A Multiple-Mirror-Telescope concept for a very compact 50-m Extremely Large Telescope

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An optical concept based on the Multiple-Mirror-Telescope principle is considered for a ground-based $50m$ Extremely Large Telescope (ELT). Its entrance pupil is filled. The optical layout fits very well into a very compact mount, either spherical or alt-az, leading to a telescope height significantly smaller than the primary mirror diameter. A second advantage is the absence of high aspheric mirrors, one of the most challenging aspects in other ELT current designs. As a counterpart of these advantages, the telescope involves 8 reflections on 7 mirrors, i.e. 4 more reflections than in other 4-mirror ELT proposals. But these 8 reflections can be reduced to 6 if a field lens is used.

Key words: telescope, Multiple-Mirror Telescope, MMT, Extremely Large Telescope, ELT, interferometer, segmented mirror, filled pupil, densified pupil.

1. Introduction

One of the major optical challenges of the already proposed 4-mirror Extremely Large Telescopes[1,2] (ELT) is the very high asphericity of at least one of the mirror which demands a real breakthrough in optical manufacturing. A second challenge is the telescope structure, which reaches a height of $\sim 180m$ for the $f/1.575$ $100m$ primary in the ESO proposal[2].

These two aspects lead us to consider a different solution, of *Multiple-Mirror-Telescope-type (MMT)*[3,4], i.e. an array of parallel telescopes on a single mount.

This solution does not include high aspheric mirrors as will be shown below, but required 4 more reflections than in other 4-mirror mentioned proposals. But these 8 reflections can be reduced to 6 if a field lens is used[4].

The compact optical design proposed below also makes the telescope typically 3 times shorter than in other designs (Figure 1). No high structure sensitive to the wind is above the primary. This compactness should also contribute to a higher overall stiffness.

2. The optical design

The ELT collecting area is made of parallel afocal Mersenne telescopes, all identical (Figure 1 and Table 1). Each Mersenne telescope has a hexagonal primary m1 in order to form a filled entrance pupil (Figure 2) of 36 or more hexagons. The m1 is an *on-axis* parabolic segment coupled with a parabolic Cassegrain or Gregory secondary M2. The Gregory version allows access to m1 focus and may be of interest to implement the m1 active optics wavefront sensor for example. The Mersenne position along the optical axis has no influence on the optical path length, relaxing the stiffness of the structure carrying the m1 array.

The Mersenne provides a beam compression or angular magnification m equals to the focal distances ratio f_1/f_2. Obviously the filled entrance pupil is diluted by M2. If the afocal beams following M2 feed a large parabolic mirror P and a hyperbolic featuring respectively the primary and the secondary of a large Cassegrain telescope, we would be in presence of a Michelson interferometer with a diluted exit pupil and a filled entrante pupil (M1). The instrument point spread function (PSF) would be a complex peaks pattern, the latter point being considered as a major drawback of interferometers by Gilmozzi[2].

But Labeyrie[5] pointed out in 1996 that *densified* exit pupils in diluted Michelson arrays can provide PSF with almost a monolithic core and much fainter surrounding speckles, instead of the usual complex peaks pattern met at diluted arrays focus. Therefore it is obvioulsy of prime importance to restore a filled *exit pupil* in our design. We finally obtain a Fizeau interferometer in the sense that entrance and exit pupils are homothetic, both being filled.

We basically find an usual telescope again, with the advantages with respect to a diluted array of the same diameter of a monolithic PSF *and* a large field of view.

