PATHLENGTH STABILITY OF SYNTHETIC APERTURE TELESCOPES
THE CASE OF THE 25 cm CERGA INTERFEROMETER

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1. Introduction

Synthetic aperture telescopes are more and more considered as a promising scheme for the next generation of Very Large Telescopes : the basic idea is to combine the beams of two or more independent telescopes. The question immediately raising when considering such a technique is the pathlength stability and the amount of pathlength difference that can be tolerated, assuming a reasonable bandwidth, to preserve coherent addition of the wavefronts and hence, high spatial frequencies observations.

To that respect the I2T (two telescopes interferometer) in operation at CERGA constitutes a remarkable test-bench for studies of mechanical, optical and atmospheric constraints that are to be faced when dealing with amplitude interferometry between several telescopes.

Random pathlength differences between the two arms of an interferometer like the I2T can be introduced by three main reasons :

1) Wavefront distorsion caused by atmospheric turbulence
2) Inclination of the baseline caused by ground motion
3) Internal deformation of the system.

The I2T interferometer can be operated either in the visible (Blazit et al., 1977) or in the near infrared ranges. The infrared interferometric experiment developed at the IFC has been already described in details by Citterio et al. (1981). An improved version of the interferometric table and the first astrophysical results have been published by Di Benedetto and Conti (1983). A complete description of the system is beyond the scope of this paper and we refer the reader to the latter reference and to Citterio et al. (1981), from which we extract figures 1, 2 and 3.

This system is extremely well suited for pathlength measurements : as seen on fig. 3 the output signals of both lock-in amplifiers (set in quadrature) are recorded. It is then easy to restore both the modulus $(x^2 + y^2)^{1/2}$ and the phase $tg^{-1}(y/x)$ of the interferometric signal. Variations of this phase correspond to displacements of the fringe pattern in the recombined focal plane, i.e. to disbalance of the pathlength along the two arms of the interferometer.

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from Citterio,O.,Conti,G.,di Benedetto,G.P.,1981,"Scientific Importance of High Angular Resolution",ESO Conference

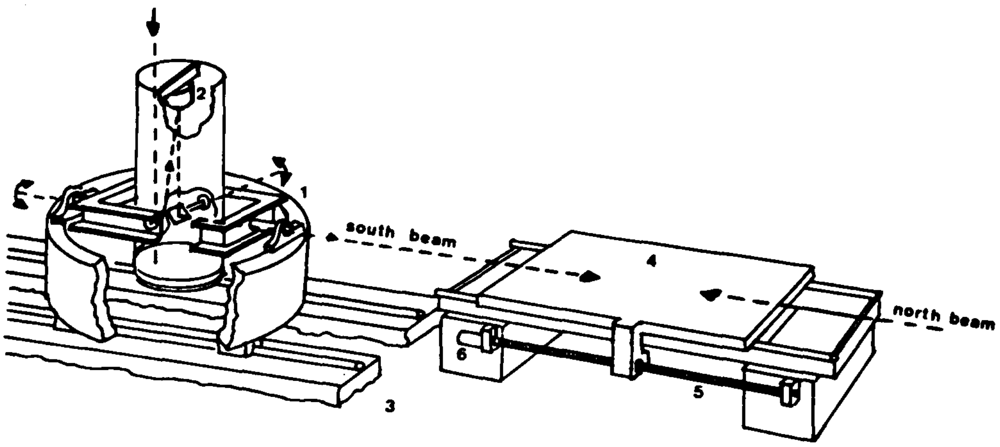

fig. 1 INTERFEROMETRIC BASE

1) 25 cm. alt-alt Coudé telescope 2)Secondary mirrors rotating support (6 different mirrors) 3) 20 m. long precision rails 4) 0.5x1 m. interferometric table 5) Precision screw for driving interferometric table 6) DC motor-encoder system

