

Optical design of a Michelson wide-field multiple-aperture telescope

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ABSTRACT

Multiple-Aperture Optical Telescopes (MAOTs) are a promising solution for very high resolution imaging. In the Michelson configuration, the instrument is made of sub-telescopes distributed in the pupil and combined by a common telescope via folding periscopes. The phasing conditions of the sub-pupils lead to specific optical constraints in these subsystems.

The amplitude of main contributors to the wavefront error (WFE) is given as a function of high level requirements (such as field or resolution) and free parameters, mainly the sub-telescope type, magnification and diameter. It is shown that for the periscopes, the field-to-resolution ratio is the main design driver and can lead to severe specifications. The effect of sub-telescopes aberrations on the global WFE can be minimized by reducing their diameter. An analytical tool for the MAOT design has been derived from this analysis, illustrated and validated in three different cases: LEO or GEO Earth observation and astronomy with extremely large telescopes. The last two cases show that a field larger than 10 000 resolution elements can be covered with a very simple MAOT based on Mersenne paraboloid-paraboloid sub-telescopes. Michelson MAOTs are thus a solution to be considered for high resolution wide-field imaging, from space or ground.

Keywords: Phased-array imaging systems, synthetic aperture imaging, telescope design, aperture configuration.

1. WIDE FIELD IMAGING WITH MAOTS

Mass, volume or technology constraints will put a limit in the manufacturing of increasingly larger monolithic telescopes. Future large telescopes will be based on distributed apertures optically linked together, as already considered for several major space missions such as JWST [1], DARWIN [2], SIM or TPF [3]. Multiple-Aperture Optical Telescopes (MAOTs) can also be considered for Extremely Large Telescopes (ELTs) under consideration for astronomy from the ground [4].

The design of a MAOT raises new issues, critical with respect to the instrument performance [5–7]: image post-processing is required to compensate for the strong oscillations of the Modulation Transfer Function (MTF), which drives the choice of the sub-aperture positioning [8, 9]. For wide-field imaging of complex objects, such as the Earth, a compact pupil and a focal-plane detection are required. In addition, all the telescopes must be cophased to correct for mechanical or atmospheric disturbances. Cophasing non-adjacent sub-apertures requires a real-time piston sensor. Such components are now used on stars by stellar interferometers and more complex devices required for very extended objects have been validated recently [10, 11].

The last specific issue of a MAOT is its optical design. Two main kinds of optical design can be considered:

- the “Fizeau” design (Fig. 1a): the aperture segments are portions of a common primary mirror;
- the “Michelson” design (Fig. 1b): independent telescopes are combined by a dedicated telescope.

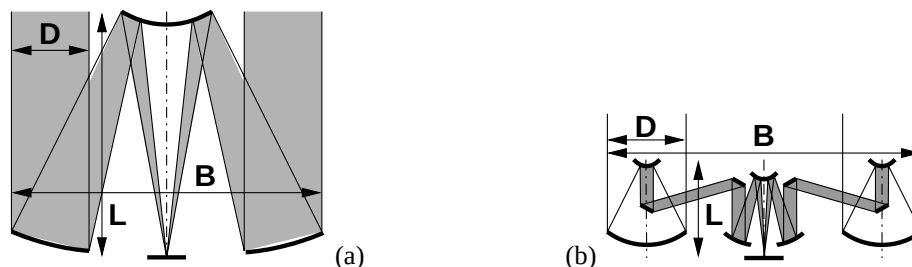


Figure 1. Principle of Fizeau (a) and Michelson (b) MAOTs, with the same maximum baseline B and sub-aperture diameter D .

Famous Fizeau designs are each Keck Telescope [12] or the JWST [1]. The Michelson design is used by ground-based stellar interferometers, such as the VLT-I [13] or the Keck-I [12]. The object is numerically reconstructed from visibility measurements in the so-called (u, v) -plane. These instruments use a small field, a large aperture dilution B/D and most often pupil-plane combination with a beam splitter. Direct focal-plane imaging with a Michelson MAOT, as illustrated in Fig. 1b, has been experimentally pioneered by the Multi-Mirror Telescope (MMT) [14], the Multi-Mirror Telescope Tested (MMTT) [15], the Multi-ap [16] and soon the LBT [3]. Under some specific conditions, described in this paper, a very wide field can be covered by Michelson MAOT as validated by simulations [17, 18] with the ASAP software [19].

