted directly on the telescope. They could be accommodated in the beam-combining facility to allow the third telescope to be used in single-telescope mode.

Given the established research at the partner universities, the university science will initially focus on infrared imaging and spectroscopy of galaxies and visible imaging of asteroids. Establishing good single-telescope science with the two fixed telescopes will be the top priority.

The fast-tracking capability of the telescopes make them ideal for fast acquisition of targets of opportunity, such as supernovae and the optical counterparts of gamma-ray bursts. Searching for optical counterparts of gamma ray bursts would be especially valuable if at least one telescope could be linked to discovery messages sent from orbiting gamma-ray observatories.

4. INTERFEROMETRY

After MRO is commissioned the development of the interferometric mode of the 3 telescopes will be accelerated. MRO is distinct from existing and planned interferometers because of its medium-sized apertures, adaptive optics, and moderate baselines. Our goal is to have high sensitivity on baselines of approximately 50 meters, with sampling of the u-v plane adequate for good interferometric imaging. Longer baselines will be considered once the observatory is successful with moderate baselines.

All ground-based sites suffer from wavefront irregularities due to atmospheric turbulence. In times of good seeing at the MRO site the Fried parameter, r_0, may be as large as 20 centimeters in the visible. This is very good, but still small compared to the 2.4-meter aperture of the telescopes. Thus, adaptive optics will be required. We are currently evaluating adaptive optics methods based upon conventional deformable-mirror systems in addition to more advanced spatial light modulator based concepts.

In planning for interferometry it is clear that the longer the wavelength the easier interferometry and wavefront correction will be, pushing interferometric work to longer wavelengths. It is also clear that the sky brightness begins to become a problem for ground-based telescopes at wavelengths longer than about 3 microns. As at several other observatories, these realities lead us to plan for interferometry at K or K' band. Given the baseline plan and wavelength combination, the MRO interferometer will have a resolution of several milliarcseconds. This resolution and good sensitivity at K band mean that MRO will be especially well suited to observing young stellar objects.

The search for extrasolar planets is currently a popular topic in the optical and infrared interferometry community. Successful searches will almost certainly rely on higher-order Bracewell nulling. This field will therefore require further development.

Given the geometry of the ridge and the plan for two fixed telescopes and one movable telescope, the u-v coverage of the interferometer is easily modeled and optimized. We envision two possible modes of operation, one in which the moving telescope sits at fixed pads and is moved periodically to give a range of baselines, called survey mode, the other in which the telescope is moved during the observations. We call this second mode the Earth–synchronous mode, implying that the telescope's motion is coupleded with the rotation of the Earth to enhance u-v coverage.

Examples of u-v coverage using a movable telescope are shown in Figure 1 & 2. In each figure a panel at top left shows the baseline plan of the telescopes and the other panels show u-v coverage at several declinations. In the u-v plots the central circle represents a single 2.5-meter aperture and the outer circle represents a 50-meter filled aperture. The units on the axes are in wavelengths at the center of the passband. It is assumed that the observing passband is centered at 2.2 microns and divided into four equally-spaced channels that provide a greater variety of u-v points.

Figure 1 shows the results of observing for four hours, two hours on each side of the local meridian, in survey mode. The fixed telescopes are separated by a 40 meter baseline which is orthogonal to the ridge top and extending 10 meters to the east and 30 meters to the west. The movable telescope sequentially sits at six positions along a 72-meter track that runs directly along the ridge crest. The local orientation of the ridge crest and track, 15 degrees west of due north, allows this configuration to provide enhanced east-west baseline coverage. Such a set of observations might be carried out by observing during the night and moving the telescope to the next position during the following day. It is clear in each case that the movable telescope allows reasonable coverage of the 50-meter circle, consistent with a good synthesized beam and good imaging. Foreshortening in the north-south direction is apparent at a declination of –30 degrees. A longer north-south track would give more acceptable coverage.

Figure 2 shows observations with the same track, telescope stations, hour angles, and wavelengths in the Earth-synchronous mode. This assumes that the telescope can be moved from station to station very quickly, and that the beam combining facility can rematch the phase and reacquire fringes very soon after the telescope is moved. The u-v coverage is still good, similar coverage at radio wavelengths has been used to make acceptable interferometric images.

