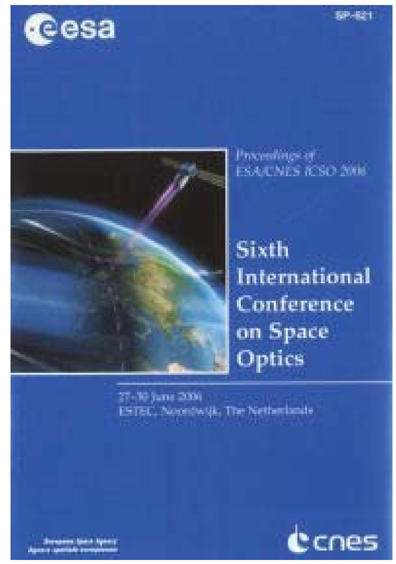
International Conference on Space Optics—ICSO 2006

Noordwijk, Netherlands

27–30 June 2006

Edited by Errico Armandillo, Josiane Costeraste, and Nikos Karafolas



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International Conference on Space Optics — ICSO 2006, edited by Errico Armandillo, Josiane Costeraste,
Nikos Karafolas, Proc. of SPIE Vol. 10567, 105670B · © 2006 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2308095

HIGH RESOLUTION EARTH OBSERVATION FROM GEOSTATIONARY ORBIT BY OPTICAL APERTURE SYNTHESYS

Mesrine M.(1), Thomas E.(1), Garin S.(1) , Blanc P.(1) , Alis C.(1) , Cassaing F.(2) , Laubier D.(3)

(1)Alcatel Alenia Space,100 Bd. du Midi B.P. 99 06156 Cannes La Bocca France,
Email:magali.mersine@alcatelaleniaspace.com
(2)ONERA, 8 rue des Vertugadins 92190 Meudon France, Email: frederic.cassaing@onera.fr
(3)CNES, 18 avenue Edouard Belin 31401 Toulouse Cedex 9 France, Email: david.laubier@cnes.fr

ABSTRACT

In this paper, we describe Optical Aperture Synthesis (OAS) imaging instrument concepts studied by Alcatel Alenia Space under a CNES R&T contract in term of technical feasibility. First, the methodology to select the aperture configuration is proposed, based on the definition and quantification of image quality criteria adapted to an OAS instrument for direct imaging of extended objects. The following section presents, for each interferometer type (Michelson and Fizeau), the corresponding optical configurations compatible with a large field of view from GEO orbit. These optical concepts take into account the constraints imposed by the foreseen resolution and the implementation of the co-phasing functions. The fourth section is dedicated to the analysis of the co-phasing methodologies, from the configuration deployment to the fine stabilization during observation. Finally, we present a trade-off analysis allowing to select the concept wrt mission specification and constraints related to instrument accommodation under launcher shroud and in-orbit deployment.

1. INTRODUCTION

Only high orbits (e.g. Geostationary or Geosynchronous) enable quasi-permanent Earth Observation, thus favouring them for military or civil surveillance missions.
To be really attractive, quasi-permanence has to be coupled with high resolution (typically metric or decametric) and with sufficiently large field of view. Knowing that the resolution of an observation instrument is roughly proportional to its diameter and to the inverse of the platform altitude, high resolution from high orbits implies very large diameter telescopes (~ 10 m). Such instrument dimensions induce problems of mass, volume and launcher accommodation. In this context "classical" technology clearly shows its limits. Optical Aperture Synthesis (OAS) has been identified as a candidate to access such missions.·
OAS has been used for on ground astronomy for several years [1] and we believe that its application to extended sources imagery (e.g. for Earth observation) might be envisaged within 15/20 years [2], [3].

Proc. '6th Internat. Conf. on Space Optics', ESTEC, Noordwijk, The Netherlands, 27-30 June 2006 (ESA SP-621, June 2006)

In this study, we have analysed interferometer configurations adapted to a 1.2 m nadir Ground Sampling Distance (GSD) and a 40 x 40 km² field of view (FOV) requirements. The two known types of interferometer have been considered, their main characteristics are briefly recalled in Fig. 1.

