16 m LARGE SLIT APERTURE TELESCOPE FOR VERY HIGH ANGULAR RESOLUTION ASTRONOMY

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ABSTRACT

The expected progress of diffraction limited imaging methods and the apparition of new super resolution techniques like differential speckle interferometry would justify the construction of a 15 m class telescope dedicated to diffraction limited observations in order to fulfil the potential of high angular resolution astrophysics of 15 m class instruments, but the construction of such a telescope is conceivable only if its cost is much smaller than the cost of the equivalent all purposes VLT. In this paper we suggest that a telescope with a long and thin rectangular primary (16 m X .4 m say), able to rotate around the optical axis to ensure a full coverage of the frequency plane, would do almost as well than a conventional 16 m aperture telescope for high angular resolution astronomy for a cost substancially reduced. The performances of such a Large Slit Aperture Telescope (LSAT) for classical and differential speckle interferometry are examined and the releases on the optical and mechanical constraints allowed by the dedication of the instrument to speckle techniques are discussed.

INTRODUCTION

Since the introduction of speckle interferometry techniques in astronomy by Labeyrie[1], methods for diffraction limited observations through the turbulent atmosphere have given numerous[2-5] results, most of it being simple geometrical parameters of astronomical objects such as stellar diameters or binary stars separations. More recently, several authors have demonstrated the feasibility of various diffraction limited imaging techniques with computer simulations and have applied it succesfully to a small number of astronomical sources.[6,7,13] A recent example is the mapping of the dust envelope of Betelgeuse in the visible by Roddier,[8,9] who used a pupil plane rotation shearing interferometer and a maximum entropy image reconstruction algorithm. The current limitations of these techniques are essentially due to the extreme seeing dependance of the SNR, the poor dynamic range of present image tubes and the relatively small resolving power of the largest existing telescopes. The situation will be greatly improved by the progress in image tube technology and by the construction, on a very good site, of a 15 meter class telescope carefully designed to minimise dome seeing. It can thus be expected

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that, by the time of completion of a VLT, several efficient diffraction limited imaging techniques will be available.

The scientific output of these techniques will then very strongly depend of the VLT observation time available for high angular resolution imaging : it will certainly be quite interesting to obtain stellar images but the real progress will be based on a study of the changes in these images (which can occur quite fast) at a lot of different wavelenghts. We believe that the complete exploitation of the potential of a 15 m class telescope in high angular resolution astronomy will require a telescope dedicated to diffraction limited observations.

One could object to us that such an instrument could not be used under bad seeing conditions,which will occur, from time to time, even at the best possible site. The weight of this argument is greatly reduced since the introduction of differential speckle interferometry (DSI) by Beckers[10] because the SNR for these techniques is much less sensitive to the seeing than for classical speckle interferometry.[11] For bright stars (visual magnitude < 5) the SNR of DSI is even almost independant from the seeing conditions.[11] Moreover, a super resolution technique like DSI increases the need for a telescope dedicated to high angular resolution astronomy because it increases considerably the number of stars resolvable with a 15 m class telescope and the number of types of scientifical results which can be expected from such an instrument.

The construction of a telescope dedicated to diffraction limited observations is conceivable only if its cost is small with regard to the cost of the equivalent all purposes telescope. In this paper we describe a telescope with a long and thin rectangular pupil, able to rotate around the optical axis to ensure a full coverage of the frequency plane, with a long dimension in the 15 m class and a width slightly bigger than a coherence cell, and we suggest that such a Large Slit Aperture Telescope (LSAT) would do (almost) as well than a conventional 15 m telescope for high angular resolution astronomy for a price much smaller.

RECTANGULAR APERTURE TELESCOPES FOR HIGH ANGULAR RESOLUTION ASTRONOMY

Speckle imaging techniques and differential speckle interferometry require a good coverage of the frequency plane. This makes it impossible to use the already existing instruments dedicated to high angular resolution, namely the multi - telescopes Michelson interferometers, such as the CERGA ones.[12] A good coverage of the Fourier plane with such an interferometer requires a large amount of sequential measurements with movable telescopes and/or "supersynthesis" using earth rotation. The life time of some stellar structures may well be too short to allow such a procedure. Filling a large aperture with a great number of small telescopes and combining all the beams with an interferometric accuracy is certainly not simpler nor cheaper than the construction of a conventional 15 m class telescope. Thus, even if such an array would have a resolution much higher than a 15 m class telescope and even if its construction is possible (the feasability of a West-East baseline optical interferometer have not been practically demonstrated), the Michelson arrays are outside the problem discussed in this paper.