The Michelson design is an attractive solution for large telescopes since Fig. 1 shows that the length L can be much smaller. The goal of this paper is to show that, from an optical point of view, a Michelson MAOT is a possible alternative to a Fizeau MAOT. The main design drivers and solutions are listed in section 2, mostly based on an analytical design approach extracted from [20]. Three applications are then detailed in section 3, to validate the analytical formulas by simulation and to illustrate with examples that a large field can be reached with simple designs.

2. OPTICAL DESIGN OF MICHELSON MAOTS

The design of a Michelson MAOT is made complex by the large number of mirrors (Fig. 1). In addition, although some optical-design softwares can handle parallel propagation in several arms, automatic optimization is not yet available to the best of our knowledge. For a Fizeau MAOT, this can be solved by considering the equivalent monolithic telescope, obscured by a virtual pupil mask. But for a Michelson MAOT, performance can only be computed for a given optical configuration. Therefore, the optical design of a Michelson MAOT is a specific task, mainly based on a physical approach and on the designer knowledge since many specific constraints have to be considered, as investigated and progressively understood by many authors for astronomy or wide-field imaging [17, 21–24]. We will concentrate here on the field aberrations of Michelson MAOTs.

2.1. Subsystems of a Michelson MAOT and notations

A Michelson MAOT is made of three main subsystems, illustrated in Fig. 1b [6, 7]:

- the AITs (Afocal Interferometric Telescopes, as explained in section 2.4) are the sub-telescopes used to compress the beams. They are characterized by their input and output pupil diameter D_n and D'_n , and by their paraxial angular magnification $G_n = D_n/D'_n$ (Fig. 2);
- the BCT (Beam Combiner Telescope) forms the common image of all the AIT beams on the focal-plane detector,
- the PAMs (Periscopic Active Mirrors) are the folding planar mirrors used to route the AIT output beams from B_n (the outer PAM) to B'_n (the inner PAM) before the BCT, including actuators to cophase the MAOT sub-apertures. They are characterized by the baseline homothety coefficient $H_n = B_n/B'_n$.

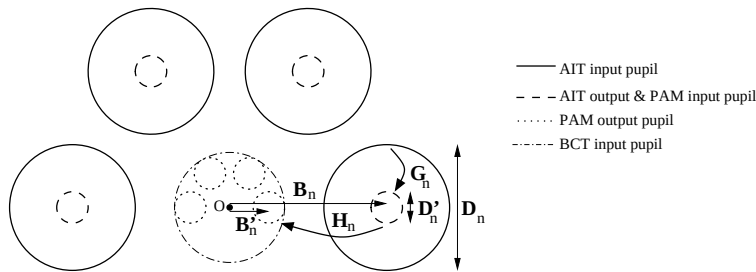


Figure 2. Notations for the MAOT pupil.

All the sub-aperture input diameters D_n are assumed to be equal. Performance can then be computed from the un-weighted average of values like G_n over all sub-apertures n , that will be denoted by $\langle G_n \rangle$.

2.2. High-level specifications

The design of a MAOT is primarily driven by the field to be covered $\pm\theta$ (the object being at infinity) and by the pupil aperture (or maximum baseline) B , which sets the angular resolution λ/B at a given wavelength λ . The field in one direction can thus be expressed as a dimensionless quantity, the number of resolution elements or Field to Resolution Ratio (FRR) $\mathcal{F}_{\text{MAOT}}$, according to:

$$\mathcal{F}_{\text{MAOT}} = \frac{2\theta}{\lambda/B} = \frac{2B\theta}{\lambda} \quad (1)$$

The number of pixels in one direction derives directly from the FRR and the focal-plane sampling. The FRR can be seen as the number of independent parameters or degrees of freedom in the image. For stellar interferometers, the FRR bounds the field that can be reconstructed from (u, v) -plane data [25]. For wide field imaging with MAOT, this paper will show that most optical constraints are directly linked to the FRR. Likewise, the AIT FRR can be defined as $\mathcal{F}_{\text{AIT}} = 2D\theta/\lambda$.