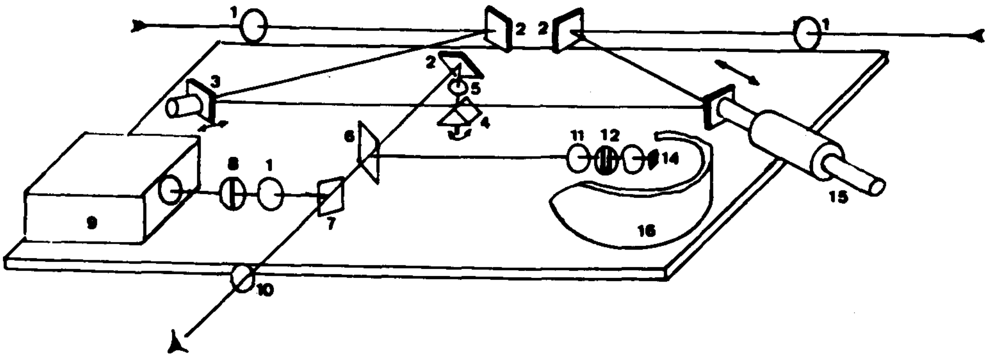

fig. 2 INTERFEROMETRIC TABLE

1) Field lenses 2) Flat mirrors 3) Piezoelectric fringe modulator 4) Roof mirror (photometric modulator) 5) Relay lens 6) I.R. beam splitter 7) Beam splitter 8) Relay bi-lens 9) TV camera for telescopes guiding system 10) Eyepiece 11) Interchangeable band-pass filter 12) Interchangeable fringe mask 14) InSb infrared detector 15) Burleigh inchworm translator 16) Liquid nitrogen dewar