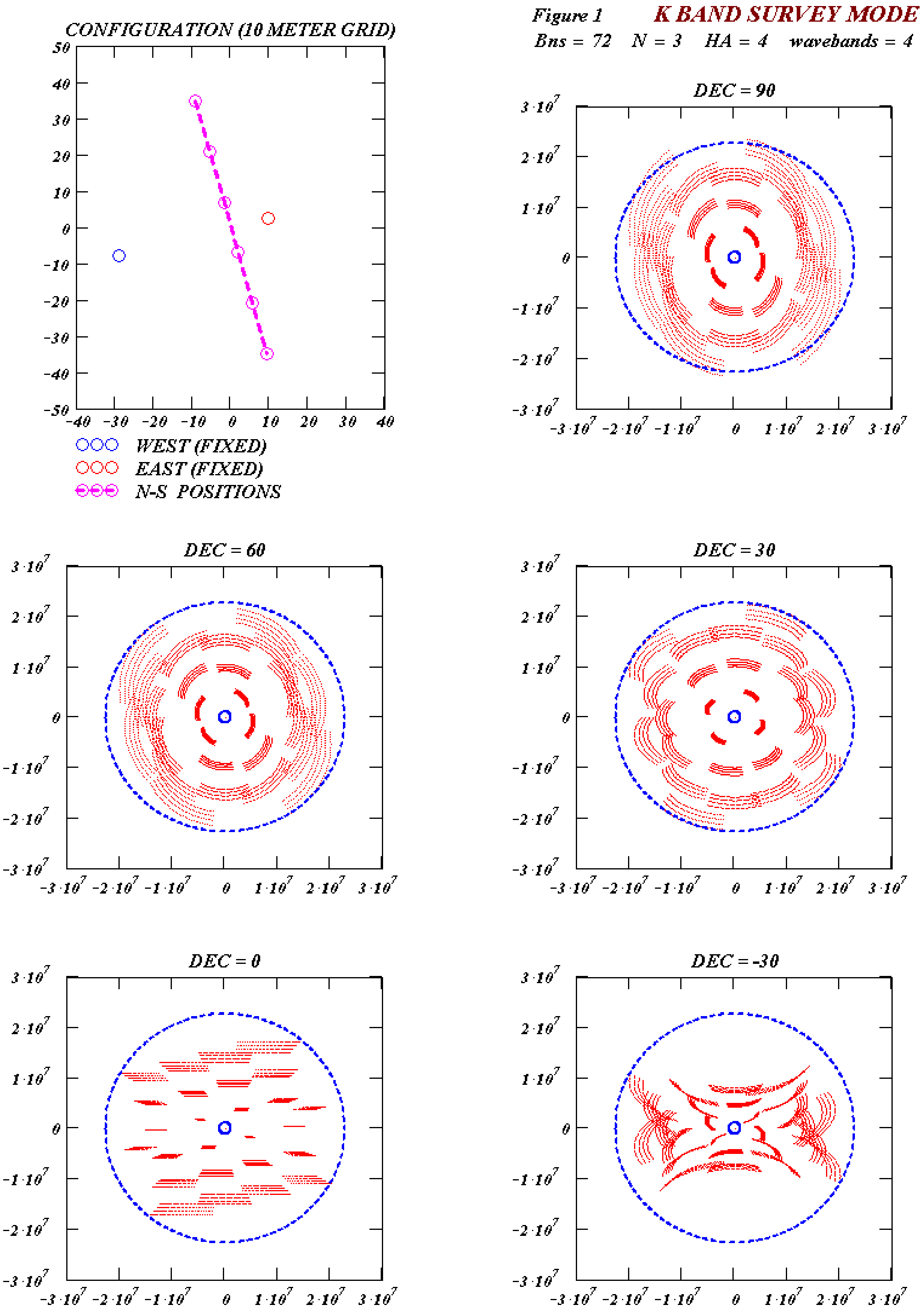