Other high-level parameters are the MTF level and the integration time, which drive free design parameters: the number, the position and the diameter of the sub-apertures. But these design parameters also impact on the mechanical structure, the cophasing complexity and the optical design performance. The final choice is thus a complex trade-off between all these constraints. We will consider the AIT diameter D , or the dilution ratio B/D , as an important design parameter. For a space telescope, volume constraints in the fairing drive the choice of the thickness L (Fig. 1).

The last high-level parameter is the MAOT error budget, from which the Wave-Front Error (WFE) allocated to each optical design contributor can be derived.

2.3. Wavefront error for a MAOT

When computing the WFE, care has to be taken regarding the choice of the reference wavefront. Section 2.4 will show that a common case is when the wavefront after the inner PAMs has a stair-like shape, as illustrated in Fig.3. Many authors have considered as the angular reference the common direction Σ_1 of all the AITs [17, 23, 26–29], leading to a wavefront error indicated by the dashed area in Fig.3a. Only recently, the choice of the best reference surface has been pointed out [24, 30]. Even if the reference wavefront Σ_2 is not the expected one as it differs from Σ_1 (Fig.3b), the wavefront error (dashed area) is much smaller in this case. The departure of the actual reference corresponds to a shift in the focal plane (tilt, magnification or distortion error), which does not affect image quality and can be corrected by classical means.

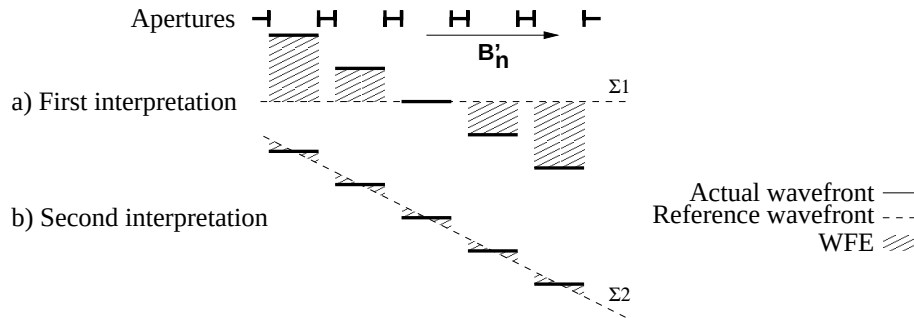


Figure 3. The two interpretations to define the direction of a multiple-aperture stair-like wavefront.

Fig. 3 clearly evidences the gain brought by the correct interpretation:

- reducing the aperture diameter D reduces proportionally the WFE with interpretation 2 (Fig. 3b), but keeps it constant with interpretation 1 (Fig. 3a);
- adding additional telescopes at large baselines does not change the WFE with interpretation 2, whereas it increases the WFE with interpretation 1.

Choosing the best reference wavefront, the one which minimizes the WFE, considerably helps the designer since it relaxes specifications or increases performance for a given MAOT design.

2.4. Constraints on the PAMs and the AITs

The first goal of the PAMs is to cophase all the beams before the beam combiner. This can be done for any point in the field by mounting PAMs on tip/tilt mounts and including additional delay-lines. But once this cophasing has been achieved for a given point, for example the center of the field, it has to be simultaneously achieved for all the other points. This requirements puts very demanding constraints on the AITs and the PAMs.

A first requirement is that all the sub-telescopes images are perfectly superimposed. Assuming focal sub-telescopes, their image plane must coincide before the BCT. In this case, the on-axis chief ray of each telescope after the inner PAM is not parallel to the BCT axis as shown in Fig. 1b, but tilted by the PAMs to intersect the BCT axis in the common focal plane. Assuming sub-telescopes with revolution symmetry, their focal surface is thus tilted with respect to the normal of the BCT axis, with a different angle for each aperture. Therefore, the focal surfaces from the sub-telescopes split away as the field increase. For wide field operation, this effect can be cancelled minimized by sending this common focus at infinity [26]. The sub-telescopes are then afocal, hence their name AIT, and the two PAMs of each arm parallel, as in Fig. 1b.