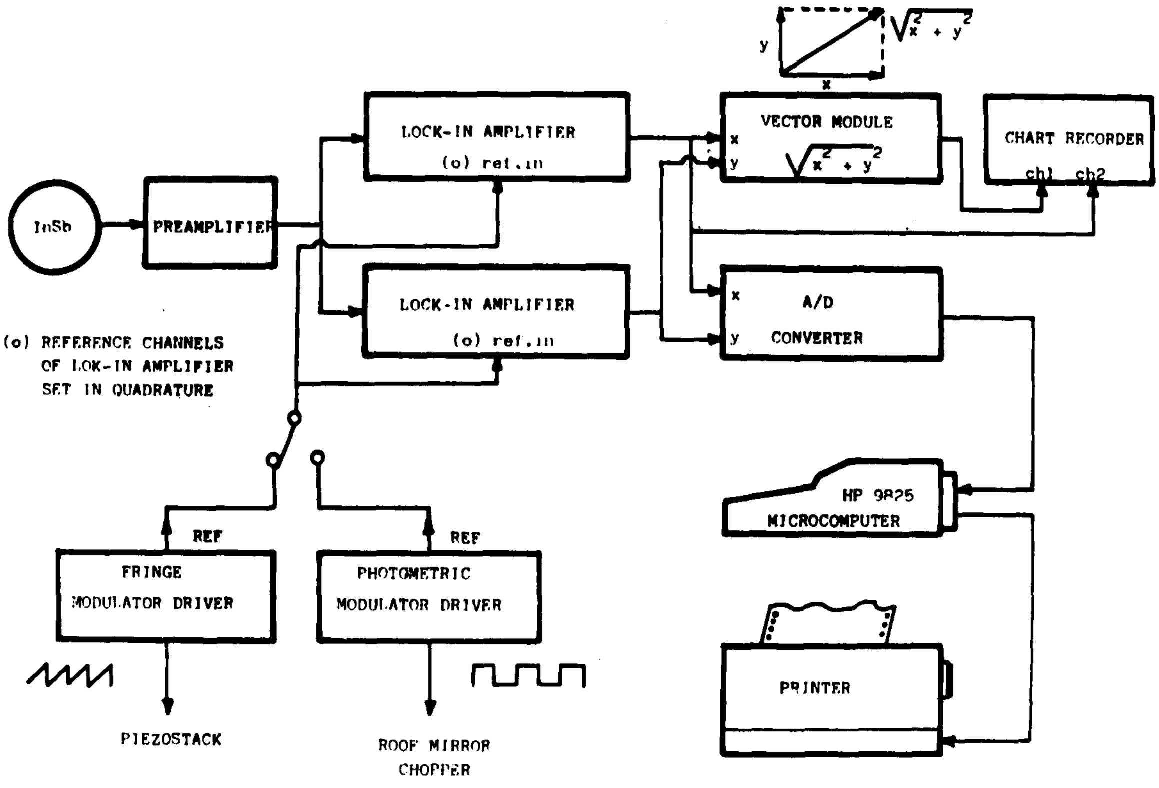

fig. 3 ELECTRONICS BLOCK DIAGRAM

(from Citterio,O.,Conti,G.,di Benedetto,G.P.,1981,"Scientific Importance of High Angular Resolution", ESO Conference, Garching)

2. Observations and data reduction

2.1 We observed the star α Boo ($m_K = -3$) at $\lambda = 2.2\ \mu m$ and with $\lambda/\Delta\lambda = \pm 0.2$ for three baselines, successively B = 8 , 12.5 and 16 meters : larger baselines could not be used because the star is resolved and the contrast of the fringes vanishes near B = 22 meters (Di Benedetto and Conti, 1983). For each observation, after acquisition of the interferometric signal, we adjusted the position of the table in order to maximize the modulus of the outputs and then recorded the data without any further correction. The observations lasted for about 90 minutes, symmetrically around the transit of Arcturus.

During this night the seeing was excellent. We had no way to measure the Fried parameter r_o, but the telescopes were clearly diffraction limited in the visible : this leads to a lower limit for r_o at 2.2 μm of 0.80 m. We also recorded meteorological data and the microseismic activity on the "Plateau de Calern" : description of the monitoring of the microseisms by horizontal pendulums has been given by Laclare and Cormier (1981). We used the N-S and the E-W pendulums located at point C (their figure 5) about 400 meters from the baseline.

2.2 The only problem with data reduction is, of course, the 2π indetermination of the phase : we need to follow the phase from point to point and make sure that any $2n\pi$ jump did not occur. The algorithm which reconstruct the phase excursion, simply chooses the shortest way, i.e. the smallest absolute value of phase increment from each point ϕ_{t_i} to $\phi_{t_{i+1}}$.

We can build the distribution of the phase increments,

$$\Delta\phi_{t_i} = \phi_{t_{i+1}} - \phi_{t_i}$$

and locate points where indeterminate 2π jumps are possible, i.e. points where $\Delta\phi_{t_i}$ approaches $\pm\pi$. Then we extract the longest sequences with continuity of the phase and negligible probability of jumps. The distributions of $\Delta\phi_{t_i}$ for these sequences are found roughly normal and their widths constitute a final test to detect possible jumps. For the results we present here, the variances of the $\Delta\phi_{t_i}$ distributions are $\sigma^2 = 0.17$, 0.25 and 0.43 rad^2 , for $B = 8$, 12.5 and 16 meters, respectively. Generally a sequence ends either because the phase varies too rapidly to be followed or because the modulus of the interferometric signal falls to the level of the noise : in both cases the continuity is lost.

2.3 Three sequences are presented on figure 4. The upper part of the figure shows the modulus of the signal : horizontal ticks are second of time, the vertical scale is arbitrary.

The lower part of the figure shows the reconstructed phase : each vertical tick corresponds to a rotation of phase of 2π , i.e. passage of one fringe to the adjacent one.

