Figure 1: *First earth removal by explosives, September 23, 1991.*

Figure 2: *The Interbeton base camp.*

Figure 3: *Drilling rig in operation, preparing the next earth removal.*

Figure 4: *Excavation material loading.*

compaction density tests are continuously made to verify that the specified loading capacity of the road, needed for the heavy transports, is obtained.

The ESO staff furthermore initiated sub-soil investigations at the location of the telescopes and started with survey work of the road leading to the Paranal area in view of improving the road, which is of paramount importance for both the construction and future operation of the VLT Observatory.

Last but not least, the ESO staff was involved in designing, contracting and in the installation of the construction base camp which provides offices, dormitories and living quarters in which they will work and live for a number of years, until the new Observatory Buildings, under design with COWI Consult in Denmark, are available.

# A Report on the Second ESO Conference on High Resolution Imaging by Interferometry

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Over 200 scientists and engineers participated in the October 15 to 18, 1991 ESO Conference on "High Resolution Imaging by Interferometry", a conference devoted to ground-based optical interferometric imaging in astronomy. This was the second conference on this topic, the first one having been held also in Garching in March 1988. In addition to four introductory and review talks, the conference included 150 contributions on single- and multiple-aperture interferometric imaging and three working sessions on adaptive optics, detectors and path-length compensation. Sixty of these contributions were given orally, the rest by means of poster presentations. To keep the size of the conference within reasonable limits and to avoid parallel sessions, the scope of the meeting excluded related topics like astrometry by interferometric means and contributed papers on astronomical adaptive optics. The latter topic will be a major topic at the April 1992 ESO meeting in Garching on "Progress in Telescope and Instrumentation Techniques". Attendees included participants from Australia, Canada, China, Japan, Mexico, the USA, the USSR, and of course many European countries.

## Tutorials

As was the case in the first conference, it was preceded by a day of tutorials intended for newcomers to the field. It is becoming very clear, however, that these tutorials have a much broader function. They are also attended by "oldtimers" (old in this field means more than half a dozen years!), including a Nobel Laureate, who wanted to catch up on recent developments in the more

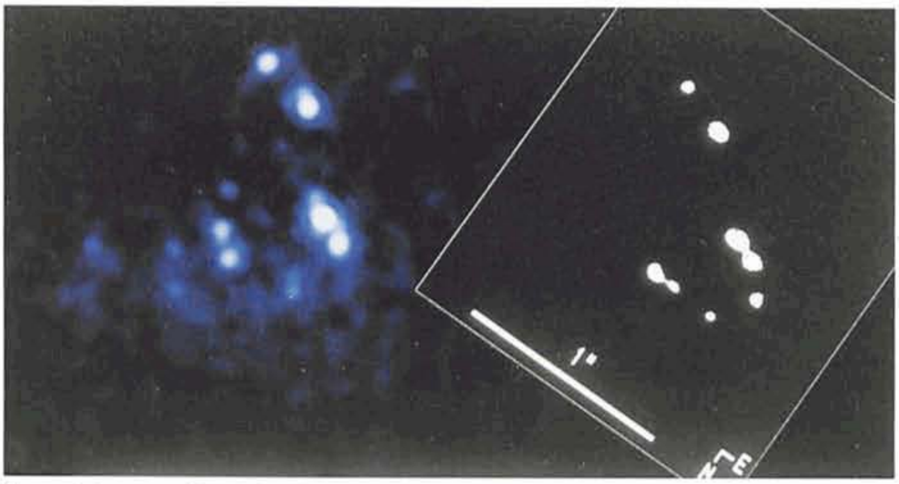


Figure 1: *Images of the object R136 in the Magellanic Clouds obtained with the Hubble Space Telescope (left, after image restoration) and by means of speckle interferometry with the La Silla 2.2-m telescope (right). (Courtesy G. Weigelt et al.)*

relaxed atmosphere associated with the tutorials and preceding the main conference. Over two thirds of the conference participants attended the tutorials which were given by François Roddier on Optics of the Atmosphere, Gerd Weigelt on Speckle Interferometry, John Davis on Long Baseline Optical Interferometry, and by one of us (FM) on Adaptive Optics.