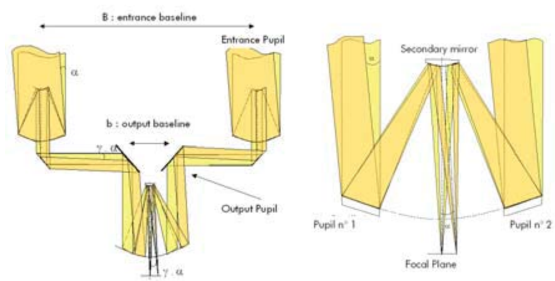


Fig. 1 Michelson (left) and Fizeau (right) interferometers

Fizeau type interferometers behave in the field of view like a classical telescope, apart from aberrations linked to the primary mirror segmentation.
Michelson type interferometers, without any particular attention in the design, are not imager instruments. Rules to respect in order to obtain images with such interferometer concepts can be found in [4] and [5].

2. QUALITY IMAGE CRITERIA AND DIMENSIONING METHODOLOGY FOR OAS INSTRUMENTS

2.1 Image chain simulation

Interferometers are mainly characterized by their synthetic entrance pupil composed of collectors which number, position and diameters have to be defined wrt mission requirements.
To perform the synthetic pupil selection, we have developed an image chain simulation detailed in Fig. 2.

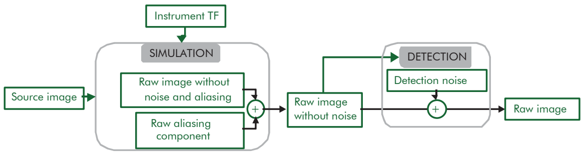


Fig. 2 Image chain simulation

This simulator generates a raw image, taking into account the Modulation Transfer Function (MTF) related to each acquisition chain component. Perturbations can be injected in the simulation in order to derive the sensitivity of the considered concept.

2.2 Image quality criteria determination

The particular shape of an interferometer MTF has two main consequences. Firstly, the raw image is not directly exploitable. Secondly, "classical" image quality criterion like MTFxSNR are not anymore adapted to the sizing of OAS instruments.
That is why the simulator also includes image processing algorithms (deconvolution, denoising) to restore an exploitable image and allows to quantify OAS dedicated Image Quality (IQ) criteria. Comparing this image with an ideal one simulated at the required resolution allows to quantify the contribution of acquisition noise, aliasing and incomplete deconvolution to IQ (see Fig. 3), on sub-regions containing low, middle and high frequencies.
The sensitivity to perturbations in the image chain can also be derived with this tool (in particular to estimate the sensitivity to co-phasing errors).

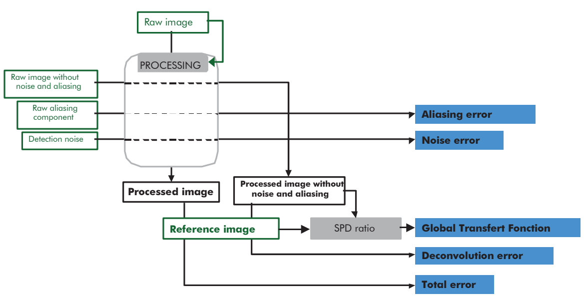


Fig. 3 Image quality criteria extraction

2.3 Synthetic pupil selection

The simulation process presented here above has been used for synthetic pupil selection. The first step consists in establishing the IQ criteria objectives by simulating a monolithic telescope fulfilling classical MTFxSNR criteria given by CNES. Numerical values of the IQ contributors of this monolithic configuration are then derived and used as goal for the OAS configuration ones.
A pre-selection of OAS configurations, of which MTF support is compatible with the specified resolution, is performed. A possible approach to optimise the frequency plane coverage is presented in [6].
IQ of each OAS configuration is then simulated in order to estimate the required SNR and thus the related integration time.
In case of too large integration time, the tested configuration is rejected or modified by increasing the collecting area. This method is illustrated in Fig. 4.