These results call for some remarks :

- Raw data have been largely oversampled in time : here, points have been averaged in accordance with the coherence time of the modulus signal found to be ∿ 100 ms.
- The mean level of noise and an idea of its fluctuations ($\pm\sigma$) is given for each graph. The dominant source of noise is the Johnson noise of the detector.
- Sudden jumps of the visibility can be seen on the upper graphs. Some of these peaks are due to "tilt" errors, i.e. lack of superposition of the

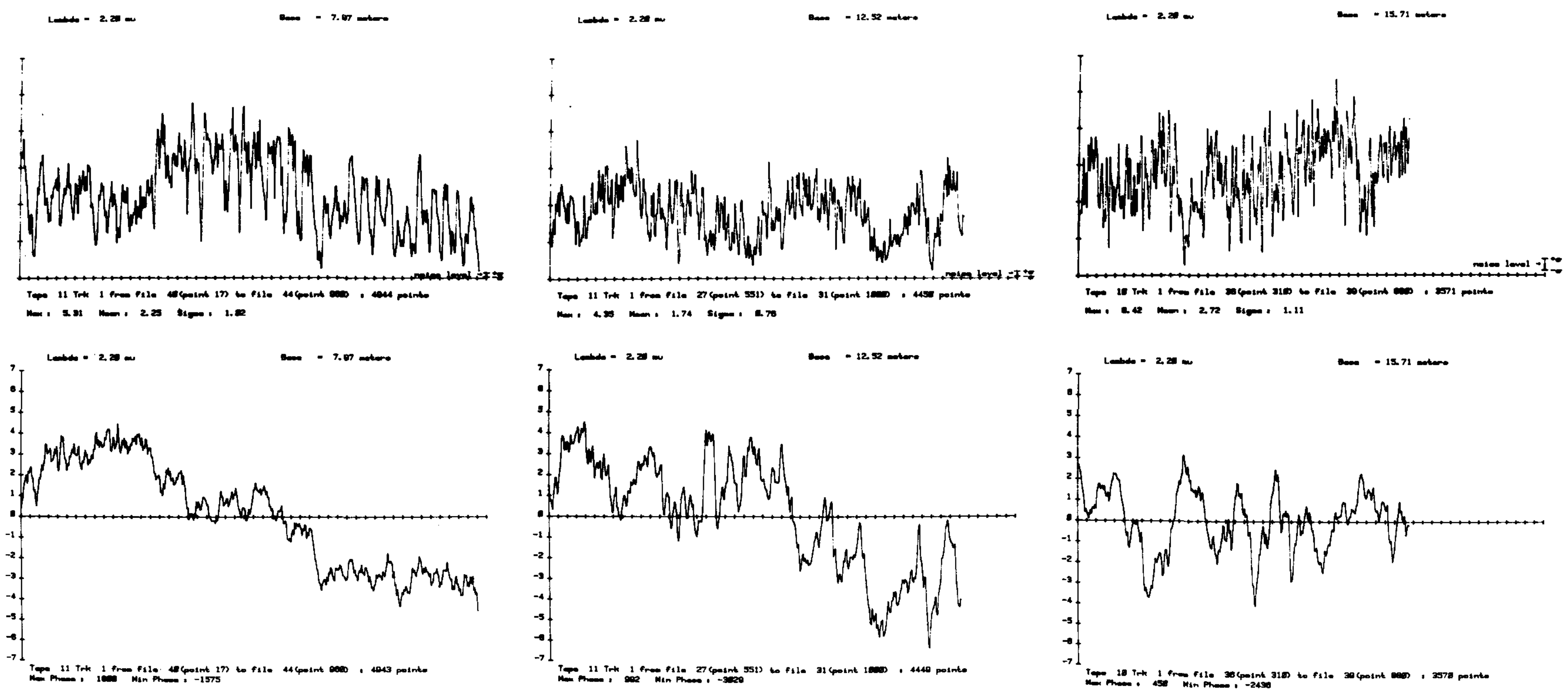

fig. 4 For three baselines, 8 m (left), 12.5 m (center), 16 m (right) are plotted the modulus(top) and the phase (bottom) of the interferometric signal

Horizontal scale : each tick is 1 second of time
Vertical scale : - arbitrary for the modulus
- for the phase, each tick represents 2π, i.e. shift of one fringe

(see text for details)

two star images in the focal plane because of wavefront tilting by atmospheric turbulence or residual guiding errors from the star-trackers. However, they are also related to a distorsion of the sawtooth interferometric modulation at high frequencies : this increases the sensibility of the system in quadrature to phase variations of π. As a consequence the fringe signal falls to zero level and this may have spoiled the reconstruction of the phase excursion for the 16 meters baseline. Consequently, this sequence should be considered cautiously. Operating with modulation frequencies smaller than 100 Hz will completely solve this problem.