## The Conference Itself

Four full days were devoted to discussions on the rapid progress in the techniques of astronomical imaging by interferometric means and in the presentation of recent astronomical results. Broadly, the techniques and their results can be divided by single-aperture imaging and multi-aperture imaging. Single-telescope interferometric imaging started in 1959 with Antoine Labeyrie's pioneering work in speckle interferometry. Since then these techniques have come a long way, reaching the stage where diffraction-limited imaging can be obtained on relatively faint, complex objects. Recently full aperture, speckle interferometry with single telescopes has been complemented with single-telescope interferometry using masks on the telescope aperture. Several results of the masked aperture observations were presented at the conference.

In terms of the development of imaging algorithms the latter provides an important step towards multi-aperture interferometric imaging in which the subapertures of the single telescope are replaced by an array of telescopes. In the resulting interference signal at the combined focus the amplitudes and closure phases are measured as is done in the single masked aperture experiments and also in radio astronomy observations. The algorithms for making images are virtually the same for all three types of observations. The trick in multi-aperture interferometry is the combination of the radiation in such a way as to obtain the highest possible sensitivity by maintaining the interference signal, or fringe, contrast.

We here summarize the parts of the conference on speckle imaging, masked aperture imaging and multi-aperture imaging. The outline of the conference is being followed. Using a number of real-time experiments in his magnificent opening lecture, Prof. W. Martienssen of the University of Frankfurt/Main demonstrated the dual nature of light, waves and particles. It was a fascinating experience, even to the conference participants most of whom are experts in this field but who, like us, forget about the beauty of light in their quest to manipulate it.

## Speckle Interferometry: Nearing Maturity?

In contrast to previous conferences and workshops on speckle interferometry, there was relatively little discussion of the many different techniques available for the analysis of speckle observations. In the past a wide variety of algorithms was always discussed and compared. The present discussions and results focussed, however, mostly on bispectrum analysis (or their analogues: speckle masking and triple correlation) for the analysis of speckle images, with a somewhat lesser attention given to the Knox & Thompson algorithms. The latter requires fewer numerical resources for data analysis, otherwise the bispectrum technique appears to be preferred. Judging from the presentation of many astronomical results one has to conclude that this type of observation is reaching a state of substantial maturity. Also the excellent agreement between the images of R136 obtained with the La Silla 2.2-m telescope with those obtained with the Hubble Space Telescope (Fig. 1) provides convincing evidence that speckle imaging has come of age.

At the conference results were presented of other objects, including observations of such diverse objects as