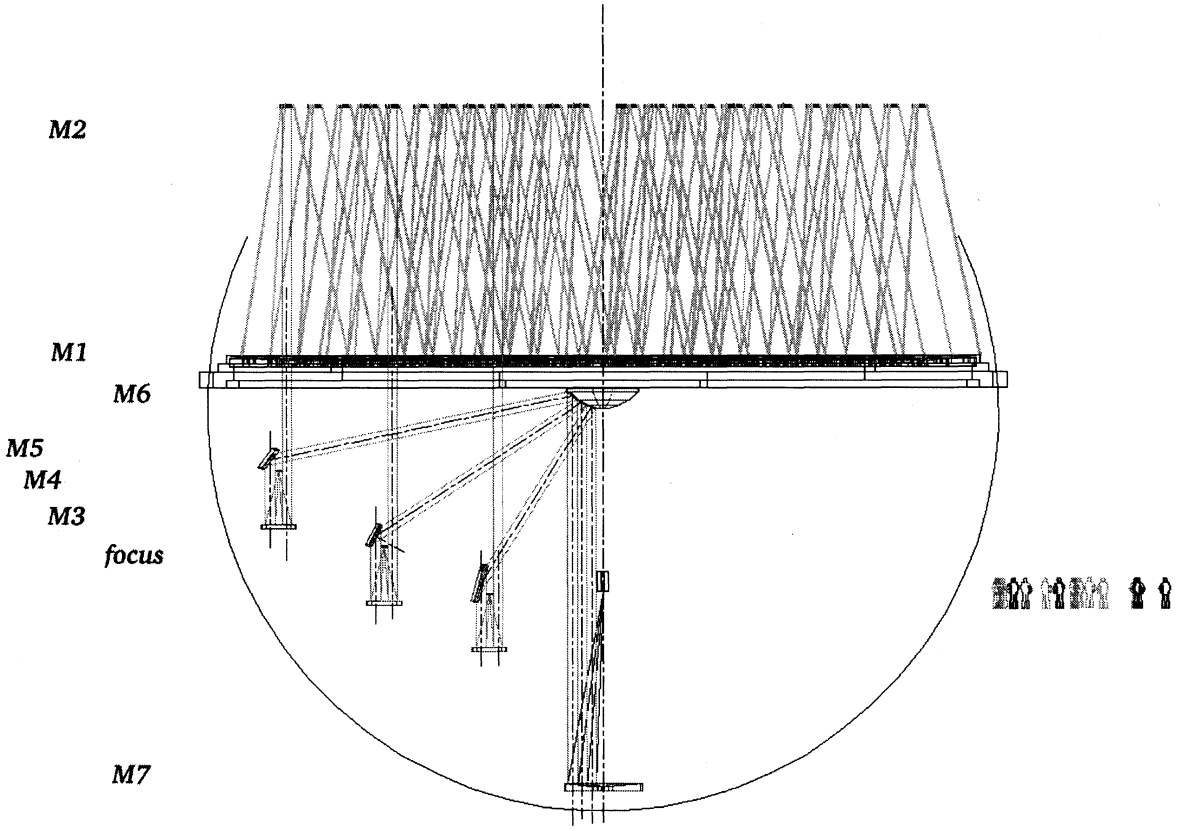

Fig. 1. Principle drawing showing a possible optical combination for a compact ELT made of 36 parallel $8m$ telescopes. The same $50m$ diameter can be obtained with an array of 390 $2.3m$ telescopes. The 8-reflection achromatic solution is represented here, but a field lens at the m1/M2 gregorian focus[4] would allow to replace the 4 reflections in the M3-M4-M5 block by two reflections on two flat mirrors. Here $m = 10.95$ (see Table 1).

M4 curvature and M5 tilt are thus chosen to provide a *densified* (here filled) pupil on M6 (Figure 1) and M6 pattern is homothetic to M1 with $D_6 = D_1/m$.

Although the M3-M4-M5 block is an achromatic solution to put the pupil on M6, another alternative is to put a field lens at the m1/M2 gregorian focus[4]. This would allow to replace the 4 reflections in the M3-M4-M5 block by two reflections on two flat mirrors (two are required for a correct image orientation). 6 reflections and one lens could thus replace the 8 reflections and give a better throughput. Nevertheless, the 8-reflection achromatic solution is discussed below.

The M3-M4-M5 block is compact enough to be mounted on a stiff structure (interferometric behaviour), even more compact if M1 is made of $2.3m$ diameter afocal telescopes rather than $8m$ telescopes.

M6 is a mosaïc of flat mirrors feeding M7 with the recombined afocal beam. M6 being in a pupil plane allows M7 to be a simple spherical mirror provided that M6 is deformed into a Schmidt reflective corrector[6]. Each M6 segment is thus an off-axis Schmidt corrector. The deformation is $\sim 150\mu m$ *ptv* for the M6 most deformed segment in the $m = 11$ 36-segment configuration, $\sim 25\mu m$ *ptv* in the 390-segment configuration, and only $\sim 9\mu m$ *ptv* in the $m = 22$ configuration (Table 1).

We take advantage of M6 being in a pupil plane to make it adaptive: tip-tilt and phasing adjustment, as well as the required Schmidt deformation, can be achieved with the M6 100000 actuators (250 or 2800 per M6 segment, for 390 or 36-segment solutions, respectively). M6 segments can be made of thin *Zerodur*-like or Aluminum plates[7].

In order to have equal optical path lengths between each 'arm' of the interferometer, the M5 mirrors are positioned on a steep parabola P of focal ratio $f/\sim 0.6$, which finally makes the overall design compact. M6 providing an afocal beam towards M7 means that P and $M6$ forms a second Mersenne Cassegrain telescope. Thus the center of each M6 segment is on a parabola which has the same focal point as parabola P.

The resulting focal length F is given by $m \times f_7$, where f_7 is the Schmidt focal length. Considering the *sphere* containing the telescope (Figure 1 or 2), a convenient choice for f_7 is $f_7 \sim D_1/4$, and with $F = 275m$ in order to have a correct image scale, one gets $m = 22$. An unvignetted field diamter of 45 $arc - sec$, typically the isoplanetic field in the near IR, can be obtained with reasonable optics sizes (Table 1).

3. Advantages and drawbacks of the design

Compactness is the first advantage of this design: for a VLT-like telescopes array of diameter $D_1 = 50m$, the ratio H

$$H = \frac{telescope\ height}{primary\ diameter}$$

ranges from $H \sim 0.8$ for a zenit distance of $z = 0°$ to $H \sim 0.9$ for $z = 60°$. This ratio is roughly ~ 1.8 for the 4-mirror proposals. If smaller telescopes ($2.3m$) with a focal ratio below 2 are used, the height ratio decreases even to $H \sim 0.5$. Figure 2 shows that the telescope can be housed in a spherical mount as proposed by Labeyrie and Cordier[8], or in a more conventional alt-az mount.