- The phase measurements are not absolute, i.e. the position of the 0 on the Y-axis of the graphs is arbitrary. However we chose this position with respect to the maximum value of the modulus of the signal. Note for example the very good correlation at B = 8m between the mean level of the modulus and the displacement of the fringes. The extent of the vertical axis roughly corresponds to the coherence length ($\pm 5\lambda$): here, the signal is lost because the fringes drift out of the coherence zone.

3 - Discussion

As stated in section 1 these variations of phase can be caused by three main reasons. We will examine them in this section :

3.1 For ground based interferometry, microseisms may be a problem because they produce oscillations of the local vertical both relatively rapid and of large amplitude. At CERGA the typical period is 6 seconds and the amplitude may reach 0".1 (Laclare and Cormier, 1981). It is easy to calculate that at $\lambda = 2.2$ µm and for B = 16m, the pathlength difference may be as large as 7.5 µm. Oscillations of the fringes related to microseisms are commonly seen at the I2T in the visible (Koechlin, private communication).

However, for these observations this is not the dominant phenomenon. The horizontal pendulums revealed no microseismic activity and we can put an upper limit to the possible phase deviations caused by ground motion of 0.5 rad peak to peak, at worst.

3.2 Sudden, large amplitude phase jumps can be seen on fig. 4 : they are caused by "mechanical" errors, i.e. variations of pathlength introduced by internal deformation of the interferometer. The design of the I2T makes it a very stable, vibration-free instrument. However the two telescopes are potential sources of pathlength variations especially because of wind loading. This was not the case here, as the wind velocity at ground has been zero during the observations.

We rather suspect the driving mechanism which slides the table to follow the theoretical position of the "white ligth" fringe. This system has not been designed for this kind of experiment but rather to follow the visible fringes, with a coherence length of ∿ 50 μm, even if it is far more precise than that. As a matter of fact, large fluctuations of the visibility caused by wandering of the fringes in and out the coherence region are often observed in the infrared with smaller coherence length when the table approaches and leaves the transit point : at these moments the velocity of the table is too small to smooth out the step-by-step nature of the translation.

3.3 It is not possible to isolate the influence of mechanical errors or even to calibrate them for these observations. However, figure 4 clearly shows that the dispersion of the typical excursions of the fringes increases with baselength. This is the behaviour expected if the dominant phenomenon is the wavefront distorsion due to turbulence.

Here, the relevant parameter is the phase structure function (Roddier, 1981) :

$$D_\phi(\xi) = <|\phi(x) - \phi(x+\xi)|^2> \qquad (1)$$

From the Kolmogorov theory of atmospheric turbulence and in the near field approximation, we know that $D\phi$ is related to the Fried parameter r_o by :

$$D_\phi(\xi) \approx 6.88\,(\xi/r_o)^{5/3} \qquad (2)$$

Hence, the standard deviation of the phase differences between two pupils separated by distance B is :

$$\sigma_\phi(B) = \{D_\phi(B)\}^{\frac{1}{2}} = 2.62\,(B/r_o)^{5/6} \qquad (3)$$

Breckinridge (1976) finds a good agreement between eq.(3) and measurements in the range 0.2 to 1.5 m.

As explained above it is difficult to disentangle, in the data of figure 4, the atmospheric contribution to σ_ϕ from other causes. On the other hand, we do not have measurements of r_o . However, we know that r_o (2.2 μm) $\gtrsim$ 0.8 m (see 2.1) and it is very likely that r_o (2.2 μm)< 2m which corresponds to 0.34m in the visible (i.e. a seeing of ∿ 0.3" !)