A two telescopes Michelson interferometer gives us a point in the frequency plane, which is insufficient, while a conventional telescope, which is too expensive, allows us to analyse an array of the Fourier plane. It seems therefore quite natural to consider a telescope with a long and thin pupil (ideally a linear one) which would make it possible to obtain a segment of the u-v plane. The complete frequency plane coverage could then be obtained sequentially, by a rotation of the pupil around the sight line, much faster than with a Michelson interferometer, and the gain in optical surface could result in a gain in cost.

There are two ways to approach a rectangular aperture concept. We can first say that"maximum use can probably be made of a given pupil area by stretching it out along a straight line, 100 m say, and invoking the Earth-rotation synthesis principle " (Bates, 1982).[7]

At this point two choices are again possible. We might be tempted to consider a single telescope with a rectangular filled aperture (60 m X 3 m say) and a surface equivalent to the surface of a circular 15 m telescope. This is the "slot aperture" concept. As stated by Angel, Woolf and Epps,[14] the potential of such an instrument for spectroscopy and photometry is almost identical to an equivalent area circular telescope, while its angular resolution is superior in one direction. The main drawbacks of such an instrument are its cost, probably quite higher than the cost of the same area circular telescope, and the necessity to ensure its rigidity by means of a coelostat like alt-azimuth mount fixed on a turntable, similar to the one currently under construction at the Nice Observatory for our prototype of solar slit aperture telescope[16] (figure 1). As shown by figure 2 such a mount allows only a partial exploration of the frequency plane during a single night. A complete sampling of the plane will require observations over a stubstancial part of the year and will be possible only for very northern stars.

The other way to use a given pupil area is to divide it between the telescopes of a linear array, whose separations must be small enough to ensure the continuity of the frequency plane coverage in the baseline direction. If such an array is made with a small number of large telescopes (four height meter telescopes for exemple), non redundantly spaced, the maximal baseline can reach 100 m, and the instrument will still be almost as efficient for spectroscopy and photometry than the equivalent area classical telescope. This is the "versatile array" concept as presented by Angel and Woolf in these proceedings.[15]

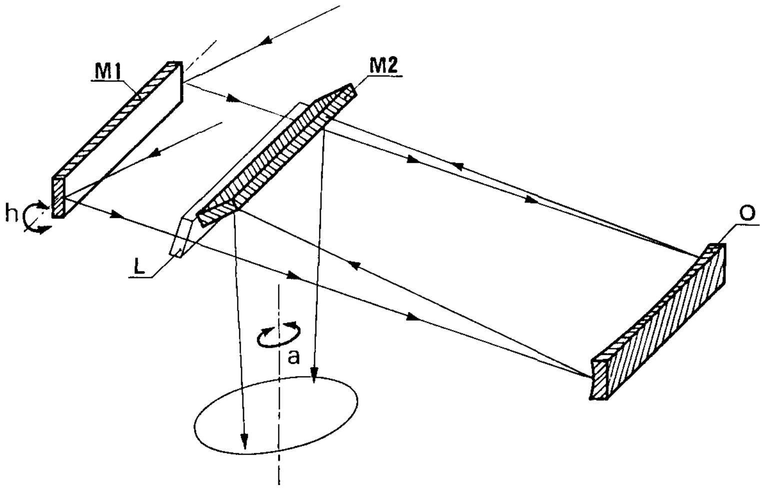

Figure 1 - Optical principle of the 80cm solar slit aperture telescope currently under construction at the observatory of Nice. The objective (O) of this intrument is a 80x6 cm rectangular parabolic mirror. the pointing is made by modyfying the altitude h (rotation of M1) and the azimuth a (rotation of the turntable). The fact that this mount keeps the mirrors fixed in the gravity field makes it very interesting for a very large Slot Aperture Telescope.