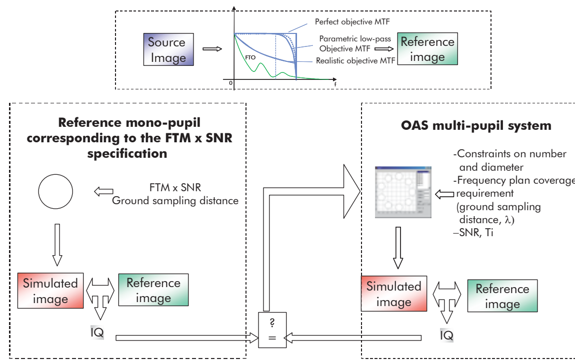
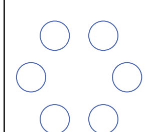
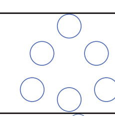
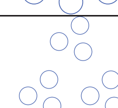
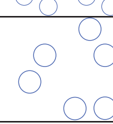


Fig. 4 Pupil selection logic

Several pupil configurations, with different numbers of pupils, diameters and positions in the plane have been selected with respect to required IQ criteria (Table 1). All of them are inscribed in a 10 m diameter circle.

Table 1 Selected pupil configurations. Reference [7] details particular applications of the Multi-instrument configuration

	Number of collectors	*Collectors diameter(m)*	*Exemple*
Circular	30 20 12 9 6 4	1 1 1.6 1.8 2.5 4.5	
Reuleaux	12 6	1.6 2.5	
Multi-instrument	9	2	
Golay	6	2.5	
Linear	4 5	1.6 1.6	

A trade off analysis has been performed to select the entrance pupil configuration studied during the optical design phase.
The trade-off criteria used are the following:

- Integration time: line of sight stability requirement, one of the major concern of high resolution from high orbit, is constrained by integration time.
- Co-phasing complexity: decreases at first order when reducing the number of pupils.
- Associated magnification (Michelson type): required afocal magnification increases with collectors diameter in order to reduce the size of the combiner. Moreover, Michelson specific aberrations also increase with magnification.
- Compatibility with Fizeau and Michelson type: in the Michelson case, configurations where sub-pupils are equidistant from the synthetic pupil centre are favoured, avoiding the use of long delay lines.
- Design complexity: tentative estimation of complexity related to mechanical design, in-shroud stacking, needed deployable parts, AOCS…

2.4 Planar configurations

After giving a mark to each configurations, two circular ones, the 6-pupil (D = 2.5 m) and the 9-pupil (D = 1.8m) have been selected.
The 6-pupil configuration relaxes significantly the instrumental design and co-phasing complexity, the in-shroud stacking and the deployment. A 35 % pupil weight reduction and a 40 % integration time decrease are foreseen with respect to the 9-pupil configuration ones. However these advantages are mitigated by the technological gap related to the manufacturing of high performance mirrors larger than 1.8 m. Developments of manufacturing and control means for 2.5 m diameter mirrors seems too costly and incompatible with current development plans.
The 9-pupil circular configuration (D = 1.8 m) is thus selected as the best compromise wrt design complexity relaxation, reduction of sub-pupil number and realistic sub-pupil diameter. This configuration is retained for the optical concept analyses presented in the following section.

Table 2 Estimated integration time and required SNR of the selected 9-pupil circular configuration

Ti (ms)	SNR
249.6 ms	285

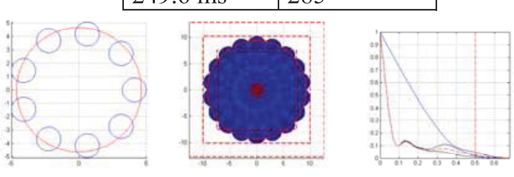


Fig. 5 Selected pupil configuration, corresponding frequency plane coverage and MTF profile

2.5 Linear configuration

The linear configuration is particular since it does not allow to obtain instantaneously the required resolution in all the directions. A full resolution image is reconstructed by combining/deconvolving a set of sub-images acquired during the pupil rotation along the line of sight axis. This particular configuration allows to reduce the required number of pupils and could avoid deployment as far as the linear telescope system is compatible with a vertical in-shroud stacking. Such concepts are patented by Alcatel Alenia Space [8].
However, this solution reveals drawbacks:

- Such an interferometer configuration is clearly limited to a Michelson type interferometer, and limited in field of view.
- While rotating, the on-ground projection of the focal plane needs to be constant, implying a contra-rotation of the focal plane supporting structure.
- The low number of sub-pupils induces very low collecting area and then increases drastically the required integration time.
- Satellite rotation ensures a natural stability of the spin axis in an inertial space, which does not mean in the Earth direction. In this case, the spin axis needs to be precessed continuously about an axis normal to the spin vector (and roughly normal to the orbit plane) to compensate this ‘unnatural’ pointing attitude.
- The number of sub-images to be acquired is large, impacting data rate and signal processing.