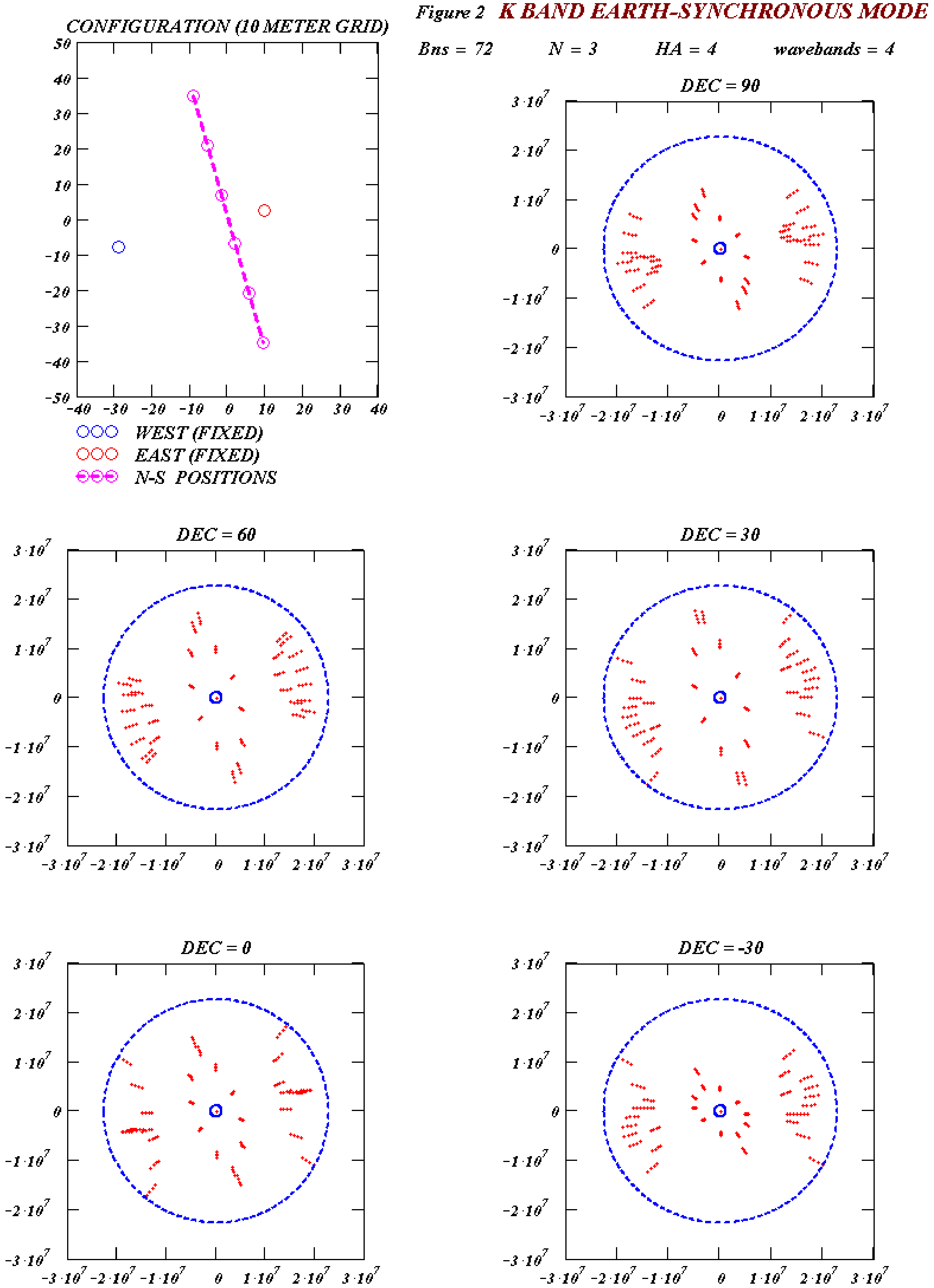