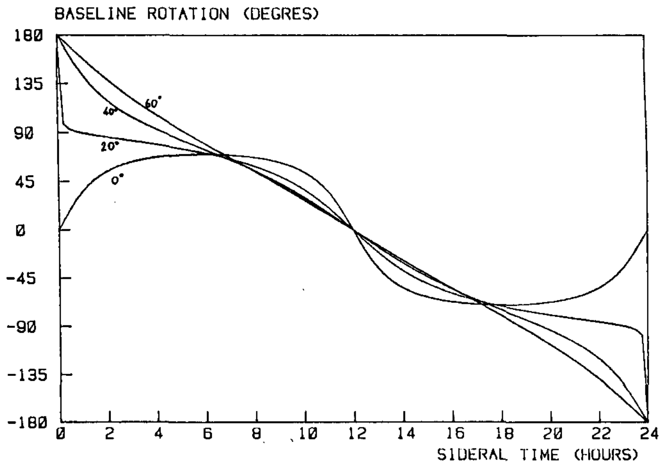

Figure 2 - Variation of the angle between the axis of the rectangular aperture, projected on the sky and the E-W direction on the sky as a function of the sideral time, for stars with different declinations (δ = 0°,20°,40°, 60°). The latitude of the observation is φ = 19°50' (Mauna Kea. Hawaï) and the stars are supposed to be transiting at midnight. It clearly appears that the exploration of all the directions is impossible in a single night.

Unfortunately, if the baseline is maintained on a North-South direction for simplicity considerations, such an instrument will present the same limitations about the frequency plane exploration than the slot aperture one, as shown by figure 3.

The common point between these two instruments is that both are intended to improve the angular resolution of a conventional telescope without degrading its potential for photometry and spectroscopy. The improvement of the angular resolution in one direction is payed by a loss in the orthogonal direction, and the earth-rotation synthesis only partially compensates that loss. Figure 4 shows the portion of the u-v plane covered during a height hours observing run of the star Betelgeuse, at an observatory located in Hawaĩ, with (a) : the C.F.H. 3.6 m telescope, (b) : a conventional 16 m telescope, (c):a slot aperture telescope of 60 m X 3 m and (d) : a North-South linear array of 4 height meter telescopes, non redundantly spaced. The transit of the star is supposed to be at midnight. It clearly appears that instruments (c) and (d) do not explore completely the portion of the u-v plane given by (b). The frequency domain covered by (c) and (d) being complementary, one solution might be the simultaneous operation, at the same location, of a " slot aperture telescope " and of a linear array of telescopes, the total surface of this pair of instruments being equal to the area of a 15 m telescope.

THE SLIT APERTURE TELESCOPE

We will now examine the second way to come to the idea of a rectangular aperture telescope. If, instead of streching out a circular pupil in a long rectangle with the same area, we shrink it down to a narrow rectangle whose length is equal to the diameter of the original circle, we discover that its potential for high angular resolution astronomy is almost unaffected, while its weight, and consequently its cost, are greatly reduced. If the length of such a Slit Aperture Telescope (SAT) is in the 16 m class it remains possible to mount it on a conventional alt-azimuth mount with an additional rotation axis making possible the full coverage of the Fourier plane. Let us now examine how the SNR for classical and differential speckle interferometry is affected by the transition from a conventional circular telescope to a SAT.

Speckle interferometry with a Slit Aperture Telescope [16,17]

Several authors [18-20] have given theoretical models for the spatial energy transfer function (ETF) of a telescope in presence of atmospheric turbulence. Whatever, the hypothesis made for the complex amplitude of the wave at the telescope aperture, Kroff and al. [18] have shown that, in the high frequency range, the ETF, that we denote as E(f), writes proportionally to the lens modulation trans-

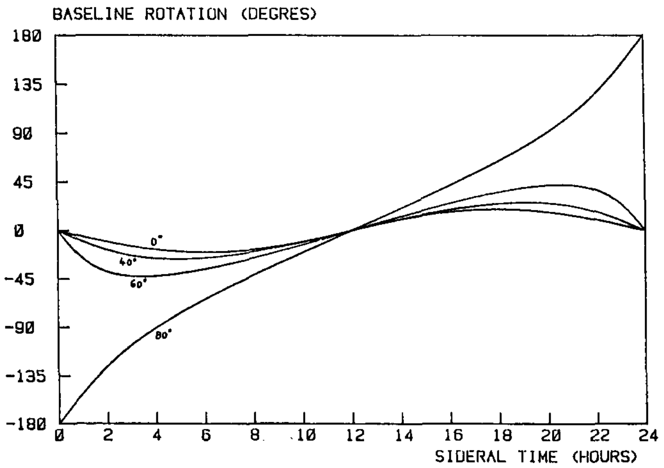

Figure 3 - Variation of the angle between a N-S baseline, projected on the sky and the N-S direction on the sky, in the same conditions than in figure 2 except for the declination of the star (δ = 0°, 40°, 60°, 80°)