On figure 5, we have tentatively plotted the best estimations of σ_ϕ in radian from our data and values from eq.(3) for r_o = 1m and 2m.

Even taking into account the large incertitudes we have placed on our estimations, it is impossible to make them fit the theory. There is a discrepancy of a factor ∿5 , assuming for r_o a value of 1m.

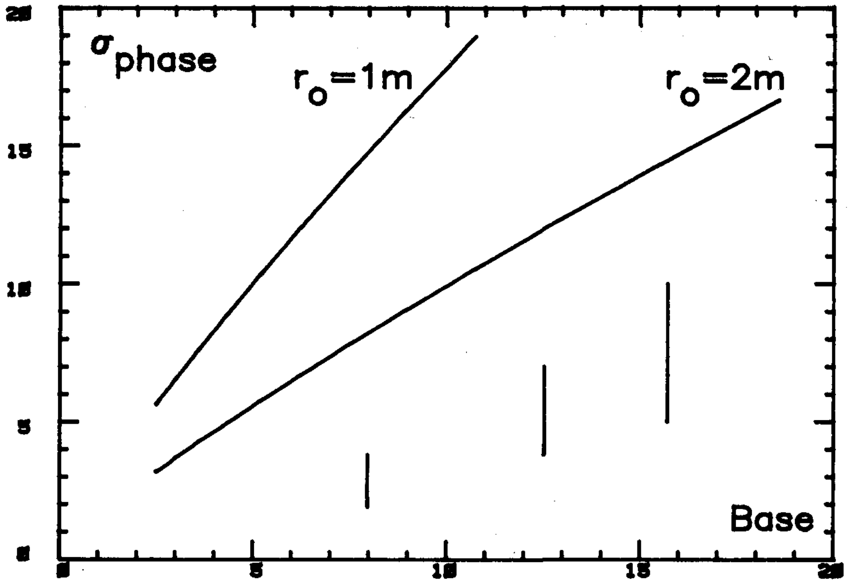

fig. 5 Vertical bars are the estimations of phase dispersion, in radian, measured at the three baselines. Continuous curves show the expected values for r_o=1 and 2 meters.

Equation (3), nevertheless, is only valid in the inertial range of turbulence, i.e. for $B \ll L$, where L is the outer scale of turbulence. We do not know L in our case, but typical values of 30 to 100 m are assumed. So, we may observe here an effect of saturation of the phase dispersion as B approaches L. The fact that σ_ϕ still increases with B, could mean that we are still too far from L, even at 16 m. However, this interpretation is questionable, the increase beeing rather steep.
Finally, we can suspect a contribution from a variation of r_o during the night. Each observations have been separated by $\sim$ 20 minutes, a timescale in which r_o can change by large amounts. On another hand L, might also change during the night.

4 - Conclusion

We have presented here observations of pathlength variations with the I2T amplitude interferometer of CERGA equiped with the infrared experiment of IFC. These preliminary datas show that :

- It is possible, on bright sources, to follow the phase of the interferometric signal.
- Hence it should be possible, at least at $\lambda \gtrsim 2.2$ μm, to correct the pathlength differences in real time.

- Microseisms remain a potential problem, but only if one wants real time pathlength correction at large baselines : a calculation similar to that of section 3-1 shows that for B = 200m one can expect pathlength excursions of 100 μm, drift rates of ∿ 15 fringes/second. A complete site testing for a large synthetic aperture telescope should include this topic.
- The I2T has shown an excellent stability, as the main cause of pathlength variations is already the turbulence for B > 8m. On the other hand the fact that the phase excursions are found much smaller that was expected from the theory is very promising. It shows that σ_ϕ tends indeed to saturate, due to proximity of the external length of turbulence, even for baselines small in comparison with projected spans of future interferometers. Nevertheless the lack of experimental informations still prevent us to understand the behaviour of the phase structure function for pupil separation comparable with the external length. Efforts should now be made in that direction, as well as systematic measurements of the external scale of turbulence.

Acknowledgments

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