This solution, even if potentially interesting, shows a higher level of criticality than planar solutions. We do not mean that it is not conceivable but it would need a particular study in order to reach the same level of confidence than for the other configurations. Linear solution is not retained in the frame of this study.

3. OPTICAL CONFIGURATIONS FOR FIZEAU AND MICHELSON INTERFEROMETERS

The two types of interferometers have been considered for the analyses of the optical configuration.

3.1 Michelson configuration

The Michelson configuration is composed of 9 afocal telescopes plus an optical system dedicated to the combination of the beams.
The optimization of the afocal configuration has been performed after analyses of the magnification impact on the aberrations and of the required number of optical surfaces.

Numerical simulations have shown that a magnification of 9 is compatible with IQ requirements at the FOV edge without vignetting.
The analyzed 2-mirror telescopes have shown unacceptable levels of field curvature.
A three-mirror Korsch configuration has thus been selected for the afocal telescopes.
Centred and Off-axis Korsch configurations have been analyzed.
Considering the combiner, no satisfying two-mirror configurations has been found.
For the three-mirror configurations, two types have been studied : Korsch and Gregory.
The selected one is the Gregory one to its higher level of compactness. It is illustrated in Fig. 6 with one of the afocal telescopes.

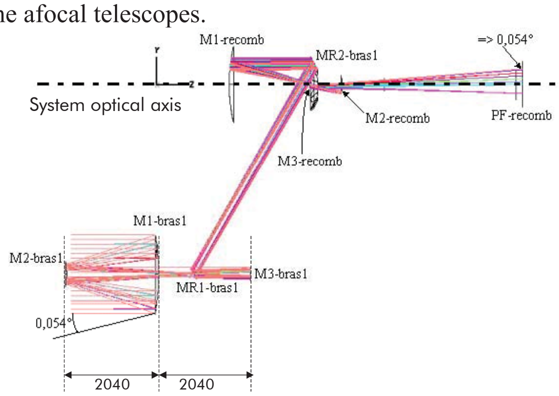


Fig. 6 One arm of the Michelson interferometer (lengths in mm)

Optical performance of this configuration is compatible with the required FOV, a Strehl ratio of 97 % (panchromatic) is estimated at the edges of the field.

3.2 Fizeau configuration

The Korsch optical layout has been selected in order to have a real pupil inside allowing the introduction of a compensation for the line of sight jitter and the wavefront errors (WFE) residuals.
Two alternatives have been considered :

- Field and pupil centred
- Off-axis field and centred pupil

These two options have been studied with varying primary-secondary distance from 22 m to 6.5 m. Fig. 7 illustrates an off-axis one. Only the centred option is compatible with a primary-secondary distance lower than 11m and thus has been selected to avoid the deployment of the secondary mirror.
The corresponding optical performance is also very good since a 99 % Strehl ratio is estimated at the FOV edge. Note that this level of performance is maintained when increasing the field up to a 80 km x 80km FOV.

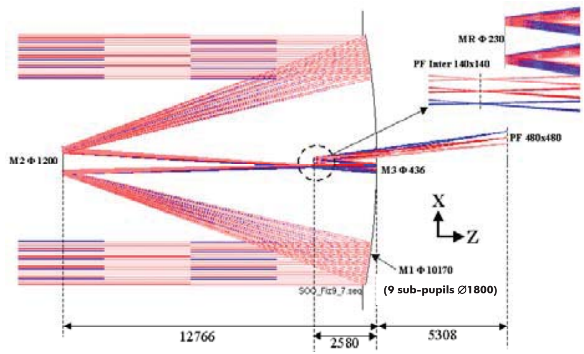


Fig. 7 Fizeau optical configuration (de-centred pupil) (lengths in mm)

4. CO-PHASING APPROACH

Multi-pupil telescopes are based on discontinued mirrors which shape or stability cannot be only ensured by the mechanical stiffness of the supporting structure.
The main perturbations identified are the line of sight instability, the sub-pupils alignment errors (piston and tip-tilt) and the high order WFE.
In order to circumvent these perturbations, a real-time correction by a co-phasing system is required.
The following chronogram (Fig. 8) illustrates the proposed correction logic for both Fizeau and Michelson concepts.
The logic is similar for both concepts except for the first steps which consist in aligning the secondary and primary mirror segments for Fizeau and the afocal telescopes for Michelson.