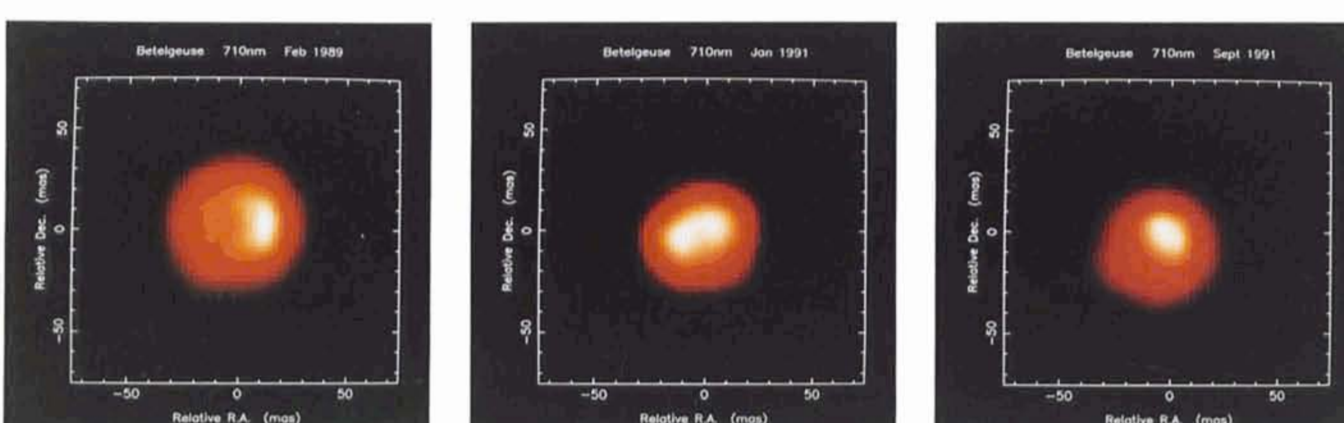


Figure 2: *Images of the variations of the red supergiant α ORI taken with the 4-m Herschel telescope at three epochs using aperture masking. The width of the Airy disk for this telescope is about 30 milli-arcsec resulting in only 3 to 4 pixels in this 50 milli-arcsec star. (Courtesy Baldwin et al.)*

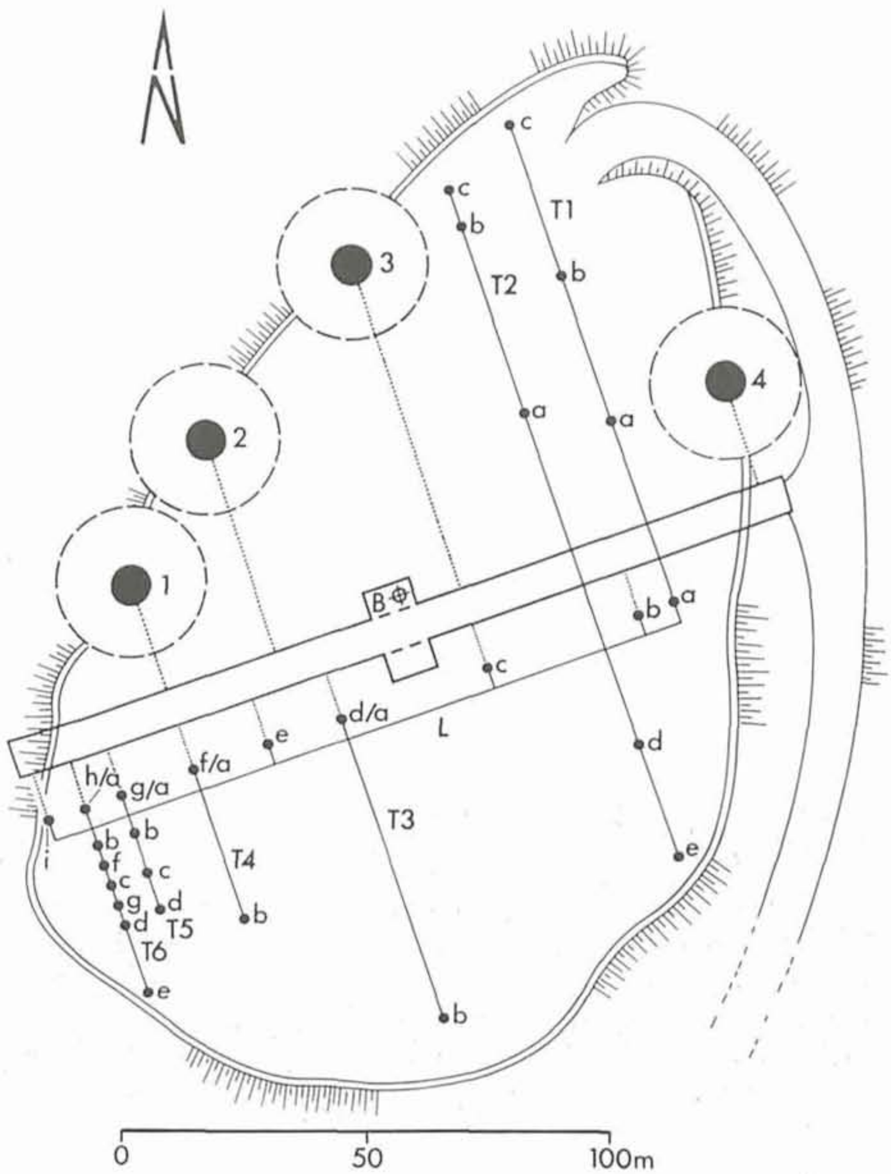


Figure 3: *Layout of the VLT Interferometer. Large dark circles indicate the locations of the 8-m telescopes. Small dark circles are the locations of the stations for the 180-cm diameter mobile auxiliary telescopes. The large rectangle is the location of the interferometric tunnel. A detailed description of the VLTI layout will appear in a future issue of the* Messenger.