A second requirement is that all focal-plane images match. Therefore, the magnification G_n of the AITs must be identical. If not, the wavefront for off-axis points has a stair-like shape as discussed in section 2.3, with a different tip/tilt on each sub-aperture.

A third requirement is the phasing condition. For any off-axis direction θ in the object space (and θ' in the PAM space), canceling the OPD between pupil n and a reference in O (Fig. 2) gives:

$$B_n \sin \theta = B'_n \sin \theta'. \quad (2)$$

The first-order Taylor expansion of Eq. (2), $B_n/B'_n = \theta'/\theta = G$ is the well known “golden rule” of MAOTs [21], or “homothetic mapping” condition between the MAOT input pupil (before the AITs) and the BCT input pupil: *As viewed from a point in the focal plane, beams from separated telescopes must be recombined so that they appear to be coming directly from a single large telescope which has been masked so as to reproduce exactly the ensemble of collecting telescopes.* In other words, from the focal plane, the Fizeau and Michelson designs are indiscernible. If the input and output pupils are not coplanar, as implicitly assumed here for simplicity, a similar longitudinal pupil mapping is required [31].

Departures from the golden rule increase the WFE as follows. From the averaged baseline homothecy coefficient $H = \langle H_n \rangle$, the averaged AIT magnification $G = \langle G_n \rangle$, their dispersion $\sigma_H^2 = \langle H_n^2 \rangle - H^2$ and $\sigma_G^2 = \langle G_n^2 \rangle - G^2$, one can compute the following errors:

$$WFE = \mathcal{F}_{\text{MAOT}} \frac{\sigma_H}{H} \quad (\text{piston, waves}), \quad (3)$$

$$WFE = \mathcal{F}_{\text{AIT}} \left| \frac{G}{H} - 1 \right| \quad (\text{tip/tilt, waves, if } D \ll B), \quad (4)$$

$$WFE = \mathcal{F}_{\text{AIT}} \frac{\sigma_G}{G} \quad (\text{tip/tilt, waves}). \quad (5)$$

Since $\mathcal{F}_{\text{MAOT}} > \mathcal{F}_{\text{AIT}}$, Eq. (3) shows that the most critical parameter is the PAM positioning accuracy σ_H , which is directly driven by the global field-to-resolution ratio. For example, considering that the lateral homothecy allocation is $\lambda/50$, then the relative error σ_H/H should be smaller than 0.00002 for a modest $\mathcal{F}_{\text{MAOT}}=1000$. With values from section 3.2, the output pupil should be positioned by the PAMs with 10 μm accuracy. Magnification-matching requirements are relaxed according to the dilution B/D , as a result of interpretation 2. Only when imaging a small field, the golden rule is thus not strictly required as first proposed by Labeyrie with the hyper-telescope concept [30].

The third-order Taylor expansion of Eq. (2) is a distortion requirement, to be compared with the usual orthoscopy requirement $\tan \theta' = G \tan \theta$ [17]. If the AITs do not follow the specific sine distortion of Eq. (2), a stair-like wavefront is obtained as in Fig. 3. According to interpretation 2, the effect of distortion is thus reduced with dilution.

A last requirement concerns AIT high-order aberrations. Since AIT pupils are de-centered with respect to the BCT pupil, aberration compensation between the AITs and the BCT is impossible with rotationally-symmetric AITs. Therefore, the AIT third-order aberrations (spherical aberration, coma, astigmatism, field curvature) directly contribute to the error budget [23].