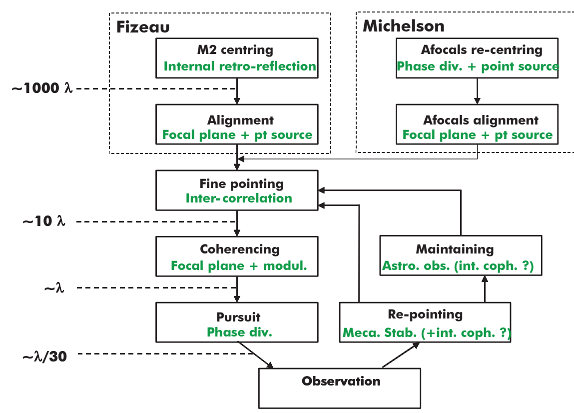


Fig. 8 Fizeau and Michelson interferometers co-phasing chronogram

4.1 Details of the co-phasing approach

- **Deployment:** Initialisation and positioning of the actuators to their theoretical command
- **Re-centring**
  Michelson: each afocal telescope is centred (individually aligned) and aligned altogether. The envisaged method is based on the use of

the same method than for the pursuit i.e phase diversity. The periscopes plan mirrors are used for the correction.

Fizeau: the secondary mirror is aligned with respect to the tertiary mirror-focal plane assembly by using the same concept that the one identified for the Michelson interferometer. The primary segments are then co-aligned using an external point-like source (ground beacon or stellar source). Each segment is identified, then their images are superimposed in the common focal plane.

- **Fine pointing:** Image stabilization during integration. The envisaged solution is the temporal inter-correlation of successive focal images. The correction can be ensured for the Michelson by a plan mirror located in a pupil plane or also by the periscopes mirrors.
  For the Fizeau a unique tip-tilt mirror located in a pupil plane is retained.
- **Coherencing:** Verification that after the re-centring step, all conditions are encountered to enter the pursuit mode. The pursuit mode method can be used at this stage, coupled with a temporal modulation of the actuators to identify the central fringe.
- **Pursuit:** This mode is activated to maintain the alignment within the required precision for the observation. This is done by the use of phase diversity method[9]. This method, presented in Fig. 9, is based on the analysis of two images of the observed scene, to recover the wave front errors. It is coupled with the use of a deformable mirror for the correction.

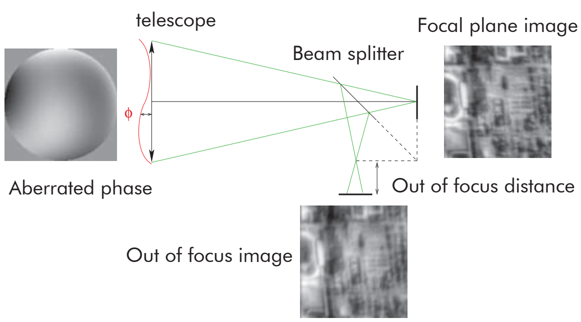


Fig. 9 Phase diversity implementation principle

- **Re-pointing:** The mechanical stability of the instrument is supposed to be sufficient to resume the co-phasing at the coherencing step after re-pointing to a new scene.

Given opto-mechanical perturbations representative of launch, deployment and in-orbit injection conditions as well as thermo-elastic effects, it has been shown that the proposed co-phasing approach is able to bring back the optical system to the required alignment level.

5. TRADE-OFF ANALYSIS

After the investigation of each interferometer type, a trade-off analysis has been perform to select the more adapted concept for the foreseen mission.