On the principle drawings given here, the M3-M4-M5 blocks are drawn at their correct position and the room seen below them and around M7 should allow to build a stiff telescope structure, without sacrifying the reasonable access to the focus. A third advantage is the absence of high aspheric mirrors and the deformation of the Schmidt corrector can probably be achieved with the M6 actuators. Another advantage in the case of the 36-segment design is that it makes use of the existing 8-m manufacturing skills and facilities.

A drawback of this design is the number of reflections: 8 on a 7-mirror train. But as briefly discussed above, the number of reflections can be reduced to 6 if a field lens is used. Aluminum layers reflectivity typically is between $R \sim 0.8$ and 0.9, but new coatings reaching $R \sim 0.95$ would give a throughput of $T = 0.66$ for the 8-reflection solution. In the 390-segment configuration, all mirrors except M1 and M7 are small enough to receive a broadband (for example $400 - 700$ nm, already available) multi-layer coating reaching $R \sim 0.998$. The throughput would reach $T = 0.89$ for the complete telescope in the range $400 - 700$ nm, but would be very low in the infrared, and this cannot be accepted.

4. Conclusion

The preliminary telescope design described above is very compact and features no high aspheric mirrors. The drawback of this solution is the 8 reflections on the 7 mirrors, although the number of reflections can be reduced to 6 if a field lens is used. With new coatings reaching $R \sim 0.95$, the throughput should be better than 65% with 8 reflections.

A weak point of this paper is that it presents no ray-tracing results to estimate the image quality over the field of view, and also no diffraction calculation of the effect induced by the M2 lattice above the primary. It should be the next step of this study.

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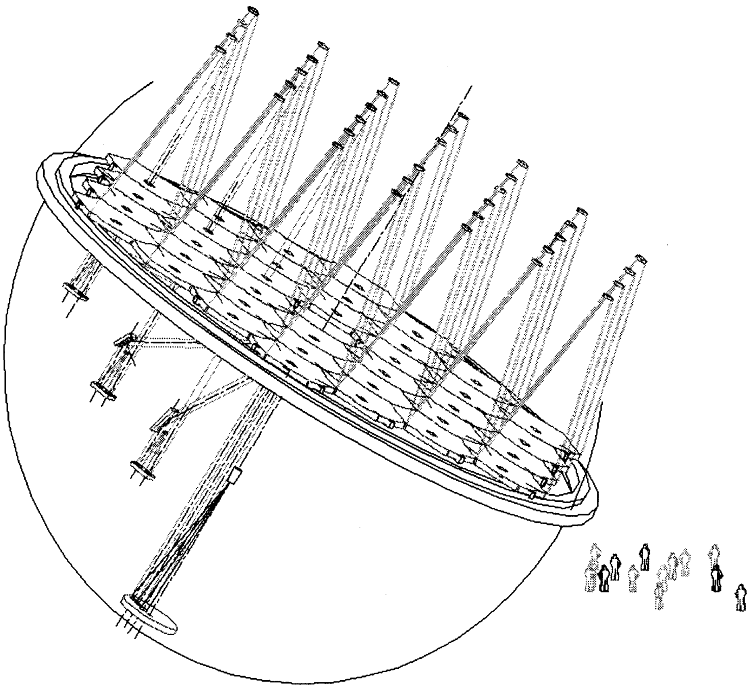

Fig. 2. Principle drawing showing the $50m$ segmented M1 array of 36 identical $8m$ telescopes. The lower part of the telescope can be under the ground level, giving an elevation above the ground no higher than $40m$. Here $m = 10.95$ (see Table1).

Table 1. Design parameters for $50m$ telescopes, for various numbers N of segments and magnifications m.

Parameters	36-segment ELT	36-segment ELT	390-segment ELT
Entrance pupil diam. D_1	48.5m	48.5m	52.9m
Mersenne m1 diam. d_1	8m	8m	2.3m
$N^{(a)}$	36	36	390
m	22	10.95	10.95
M2 diam. D_2	0.364+ field = 0.368m	0.730 + field = 0.737m	0.210 + field = 0.212m
M3 diam. D_3	2.2m	2.2m	2.2m
M5 max length	2.7m	2.7m	0.85m
M6 diam. D_6	2.20m	4.43m	4.83m
M6 segment diam. d_6	0.364 to 0.470m	0.730 to 0.943m	0.210 to 0.272m
f_7/D_6	5.68	2.78	2.78
M7 diam. D_7	2.4m	4.6m	5.0m
Unvignetted FOV diameter	$45''$	$90''$	$90''$
Resulting F/D_1 ratio	5.68	2.78	2.78
Image scale	$1330\mu m/''$	$655\mu m/''$	$655\mu m/''$

[a] The number of hexagonal segments is $N = 3n(n+1)$ (missing the single central mirror) where n is the number of segments across the mirror radius. For $n = 3$, $N = 36$, and for $n = 11$ and $N = 396$. Removing the useless first ring of 6 M1 segments above M6 gives $N = 390$.

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