a visible speckle camera (see also September 1991, *The Messenger*). Both of these cameras will make use of the unique high imaging qualities of the VLT telescopes. In their performance they will be aided by the VLT adaptive optics which can be viewed as a way of improving the astronomical seeing hence enhancing the sensitivity and limiting magnitude of the cameras.

In contributions by Roddier and one of us (JMB) the point-spread function of so-called partial adaptive optics was discussed. The VLT adaptive optics will be designed to work fully at 2 μm under median seeing conditions. At shorter wavelengths it will work partially. It is becoming very clear through numerical modelling that in such a partially functioning adaptive optics system the point-spread function consists of a spike with the characteristics of an Airy disk superposed on a broad halo with the width approximating the seeing disk. The shape of this function is not unlike that of the aberrated Hubble Space Telescope. The fraction of the total energy in the spike characterizes the point-spread function well. It amounts to 10% or more at visible wavelengths depending on the seeing. Because of the narrowness of the spike (0.0125 arcsec at 500 nm) and the relatively large width of the halo (0.5 arcsec) the relative central intensity of the spike is large. Roddier therefore suggested that long-exposure images may be used to good advantage over speckle images to give a better limited sensitivity than speckle cameras, of course after image restoration for the background halo (à la Hubble). The VLT Visible Speckle Camera will probably be designed to accommodate this partial adaptive optics, long-exposure imaging mode.

Eta Carinae, the Seyfert galaxy NGC 1068, the Galactic Centre (see September 1991 issue of the *Messenger*) and the Sun.

## Impact on the VLT Instrumentation Programme

With the 8- to 10-m diameter telescopes coming on the scene, the technique of speckle interferometry will result in images with a linear resolution 4 times larger than shown in Figure 1 (or 16 times the number of pixels per resolution element). The VLT instrumentation programme includes two instruments for diffraction-limited imaging with the individual VLT telescopes: a near-infrared camera for the 1 to 5 μm region to be built by a consortium headed by the Max-Planck-Institut für Astronomie and

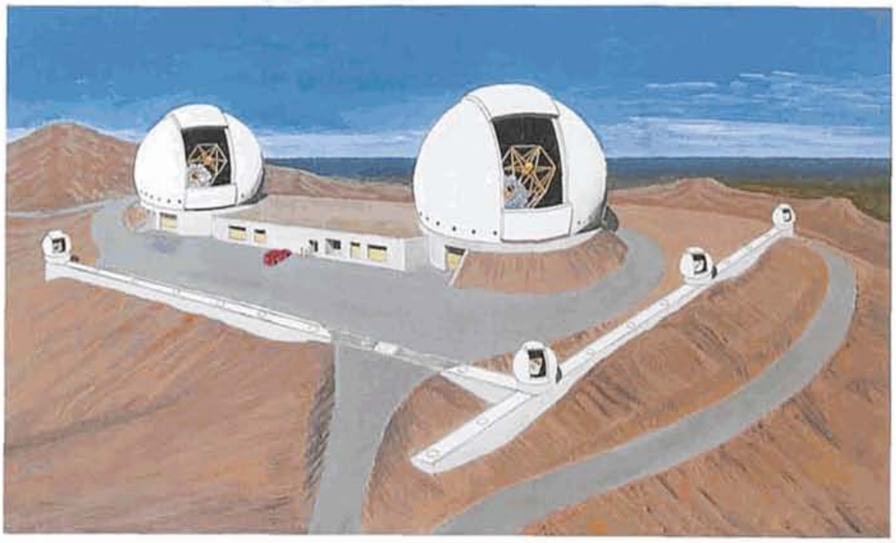

Figure 4: *Artist's view of the planned Keck Interferometric Array consisting of two 10-m telescopes and 4 movable 150-cm telescopes. (Courtesy A. Meinel et al.)*