2.5. Possible AIT implementation

The simplest AITs are Mersenne telescopes, made of two confocal parabolic mirrors. Mersenne telescopes are free from spherical aberration, coma and astigmatism. The amplitude of field curvature and distortion can be computed from the AIT magnification G and primary focal length f_1 , in accordance with [23, 29]. Assuming $f_1 \simeq L$ (cf Fig. 1a), the effect of field curvature and distortion at field edge are respectively :

$$WFE \simeq \frac{\lambda \mathcal{F}_{MAOT}^2}{35L} \times |G - 1| \left(\frac{D}{B} \right)^2 \quad (\text{defocus, waves}), \quad (6)$$

$$WFE \simeq \frac{\lambda^2 \mathcal{F}_{MAOT}^3}{40B^2} \times (G - 1)^2 \left(\frac{D}{B} \right) \quad (\text{tip/tilt, waves}). \quad (7)$$

The first term in Eqs. (6)-(7) is fixed by high-level specifications, whereas the second involves free design parameters. Eqs. (6)-(7) show that the WFE decreases as the dilution increases. The WFE is very sensitive to the aperture dilution since distortion is negligible in most cases, and field curvature evolves with $(D/B)^2$.

A three-mirror AIT, like the Offner afocal [32], can correct for field curvature, but we have demonstrated that no design with sine distortion exist, in agreement with other authors [17, 24]. The distortion error for Offner AITs is very similar to Eq. (7). To achieve a sine-distortion, designs with at least four mirrors are required, like an Offner afocal with an additional aspherized folding mirror [17] or an intermediate focal-plane corrector [18, 33], or back-to-back Cassegrain-Gregory telescopes [34].

2.6. Constraints on the BCT and implementation

The design of the BCT is similar to the design of any standard monolithic aplanetic telescope, since § 2.4 has shown that beams should be afocal and stigmatic in the PAM space. The BCT primary diameter is $D_{BCT} \simeq B/G$ and its focal length is $f_{BCT} = f_{MAOT}/G$ where the MAOT focal length f_{MAOT} is set by detector sampling in the image plane.

The main difference is that the BCT aberrations should be considered only over the MAOT effective aperture and not over the full BCT aperture. Another specific aspect is that the BCT is fed laterally by the PAMs. Therefore, unusual designs with large secondary or tertiary mirrors can be used [17].

A three-mirror telescope, such as a Korsch telescope, can correct all third-order aberrations except distortion. But a global distortion does not affect image quality and can be compensated by post-processing. Therefore, at third-order, a perfect BCT can be derived from classical designs.

3. APPLICATION TO THREE MAOT DESIGNS

From the results of the physical analysis summarized in section 2, an analytical tool has been implemented at ONERA to help in the simulation and the design of MAOTs from high-level requirements. Three examples of MAOTs are used in this section to illustrate this tool and results of section 2. Cases 1 and 2 deal with Earth observation from space, whereas Case 3 deals with astronomy from the ground. Results are over-plotted on Fig. 4, where the Strehl ratio $\mathcal{S}$ is directly computed from the WFE with the usual formula [23]. The two first cases have also been used to validate these analytical results with results from commercial optical-design softwares.

3.1. Case 1: LEO Earth observation

This first case is extracted from the EUCLID RTP 9.2 study [35], conducted in the 90's in cooperation between ONERA and three Belgian entities, SpaceBel Instrumentation (SBI), Centre Spatial de Liège (CSL) and Université Libre de Bruxelles (ULB). This study derived the concept illustrated in Fig. 5. The three AITs have their primary mirror just behind the main central plate, their secondary mirror above and their tertiary mirror below. The plate between the AIT tertiary mirrors supports the inner PAMs while the outer PAMs are hidden in the AITs. The off-axis BCT in the left-side box is fed by the folding mirror on the central plate between the AITs.

With Mersenne AITs, Fig. 4 shows that the field is rather small ($\mathcal{F}_{MAOT} \simeq 2500$). An Offner AIT gives better results but the field is still limited to $\mathcal{F}_{MAOT} \simeq 7500$. The ASAP simulation performed by CSL confirmed that distortion was the limiting factor [18]. To reach a larger field, a corrector made of two small aspherized periscopic mirrors had to be inserted near the intermediate focus of each AIT to cancel distortion. The performance of this last design is not plotted in Fig. 4 since WFE=0 at third-order.