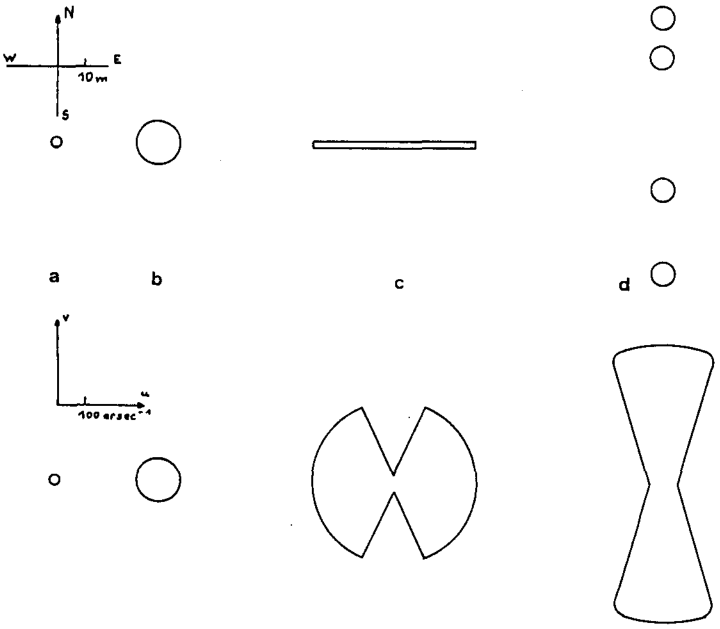

Figure 4 -Portions of the frequency plane covered during a height hours observing run on the star Betelgeuse (δ = 7°) with several types of instruments located in an observatory in Hawaï (λ = 20°). a : 3.6 m C.F.H. telescope, b : 16 m VLT, c : Slot Aperture Telescope of 60x3 m , d : N-S non redundant linear array of 4 height meter telescopes.

fer function (MTF) of the telescope T(f) :

$$E (f) = T (f) / N$$

the reducing factor N is the number of speckles present in the image and f is the spatial frequency in rad^{-1} on the sky. For a circular aperture of diameter D operated in presence of atmospheric turbulence defined by the Fried's parameter r_o[21], the number of speckles N in the image is given by the number of coherent areas on the pupil which is of the order of $(D/r_o)^2$. When a one-dimensional telescope of size D x r_o is used, the number of speckles reduces to D/r_o. As a consequence, for a given amount of turbulence, we obtain, for the high frequencies of the signal, a contrast gain of $\sqrt{N} = D/r_o$ with the SAT, compared to the circular aperture having the same resolution limit.[22] This contrast gain has been confirmed by an experimental determination of the ETF of a slit telescope in presence of atmospheric turbulence made for a 9.5 x 165 cm aperture obtained by diaphragming the 193 cm telescope of the Haute Provence Observatory (France). The comparison of the experimental ETF obtained during the same night, and for a comparable turbulence, as it can be checked from the low frequency parts of the ETF, is done in figure 5 for the two telescope types. The length of the arrow which is quoted $\sqrt{N}$ represents the ratio of the areas of the two telescopes, i.e. the theoretical contrast gain, in good agreement with observations.

For faint objects, the SNR of speckle interferometry experiments is dominated by the photon noise. The photon noise is inversely proportional to the collecting area. Thus the increase of photon noise due to the transition from a circular pupil to a rectangular one is exactly compensated by the contrast gain produced by the operation and the SNR is unaffected as long as the width of the pupil remains larger than the seeing parameter r_o. The circular pupil keeps an advantage because it gives all the directions of the Fourier space at the same time. To obtain the same result with the SAT we need a sequential exploration during a time proportional to the ratio D/l between the length and the width of the slit aperture. This is equivalent to a loss of SNR equal to $\sqrt{D}/\sqrt{l}$. This result can be extented to most of the techniques derivated from speckle interferometry.