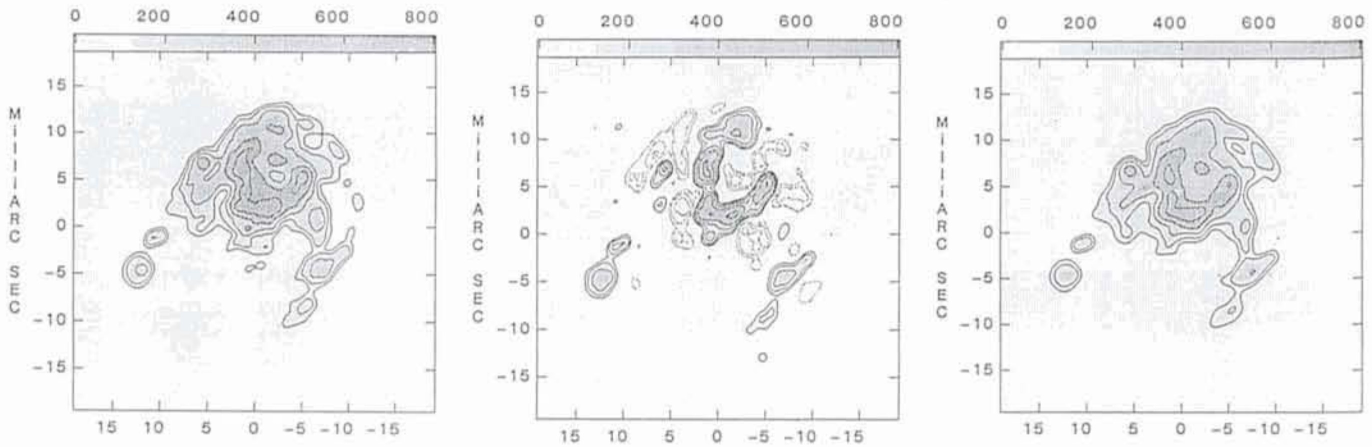


Figure 5: *Image reconstruction with the VLT Interferometer 8-m-telescope array (no auxiliary telescopes used). Left: input test image. The image is observed at 1 μm wavelength where the radius of the Airy disk is 30 milli-arcsec. The object is therefore just unresolved with the individual 8-m telescopes. Declination = 65°. Middle: image reconstructed without using the central (u,v) plane coverage resulting from a single 8-m telescope. Right: image reconstruction including the single 8-m (u.v.) plane coverage. (Courtesy R. Braun et al.)*

## Aperture Masking: a Step Towards Multi-Aperture Interferometry

Many large-aperture telescopes (e.g. Hale telescope, Herschel telescope and Anglo-Australian telescope) are now being successfully used for high angular resolution imaging using aperture masks to mimic multi-aperture interferometry. Figure 2 shows a fine result of these experiments for the variable red supergiant star Betelgeuse.

These experimental observations are of great importance not only because of their astrophysical impact but also as a precursor to the imaging with multiple aperture interferometers. By using aperture masking the validity of imaging algorithms can be evaluated under realistic observing conditions, including various levels of photon noise.

## Multi-Aperture Interferometry

A great deal of time was devoted to discussing the progress in multi-aperture interferometry. In contrast to speckle interferometry this is a field which is experiencing rapid advances in the development of experimental techniques but with the ability to do full two-dimensional imaging still to be realized. Interferometers in existence are now used to do astrometry (not within the topic of the conference) and to determine a limited number of parameters on stellar objects like diameters and binary orbits and separation. Table 1 lists the interferometers presently routinely in operation.

The last two interferometers in Table 1 (SUSI and COAST) have only recently come into operation and first results were reported at the conference. What is especially impressive in these new interferometers is that "first fringes" are obtained soon after the installation of the interferometer testifying to the fact that the construction of optical interferometers and delay lines with the required opto-mechanical and operational properties is well within the state of the art.