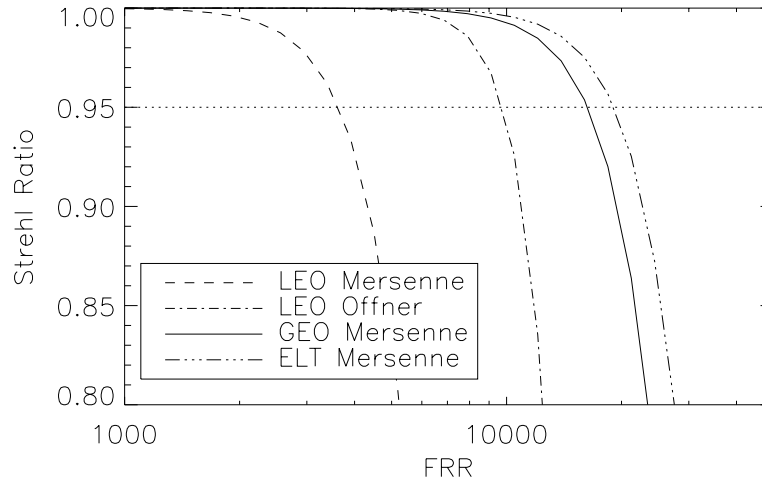


Figure 4. Analytically-derived performance of MAOTs described in sections 3.1 (case 1), 3.2 (case 2) and 3.3 (case 3). The error budget given by Harvey ($S \simeq 0.95$) [23] is also plotted (...).

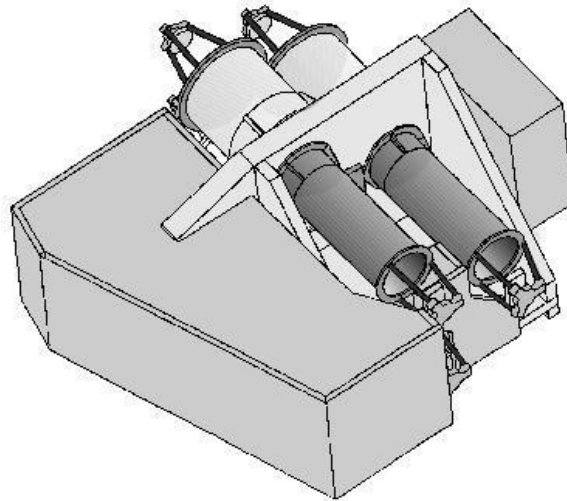


Figure 5. Perspective sketch of the concept for the EUCLID RTP 9.2 instrument derived by the ONERA-SBI-CSL-ULB consortium.

3.2. Case 2: GEO Earth observation

The second case is based on a study in progress at ONERA with a DGA/SPOTI contract and a CNES participation. The goal is to define an instrument for Earth observation from the GEO orbit. A decametric baseline is required for a metric pixel pitch on the ground, in the visible. Since the main goal of this example is to check the analytical derivations of § 2, the selected configuration is not intended to be fully representative of a real system. It is based on a linear arrangement of 4 Mersenne telescopes, as described in Fig. 6 and Table 1. The BCT is a Korsch telescope for simplicity.

When considering only distortion, our simulation tool finds that a 0.95 Strehl Ratio corresponds to $\mathcal{F}_{\text{MAOT}}=30\,000$ (5.2 arcmin field), as confirmed by Lucke's paper [24]. But Mersenne telescopes are primarily limited by field curvature: Fig. 4 shows that the FRR is close to 15 000 with values from Table 1. Such a (circular) field allows a wide range of applications.

This result has also been confirmed by a numerical simulation performed with the Huygens propagation module of Zemax. The whole MAOT configuration (AIT+PAM+BCT), derived by our analytical design tool, has been used directly under Zemax, without any additional optimization. The computed MTF (Fig. 7) shows the 6 expected satellite peaks, with