High angular resolution astronomy needs more and more a combination of high angular resolution and high spectral resolution informations. With a 2 D telescope, the natural approach is to analyse sequentially 2 D images at different wavelength. SATs are suited for the alternative approach often used in solar astronomy, based on the recording of spectrograms combining spatial information in one direction and spectral information and on the sequential analysis of the orthogonal direction. If the number of desired spectral elements is bigger than D / l , the comparation turns at the advantage of Slit Aperture Telescopes. This is particularely true for diffrential speckle interferometry experiments which

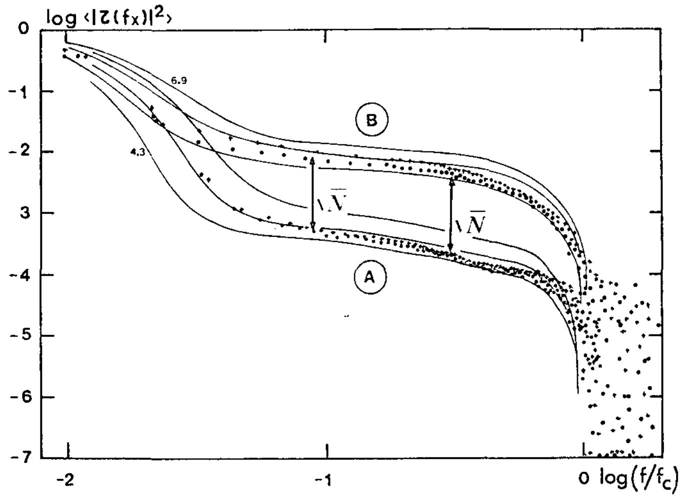

Figure 5 - Experimental energy transfer function (+ and ●) for two configurations of the telescope pupil :(a) classical circular aperture (D = 193 cm) and (b) rectangular slit aperture (9.5 cm x 165 cm). The theoretical curves (full line), deduced from the Korff's log-normal model are computed for three different values of the Fried's parameter r_o (4.3, 5.6 and 6.9 cm). The theoretical contrast gain obtained with the slit aperture is shown by the length of the narrow noted √N (ratio of the telescope surfaces). Experimental results are in good agreement with theoretical predictions.

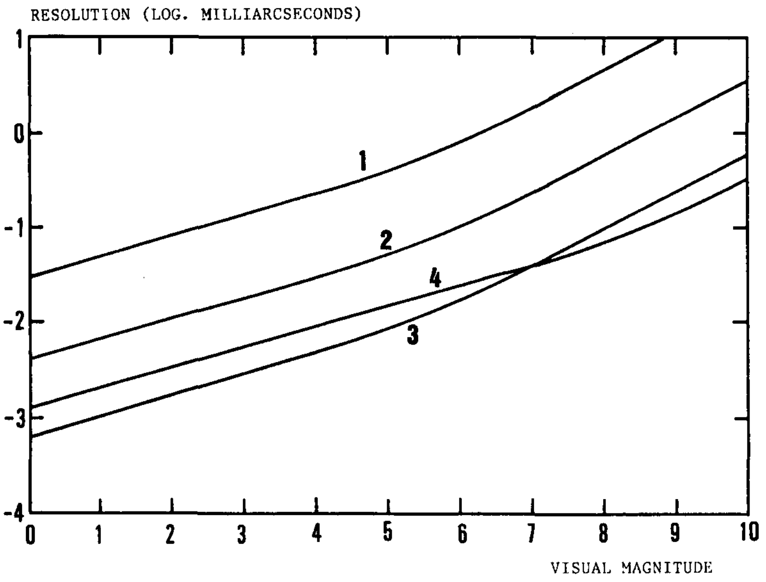

Figure 6 - Resolution for a DSI experiment with : (1) a classical telescope with an area equal to the SAT one, (2) a SAT with a 16 m x .4 m aperture, (3) a 16 m VLT, (4) multiline DSI with the SAT

are based on the simultaneous analysis of speckle interferograms at a large number of different wavelengths.

Differential speckle interferometry with a Slit Aperture Telescope.