In addition to the operational inter-

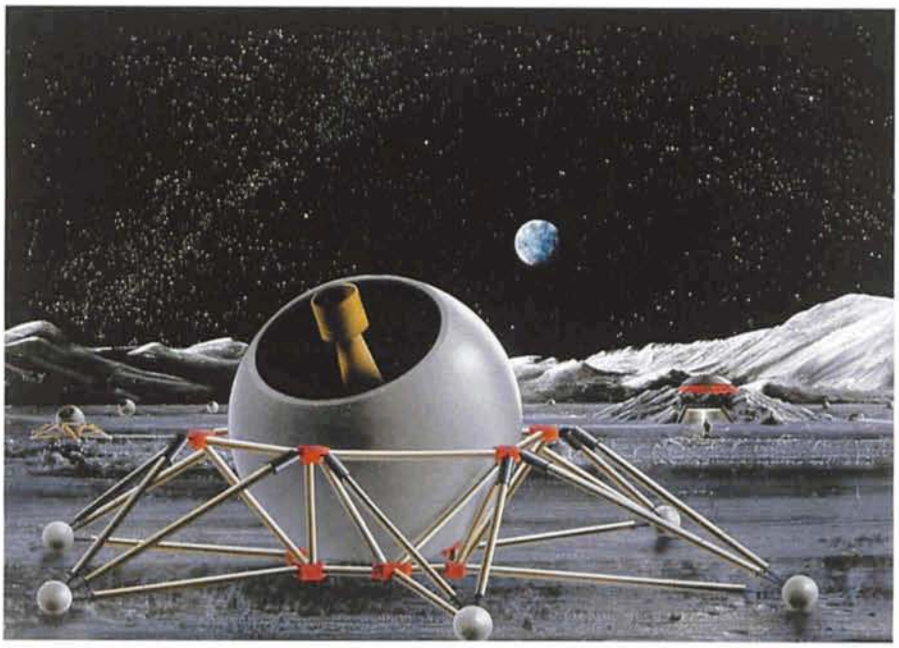

Figure 6: *Artist's view of Antoine Labeyrie's proposal for a Lunar Optical Very Large Array. In foreground one of the 27 telescopes on its transporter. To the right in the background the beam-combining station. (Courtesy A. Labeyrie.)*

Table 1: *Optical Interferometers now in Operation*

| Location | Maximum Baseline | Number of Telescopes[a] | Telescope Aperture |
|---|---|---|---|
| CERGA/I2T | 140 m | 2 | 26 cm |
| CERGA/GI2T | 70 m | 2 | 150 cm |
| CERGA/Soirdete | 15 m | 2 | 100 cm |
| MMT | 5 m | 6 | 180 cm |
| Mt. Wilson/Mark III | 32 m | 3 | 5 cm |
| Mt. Wilson/ISI | 13 m | 2 | 165 cm |
| Narrabri/SUSI | 640 m | 2 | 14 cm |
| Cambridge UK/COAST | 100 m | 2 | 40 cm |

[a] = Number of telescopes in use at this time. Often more telescopes are planned.