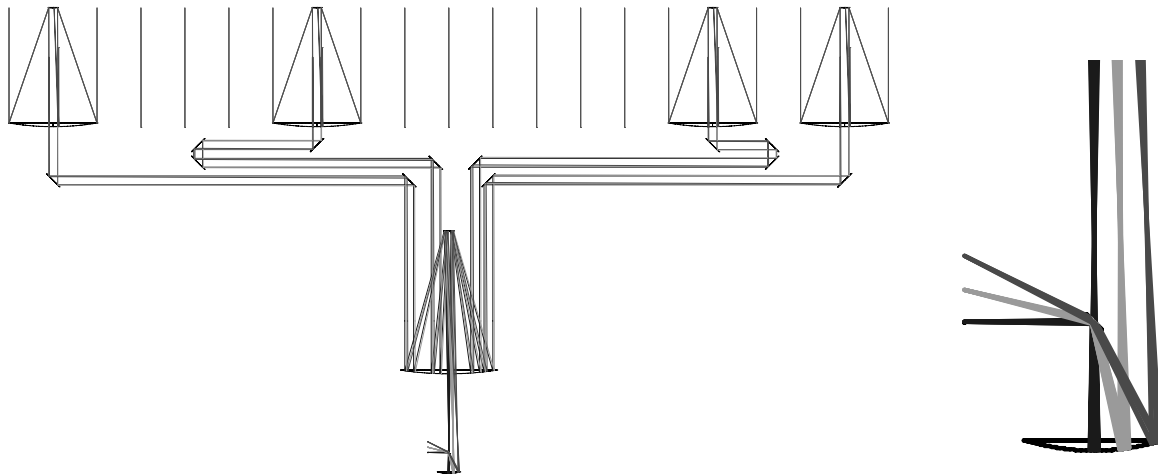


Figure 6. MAOT used for the Zemax simulation (left) and detail near the focal plane (right). Numerical values are listed in Table 1.

Table 1. Numerical values used for Case 2 (Fig. 6) and Case 3.

Parameter	Notation	Value (case 2: GEO)	Value (case 3: ELT)
Maximum baseline	B	10 m	100 m
Wavelength	λ	$0.5 \mu\text{m}$	$0.5 \mu\text{m}$
AIT positions	—	$-3P, -P, 2P, 3P$ with $P=1.5$ m	—
AIT type	—	Mersenne	Mersenne
AIT diameter	D	1 m	8 m (same as VLT-I)
AIT f -number	F_{AIT}	1.5	1.8 (same as VLT-I)
AIT magnification	G	10	100 (same as VLT-I)
BCT type	—	Korsch	—

height $1/4$. The MTF cut-off frequency varies significantly with the field. We understand this behavior as the effect of distortion. But the major result is that the level of the MTF is not affected when varying the semi-field up to 0.024 deg ($\mathcal{F}_{\text{MAOT}} \simeq 17\,000$), in accordance with Fig. 4. The MTF is affected for the largest angle $\theta = 0.034$ deg, corresponding to $\mathcal{F}_{\text{MAOT}} = 23\,000$.

3.3. Case 3: ELT for astronomy

This last case corresponds to a 100 m class ELT. Most ELT proposals are based on Fizeau designs with highly-aspheric surfaces and challenging Multi-Conjugated Adaptive Optics systems [4]. An alternate approach is to make a Michelson MAOT from nearly commercially-available components:

- Serial production of 10 m-class identical telescope, that can be used as AITs, has been validated by the VLT,
- Hectometric mounts, as used by radio-telescopes, can support the AITs with their individual weather protection,
- Efficient adaptive-optics (AO) correction has been demonstrated on 10 m class telescopes by NAOS [36],
- Cophasing over decametric baselines has been achieved by ground-based stellar interferometers. Merging AO and piston correction is currently under development at VLT-I and Keck-I.

Advantages of such a system are that a failure of a few sub-systems still allows the whole system operation, with reduced performance, and spare components are common to all AITs. Similar designs have already been proposed [37–39].

With a classical “on-axis” AO correction, the atmospheric isoplanetic patch (about 5 arcsec at $\lambda = 0.5 \mu\text{m}$) corresponds to $\mathcal{F}_{\text{MAOT}} \simeq 5\,000$, roughly for all wavelengths, which is already a rather significant field. With a configuration such as the one given in Table 1, Fig. 4 shows that the FRR is about $20\,000$ for Mersenne AITs. The effect of the large magnification G