Differential speckle interferometry (DSI) is a super-resolution technique which makes it possible to obtain information with a spatial resolution much better than the telescope diffraction limit.[10,23] The long list of potential astrophysical applications goes from the determination of stellar rotation axises and the study of the dynamics of stellar systems such as binary stars and open clusters to stellar imaging with a submilliarcsecond resolution. The feasability of this technique has been already experimentaly tested.[24]

DSI techniques can be applied to the study of astronomical objects which have spatial features resulting in recognizable spectral signature . This feature can result in a displacement between two set of speckle, analysed at two different wavelengths typically in a line wing and in the continuum, which can be measured even if it is far smaller than the speckle size.

It has been shown that the uncertainty σ on the measuring of the speckle displacement in a DSI experiment, which gives its resolution, is inversely proportional to the square root of the number of independant coherence cells in the telescope pupil and is proportional to the smaller speckle size.[11,23] The number of coherence cells is proportional to the aperture area, and the speckle size is inversely proportional to the aperture largest dimension. Therefore σ is proportional to D^{-2} for a circular aperture of diameter D and to $D^{-3/2}.l^{-1/2}$ for a slit pupil of length D and width l. This relations show that the transition from the circular aperture to the slit aperture results in a loss of resolution equal to $\sqrt{D}/\sqrt{l}$. The loss can be compensated by the fact that SATs make possible the use of spatio-spectral images, and thus allow us to combine the information resulting from all the spectral lines in a given wavelength range, which produces a gain in SNR with regard to a DSI experiment based on only two images.[24]

Figure 6 shows the resolution of Differential Speckle Interferometry experiments with a 16 m X .4 m SAT (2), a classical telescope with a surface equal to the SAT one (1) and a classical telescope with a diameter equal to the length of the SAT (3) and the curve (4) shows the resolution of a DSI experiment using the SAT and combining information coming from one hundred spectral lines. We can see that for faint stars multiline DSI with a SAT is more efficient than monoline DSI using a conventional aperture of same maximal resolution. The SAT must be rotated to set the aperture parallel to the speckle displacement but this operation needs only two measurements with the pupil in two orthogonal directions.

THE DESIGN OF A SLIT APERTURE TELESCOPE

The dedication of a telescope to speckle observations results in several releases in the optical and mechanical constraints which might simplify its design and reduce its cost.

Telescope aberrations.

Several authors have checked the possibility to use a strongly aberated telescope for speckle observations.[25,26] It has been shown that the maximun tolerable difference between the actual telescope surface and the perfect paraboloid may be of the order of[25,27] :

$$\varepsilon = \frac{1}{8}\frac{\lambda D}{r_o}$$

where λ is the wavelength, D the telescope diameter and r_o the Fried's parameter This wavefront tolerance allows us to make the parabolic primary mirror with several spherical mirrors with different curvature radii. For example a 16 m aperture parabolic mirror with a 16 m focal length can be approximated with 40 cm spherical mirrors whose curvature radii vary between 32.002 m and 34.894 m In these conditions the maximal wavefront error is equal to 1µm, which must be compared to the 6 µm tolerance given by the above formules for λ= 600 nm and r_o = 0.2 m. This result show that the ETF of the instrument will not be substancially degraded by spherical aberation until Fried's parameter reaches 1.2 m. The other way to takes advantage of the wavefront tolerance is to built a good parabolical surface and to release the constraints about the rigidity of its supporting structure. The choise, or the point of compromise, between the two terms of this alternative is strongly dependant on the progress made on the manufacturing of non circular off axis parabolical mirrors. Such a construction is investigated for the University of California VLT project[28] and at the Observatory of Nice for our prototype Solar Slit Aperture Telescope.

Telescope field.

The usable field in speckle observations is limited by the size of the isoplanatic patch, which is certainly much smaller than 1 arcminute. This allows us to design a very fast primary (f/1 or faster) with a very small, and very light secondary mirror. Corrective optics will not be needed.