Trade-off criteria selected for this exercise are:

- **Field of view limitation**: geostationary observation systems are beneficial if they bring a real gain wrt low earth orbit missions. This gain, linked to permanent observation must not be limited by a too small FOV. This parameter is then considered as crucial.
- **Optical configurations sensitivity**: sensitivity of the optical elements is critical whatever the interferometer type. However, the Michelson concept, due to its large number of optical surfaces and to its combiner sensitivity, presents more critical elements than the Fizeau concept.
- **Deployment**: for the Fizeau concept, the primary mirror segments are the only deployable parts of the configurations. In the case of the Michelson, the recombination optics does not allow the use of fixed afocal telescopes that should also include two different deployable mechanisms for each one.
- **WFE correction**: the major difference between both concepts comes from the correction method. For Fizeau, the wavefront error sensor is used to command a deformable mirror, the primary mirror segments and eventually the secondary. For the Michelson, an optical delay line and a tip/tilt mirror have to be implemented in each interferometer arm.
- **Line of sight stabilization**: the line of sight stabilization present a higher difficulty for the Michelson configuration since no common real pupil plan exist in the optical configuration. The correction thus has to be performed with the optical delay lines and tip-tilt mirrors located in each arms.
- **Manufacturing complexity and optical elements number**: the main difference between the two interferometer concepts is once again due to the large number of optical elements of the Michelson interferometer and to the combiner complexity.
- **Solar entries baffling**: the same level of difficulty is foreseen for the two concepts.
- **Mass**: due to its large number of optical elements, the Michelson mass will be higher than the Fizeau one.
- **Straylight**: for the Fizeau interferometer the straylight handling is classic since Korsch configuration shows locations where it is easy to implement diaphragms and baffling. For

the Michelson interferometer, this is also true for the afocal telescopes but criticality remains for the combiner.

- **Global transmission of the optical chain**: a high SNR is required for these types of instruments to compensate for the low MTF level and the reduced collecting area. The Michelson interferometer is disadvantaged here due to the afocal telescopes central obscuration and the number of optical surfaces.

Table 3 Trade-off criteria notation for the two configurations

		Fizeau interferometer		Michelson interferometer	
Figure of merite	**Weight**	**Score**	**S x W**	**Score**	**S x W**
Field of view limitation	3	3	9	2	6
Deployment complexity	3	2	6	1	3
Co-phasing system complexity	3	2	6	1	3
Line of sight stabilisation	3	2	3	1	3
Optics manufacturing and number	2	2	4	1	2
Solar entries baffling	2	2	4	2	4
Mass	2	2	4	1	2
Straylight	2	2	4	1	2
Optical configuration sensitivity	1	2	2	1	1
Optical transmission	1	2	2	1	1
Total			**47**		**27**

As a result to this trade-off analysis, the Fizeau type interferometer has been selected in the framework of this study. The following architecture phase of this study has lead to an original opto-mechanical concept not presented here as patent pending.

6. CONCLUSION

Given a set of IQ criteria, quantified in order to answer the mission specified by CNES, 12 pupil configurations have been proposed in the frame of this study. After a first trade-off, the 9 circular sub-pupil configuration has been selected (∅pupil = 1.8 m, ∅base ≈ 10m).

This selected configuration has been used to analyze optical configurations for each interferometer type (Fizeau and Michelson).

The Fizeau configuration is a 3-mirror Korsch configuration where each sub-pupil is a segment of the primary mirror.

The Michelson configuration is made of afocal collectors (Korsch centred with a magnification of 9) which output beams are injected in a 3-mirror combiner (Gregory type).

In parallel to this optical configuration study, co-phasing and line of sight stabilization systems have been analyzed. A control logic has been proposed, from the in-orbit injection to the fine stabilization during acquisition, in accordance with the mission requirements. Phase diversity has been selected to measure the WFE and corrections are ensured : either by a deformable mirror and the M1 segments for the Fizeau, or by piston and tip-tilt mirrors for the Michelson.

Given these pupil configurations, optical analyses, co-phasing strategies and adding mechanical architecture criteria, a trade-off has been performed between the Fizeau and Michelson interferometers. Result of this trade-off shows a significant advantage of the Fizeau, mainly for optical, mechanical aspects and control complexity in the case of the Michelson.

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