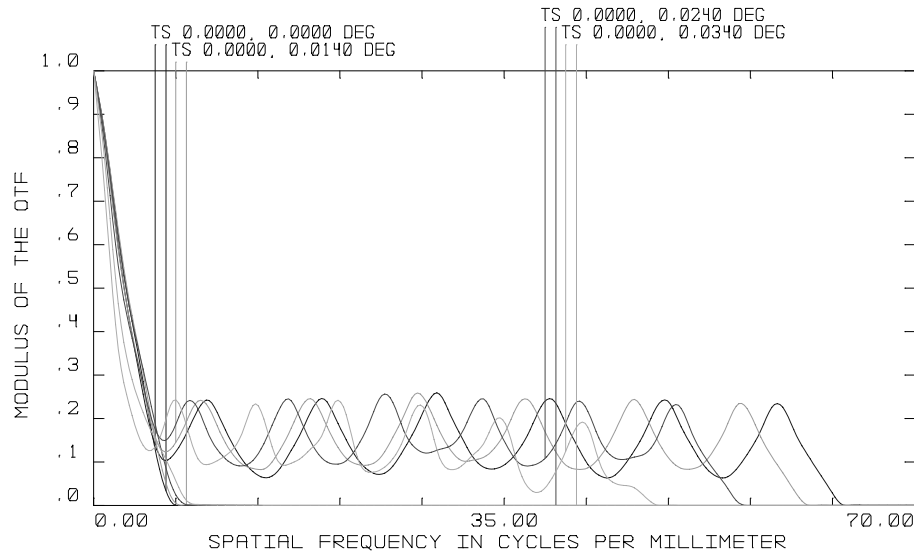


Figure 7. MTF of the MAOT of Case 2 (Fig. 6), for four different field angles.

(Eqs. 6, 7) is attenuated by the large dilution B/D . This FRR is more than required to cover the field imposed by on-axis AO correction, and even allows the implementation of more complex AO systems.

4. SUMMARY AND CONCLUSION

The design of a Michelson MAOT is a difficult task for four reasons. Many free parameters are to be fixed, but no generic configurations (like the “Ritchey-Chretien” or “Korsch” monolithic telescopes) exist yet, no optical-design software can perform non sequential optimization, and many constraints specific to MAOT operation have to be considered. Most of the few Michelson MAOT demonstrators suffered from problems linked to their design choices.

A good MAOT design requires therefore a good physical understanding of the instrument. The choice of the best reference wavefront, identified only recently, allows to reduce the wavefront error induced by sub-telescope or periscope aberrations by decreasing the sub-aperture diameter D , without affecting the MAOT resolution set by the maximum baseline B . The number of sub-telescopes should then be increased accordingly to maintain frequency coverage or photometry, but this does not affect the WFE. Therefore, a large field of view (larger than 10 000 resolution elements) can be obtained with simple designs, based on the simplest AITs (afocal two-mirror Mersenne telescopes) and a three-mirror BCT.

Another result is that the MAOT Field to Resolution Ratio is the most critical design parameter. Some authors consider decametric baselines with a semi-field close to 10 arcmin in the visible, leading to $\mathcal{F}_{\text{MAOT}} > 100\,000$. Such a large FRR requires a huge focal plane and complex optical designs to control all the aberrations. An alternate solution is to use simpler designs and to scan the field, since MAOTs are rather considered for astronomy or Earth observation from high orbits.

Based on this analysis, a tool has been developed at ONERA to compute analytically the global MAOT aberration from the third-order aberrations of the sub-systems. This tool allows a quick performance estimation and the optimization of free parameters. A numerical optimization for higher orders can be performed in a second step. This tool has been validated by simulations with commercial numerical optical-design softwares, showing that the FRR can be considerably increased by increasing the dilution ratio B/D while using simpler telescopes. The third example shows that a rather conservative Michelson ground-based MAOT can cover a fairly wide field (10 K×10 K simultaneous pixels) with ten times the best resolution currently available.

The challenging astronomical missions under development (such as DARWIN [2], SIM or TPF [3]), with highly demanding requirements, will develop and validate most components for Michelson space interferometry. Using a relevant aperture configuration including optical design constraints [8,9], an efficient cophasing strategy [5–7, 11], an optimized image processing [35] and a wide-field design such as presented here, Michelson MAOTs are thus a solution to be considered for high resolution wide-field imaging, from space or ground.

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