Figure 7 display a possible design for a 16 m Large Slit Aperture Telescope. The telescope has three rotation axises : the conventional azimuth and altitude axises and a third one allowing rotation of the instrument around the sighting direction. The rectangular 16 m X .4 m primary mirror has a focal length of 16 m. It is segmented in 32 spherical mirrors (cf. figure 7′) grouped in 7 blocks which are actively controlled in order to compensate the deformation of the instrument. The radii of curvature of the spherical mirrors vary between 32.068 m and 34.894 m. The two mirrors in the orthogonal direction are intended

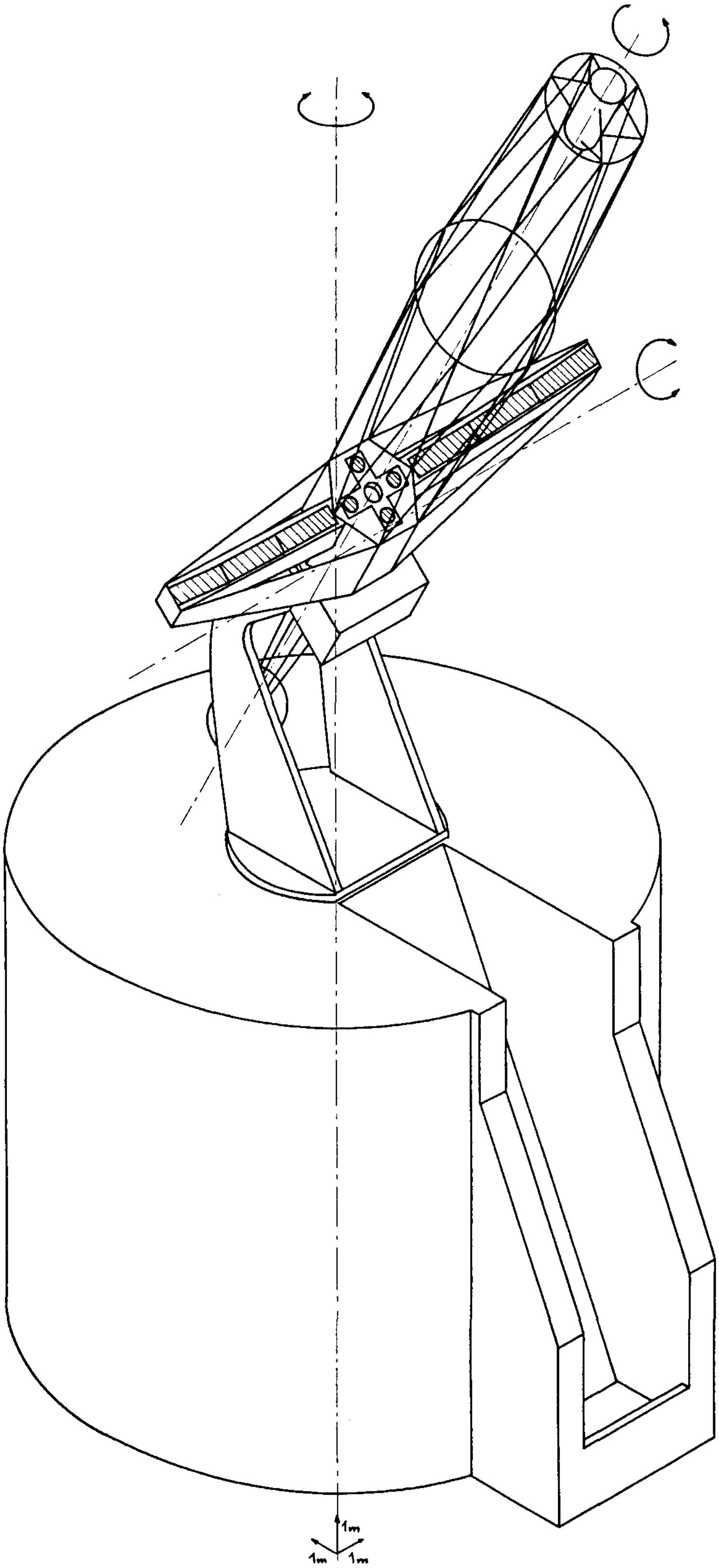

Figure 7: A possible design for a 16 m L.S.A.T.