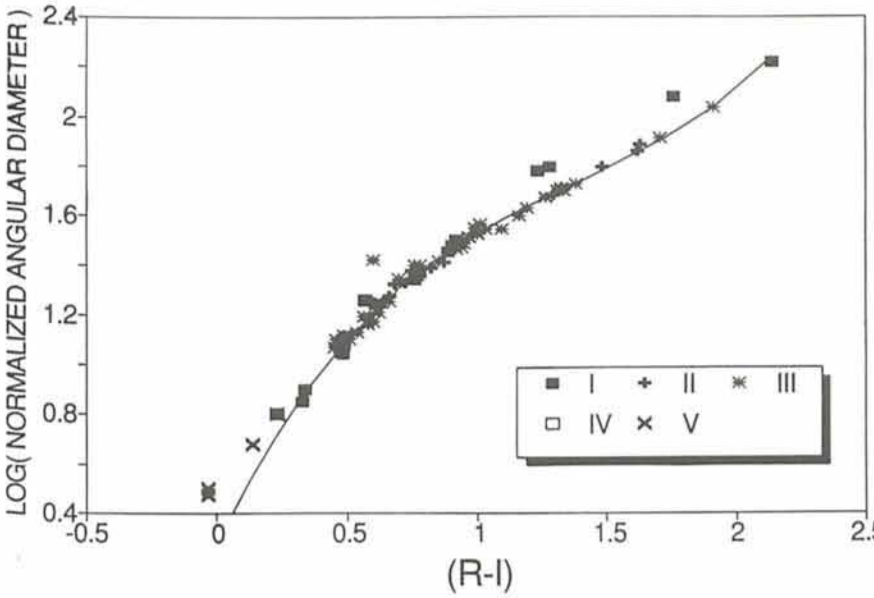


Figure 7: *Diameters of stars normalized to the same magnitude as a function of spectral type as observed with the Mark III interferometer. (Courtesy A. Quirrenbach et al.)*

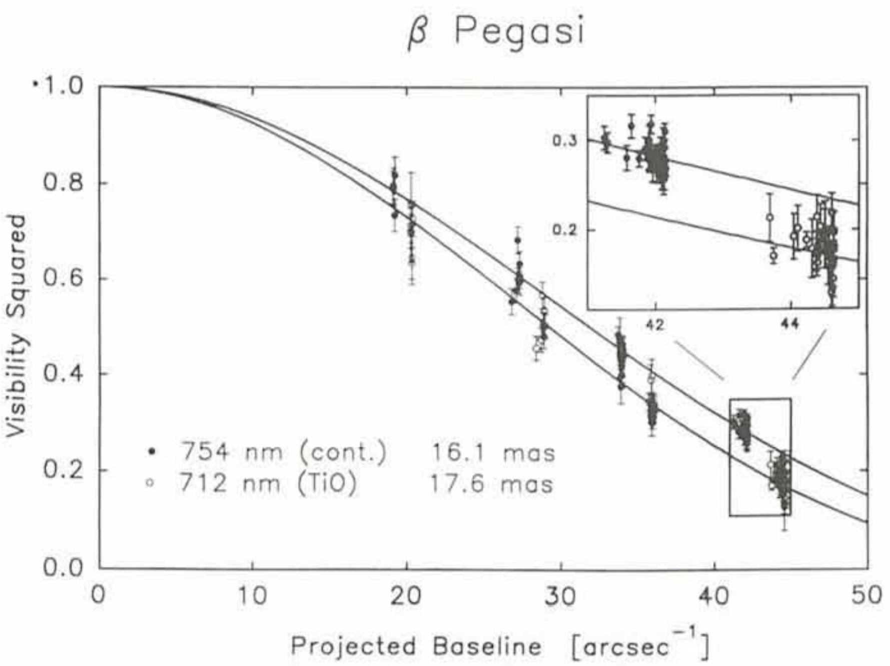


Figure 8: *The fringe visibility as a function of interferometer baseline for two spectral bands centred respectively on a TiO molecular band and the nearby continuum for the giant star β PEG. The derived diameters of respectively 0.0176 and 0.0161 arcsec have an error of ± 0.0001 arcsec so that the differences are real. The differences are an important diagnostic for the extended atmosphere. (Courtesy A. Quirrenbach et al.)*

ferometers listed in Table 1, a number of interferometers are in the construction and planning phase. The former include the Big Optical Array (BOA) by the US Naval Research Laboratory, the US Naval Observatory Astrometric Interferometer, the ESO VLT Interferometer (see Fig. 3), the IOTA array by the Center for Astrophysics, an array at the Khazan Observatory (USSR), and the IRMA array by the University of Wyoming. In the planning phase are the Optical Very Large Array (OVLA) by Antoine Labeyrie, the Keck Interferometric Array (KIA) shown in Figure 4, the CHARA interferometer of Georgia State University, and extensions of some of the arrays listed in Table 1.

Most of these arrays are intended to produce images in ways similar to the way this is done in radio interferometers using image synthesis techniques relying on tracking the object while it moves across the sky, thus causing the generation of a number of tracks in the (u,v) Fourier transform plane. The relatively large sizes of some of the telescopes involved causes these tracks to be relatively "fat" and to give a good (u,v) plane filling near the low frequency origin. The latter is very important in giving high quality images (see Fig. 5).