Figure 1 **K BAND SURVEY MODE**

Bns = 72 N = 3 HA = 4 wavebands = 4

Figure 2 **K BAND EARTH-SYNCHRONOUS MODE**

Bns = 72 N = 3 HA = 4 wavebands = 4



5. CONCLUSION

We believe that optical and infrared interferometry will follow the historical path of radio interferometry. Now that several interferometers with small telescopes and moderate baselines are working the development of the discipline is likely to take the same paths followed in the development of radio interferometers. We view MRO as being the infrared analog of the three-element Green Bank Interferometer, which has run so successfully for so many years.

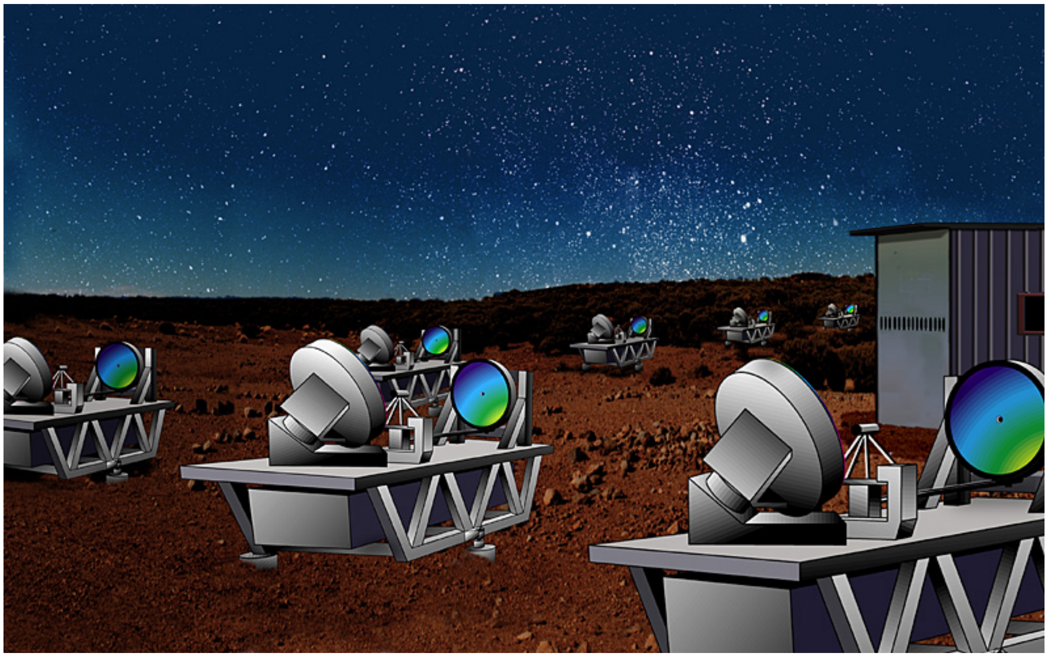
Just as the two movable telescopes of the Green Bank Interferometer gave many more baselines by spatio-temporal trading away of time for baselines, so will the MRO. Combining the beams from three telescopes has the interesting positive consequence of minimizing the number of times that the beam amplitude from each telescope is divided, maximizing sensitivity, while still allowing phase closure techniques.

6. REFERENCES

1. Garstang, R. H. 1989, Annual Reviews of Astronomy and Astrophysics, 19, 27
2. Colgate, S. and Moore, E. 1975, PASP, 87, 565

LOA: The Large Optical Array

Chris Haniff and David Buscher
(on behalf of the LOA Consortium)



• An optical/near-IR synthesis telescope for 0.3 milliarcsecond imaging

- Galactic and extragalactic capabilities
- Broad-based astronomical programme

• A broad collaboration between UK universities

- UK technical consortium: Cambridge, Durham, ICSTM, UCL
- Science steering group: 8 further UK universities

• Unmatched by all planned and existing arrays

- 15 telescopes → rapid high-quality imaging of complex objects
- 1.2 m collectors → sensitivity to reach magnitude 14 at J, H and K
- Baselines up to 500m → sub-milliarcsecond resolution
- Broad spectral coverage (0.6-2.4 μm), with resolution R≥250

Design: AVG

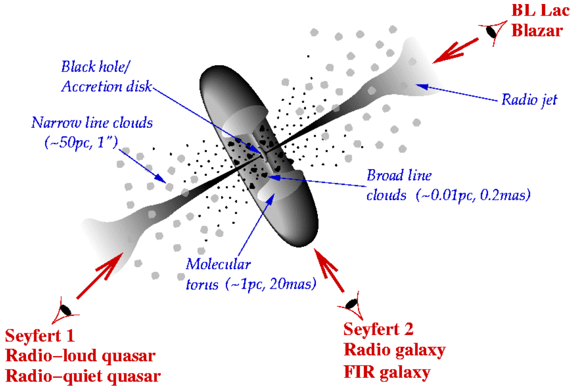
Leiden 2000

LOA Science

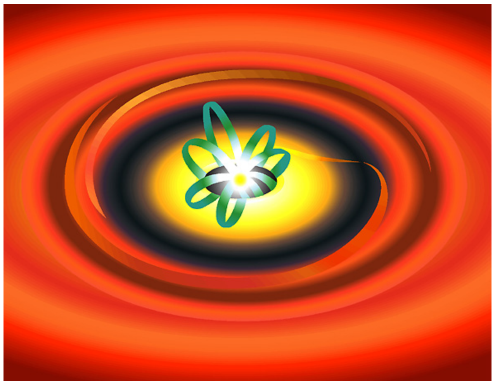
Broadly based, but centred on 3 key areas:

• Active galactic nuclei

- >50 targets out to 100 Mpc at 0.2-200 mas resolution
- Imaging of the nuclear dust component, the BLR, synchrotron jets, and nuclear & extra-nuclear starbursts



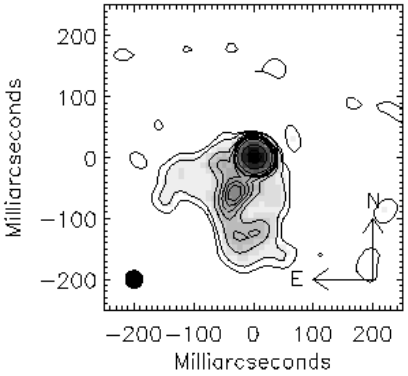
• Star and planet formation



- Protostellar discs in Taurus and Orion on sub-AU scales
- Disc clearing
- Magnetically channeled accretion
- Jets and outflows
- Low mass companions

• Stellar accretion and mass loss

- Mass loss at 1 R_* in AGB stars and PN progenitors
- Be emission nebulae and WR winds
- Eclipsing binaries on Roche lobe scales
- Direct measurement of Cepheid and Mira pulsation



2.2 μm interferometric image of dust envelope around VY CMa. Observations from a 15 element array with resolution ≈ 40 mas

Design: AVG

Leiden 2000

LOA Technology

• Based on proven technology (COAST)

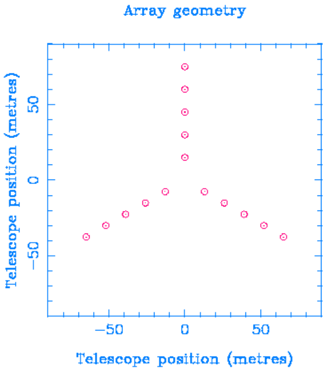
- Cambridge Optical Aperture Synthesis Telescope - optical/near-IR interferometer with 5 × 0.4 m unit telescopes currently operating with baselines up to 50 m

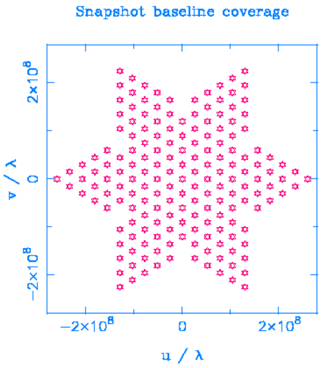
• The challenge: limiting magnitude J,H,K=14

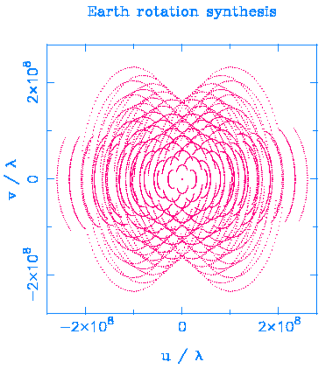
- Minimise number of optical surfaces and optimise coatings
- Capitalise on active and adaptive optics

• Array layout

- Y design for excellent snapshot imaging
- Semi-redundant for phase bootstrapping

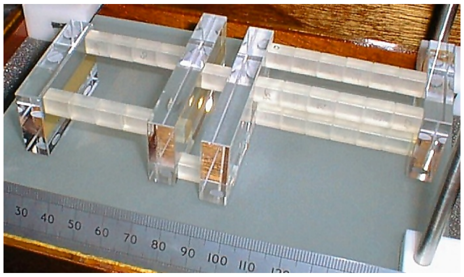

Array geometry


Snapshot baseline coverage


Earth rotation synthesis

•Beam combination

- Several beam combiners to maximise signal to noise
- Miniature beam combiners for thermal and mechanical stability



Contacts

Chris Haniff and David Buscher
Astrophysics Group, Cavendish Laboratory,
Madingley Road, Cambridge CB3 0HE, UK
Email: cah@mrao.cam.ac.uk, dfb@mrao.cam.ac.uk

Design: AVG

Leiden 2000