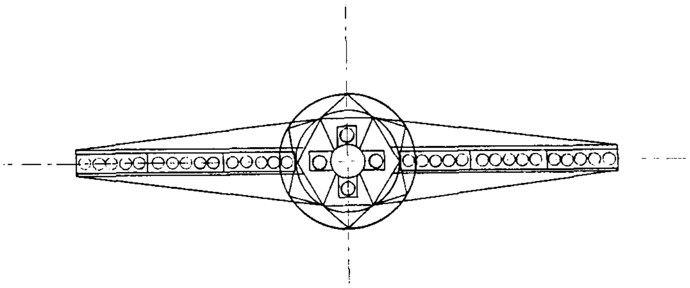

Figure 7' - A possible design for the LSAT : frontal view of the instrument.

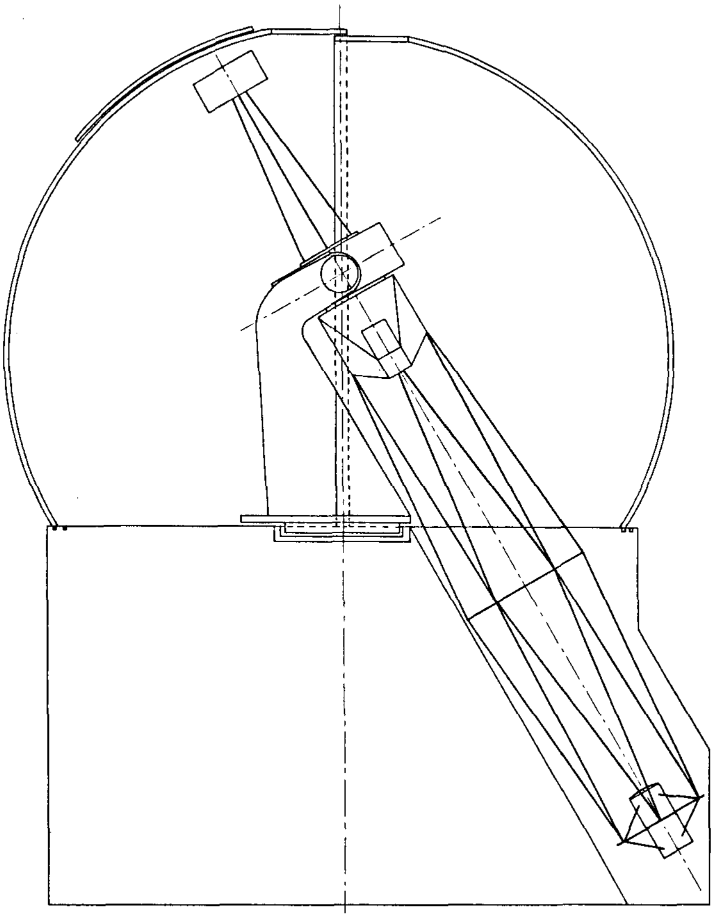

Figure 7'' - A possible design for the LSAT : telescope building.

to reduce the central obstruction due to the primary and to make possible the obtention of the zero frequency information in incoherent holography using a rotation shearing interferometer. The diameter of the secondary mirror is .8 m. The instrument is designed as an essentially domeless one. A light low cost structure od radius 9 m is enough to cover the telescope when not in operation. (cf. figure 7").

CHOISE OF THE APERTURE DIMENSIONS.

Aperture length. The scientifical potential of a SAT depends strongly on the resolution. Thus, the length of its pupil must be as large as possible. This length is limited by the fact that the cost of the relescope and the floppyness of the primary mirror will increase with it. It would also be impossible to rotate a too long pupil around the optical axis. For the telescope presented in this paper we have choosen a mirror length equal to 16 m because we believe that the feasability of such an instrument is guarented by the feasability of 15 m class VLTs. It would be possible to apply to SATs all the technologies developped for VLTs, especially about active support of the primary and about the manufacturing of off-axis non circular parabolic mirrors.

Aperture width. The width of the pupil must be larger than the Fried's seeing parameter r_o . In this paper we have choosen a width of 40 cm because it is larger than r_o for excellent seeing conditions and because that makes it possible to built the primary with small circular spherical mirrors.

CONCLUSION.

In this paper we have tried to show that, as far as diffraction limited astronomy is concerned, the performances of a SAT are comparable to these of the equivalent resolution circular aperture telescope. This is especially true if a combination of high angular and high spectral resolution is needed. The fundamental advantages of a SAT are its reduced cost and its availability for high angular resolution astronomy. The interest of the construction of such an instrument very strongly depends on a precise evaluation of its cost and this is our next goal.

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