At a minimum one night is needed to generate an image as shown in Figure 5. Often more than one night might be needed if a good signal-to-noise ratio is required. An important advantage of the VLT Paranal site is the large periods of clear skies allowing uninterrupted (u, v) plane tracks. Time synthesis techniques are, however, obviously inadequate for observations of full images of objects which change on a rapid time scale (less than one day). For that type of interferometric imaging "snapshots" are desired which can only be obtained by arrays of many telescopes or by the capability to rapidly reconfigure an array with fewer telescopes. Antoine Labeyrie described his plans to construct such an Optical Very Large Array, or OVLA, containing 27, or perhaps even 130, telescopes on Earth and eventually on the Moon. Figure 6 shows an artist's view of the lunar version of OVLA. A price to pay for making snapshot images by the simultaneous use of so many telescopes at once, over an array of a few telescopes, is the loss in signal-to-noise. This results from the need to mix in optical interferometry all radiation directly, so that the signal for each two-telescope baseline contains the photon noise of the light collected by all telescopes. This is a major difference between optical and radio interferometers where such a loss does not occur.

## Some Results of Multi-Aperture Interferometry

As already mentioned, full imaging with multi-aperture arrays has not been achieved yet. The results of aperture masking experiments (see Fig. 2) gives confidence that the imaging arrays now being implemented will result in astronomical images within the not too distant future. Impressive results were, however, presented at the conference on the orbit of spectroscopic binaries and on stellar diameters, including asymmetries in the shape of stars like Mira. As an example we show in Figures 7 and 8 some of the diameter observations made with the Mt. Wilson Mark III interferometer.

### Major Uncertainties about the Atmospheric Wavefront Structure Function

The spatial frequency distribution of the wavefront distortions introduced by the earth atmosphere is of great importance for the behaviour of interferometers and for the wavelength dependence of the seeing disk size. Frequently it is assumed to correspond to a Kolmogoroff distribution which results in the RMS wavefront differences to grow as the baseline to the power 5/6. Serious concerns were expressed at the conference about the validity of the Kolmogoroff distribution. Observations with the two Mt. Wilson interferometers (Mark III and the ISI, see Table 1) give very different results. Whereas the Mark III interferometer indeed gives results consistent with a Kolmogoroff distribution, the ISI researchers find the exponent to decrease from ≈ 5/6 to ≈ 1/2 for good seeing conditions. This is a very large difference which will have a major influence on the predicted performance of interferometers and large telescopes.

### Future Meetings

ESO plans to hold its next meeting in this conference series (High Resolution Imaging by Interferometry III) in the spring of 1994. The topic of adaptive optics, of major interest for interferometry, will be dealt with extensively in the April 27–30, 1992 ESO conference on "Progress in Telescope and Instrumentation Techniques". From January 11–15, 1993 the IAU Symposium No. 158 in Sydney, Australia, on "Very High Angular Resolution Imaging" will focus on interferometric imaging at both optical and radio wavelengths.



## PROFILE OF A KEY PROGRAMME

# Optical Identification of Celestial High Energy Sources


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The problem of the optical identification of high energy (X-and γ-ray) sources is a classic of modern astronomy. It is only through the optical studies that one can gain complete understanding of objects, galactic and extragalactic alike, which emit a lot of their energy, through thermal and non thermal processes, in photons 1000 or one million times more energetic than the optical ones. For hard X-rays and γ rays the problem is complicated by the source location accuracy, limited by the physics of the detection interaction. In particular, the focussing of photons is only possible if their wavelength is comparable to the surface roughness of the reflecting surface, and this happens, in practice, only up to a few keV.

This is why, in the presence of a poorly positioned high-energy source, one tries to exploit the soft X-ray domain to zero on the possible optical counterparts. Broadly, this has been the strategy adopted in our Key Programme "Optical follow up identification of hard X-ray/soft γ-ray sources discovered by the SIGMA telescope" (see also Bignami et al., 1990). About two thirds of it have already been carried out, and the first