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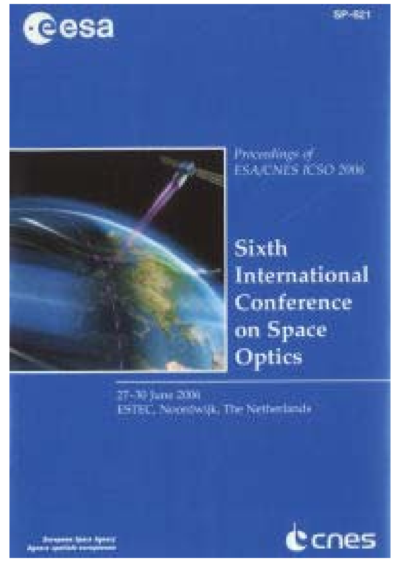


# *An interferometer for high-resolution optical surveillance from geostationary orbit*

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# AN INTERFEROMETER FOR HIGH-RESOLUTION OPTICAL SURVEILLANCE FROM GEOSTATIONARY ORBIT

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## ABSTRACT

The activities described in this paper have been developed in the frame of the EUCLID CEPA 9 RTP 9.9 “High Resolution Optical Satellite Sensor” project of the WEAO Research Cell. They have been focused on the definition of an interferometric instrument optimised for the high-resolution optical surveillance from geostationary orbit (GEO) by means of the synthetic aperture technique, and on the definition and development of the related enabling technologies. In this paper we describe the industrial team, the selected mission specifications and overview of the whole design and manufacturing activities performed.

## 1. THE PROJECT

The activities described in this paper have been developed in the frame of the EUCLID CEPA 9 RTP 9.9 “High Resolution Optical Satellite Sensor” project of the WEAO Research Cell. They have been focused on the definition of an interferometric instrument optimised for the high-resolution optical surveillance from GEO by means of the synthetic aperture technique, and on the definition and development of the related enabling technologies. The activity has been performed by a Consortium formed by Alcatel Alenia Space-Italia, CSL, AMOS and MicroMega Dynamics (Belgium), INETI and ISR (Portugal). This paper summarises the activities performed both concern the instrument study and the developed breadboards.

## 2. THE ORBIT

The geostationary orbit (GEO) is commonly used for telecommunication and meteorological missions, rarely for scientific missions, very limited for remote sensing. For this purpose, low orbits (LEO), typically between 500 to 1,000 km in altitude, are employed in order to get higher spatial and radiometric resolutions. However the GEO offers several advantages for the earth observations, which are: possibility of a continuous observations of the same geographic area of interest, coverage of the whole hemisphere and possibility of re-visiting in a short time the same region, real-time dissemination of the data towards the users and constant observation angles. These features are particularly important in the tactical and strategic surveillance.
The distance from the Earth (about 36,000 km) represents the main obstacle to the full exploitation of the GEO orbit for the remote sensing. This implies that, to achieve a given spatial resolution and to collect a given photon flux at a given observation wavelength, an instrument with aperture tens of times larger than those employed in LEO must be utilised in GEO. For example, to perform ground observation at very high spatial resolution of about 1 meter in the visible spectral band with a monolithic-mirror telescope, an aperture of about 30-m would be required.
With a monolithic-mirror telescope the resolution increase associated to a large aperture is paid first of all in terms of instrument mass. A large primary mirror implies, in addition, the need of the availability of a large volume under the launcher fairing for the accommodation of the instrument. A solution to the problems related to the large aperture, in the cases when the issue is the high resolution and not the light collection (like for the observation of a portion of the Earth surface), is represented by the synthetic aperture technique. It consists in the reconstruction of the original image of an object starting from that formed on the common focal plane of a set of telescopes (or a

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multi-aperture telescope). To this purpose, the set of telescopes (subapertures) must observe simultaneously the object while maintaining constant, within a fraction of wavelengths, the phase of the various wavefronts which are combined together (so to fulfill the coherence and co-phasing conditions, and to operate consequently like an interferometer). The utilization of an optical system constituted by a set of smaller apertures equivalent for resolution to a single monolithic mirror telescope brings considerably advantages in terms of mass saving and reduction of the storage volume. The activities implemented within this RTP are focused on the definition of an interferometric instrument optimized for the high-resolution optical surveillance from GEO by means of the synthetic aperture technique, and on the definition and development of its enabling technologies.

## 3. THE ROADMAP

At the beginning of the activity, a set of reference mission specifications have been derived, together with a set of instrument requirements in terms of observation parameters.

The choice of the operational mission characteristics has been done on the basis of a selected number of performance parameters related to the following supposed user needs: an on ground FOV 5 x 5 $Km^2$, a spatial resolution about 0.004 arcsec (corresponding to 0.7meters) at 0.65µm, a spectral band from 0.4 to 0.9µm, continuous coverage of the areas of interest to allow non-interrupted monitoring of critical situations (except for overcast weather conditions).
This implies that a 40m class GEO instrument is required, thus an instrument that needs to distribute the optics on a satellite constellation that is considered very critical for a demonstration mission, or it should be assumed the availability of future technologies, presently not existing, for the optics and their deployment in orbit. Thus a reduced diameter is proposed for the demonstrator, so that it can be hosted on a single satellite using state of art technology.

Concerning the demonstrator orbit, the choice of a LEO system instead of GEO doesn't simplify the instrument complexity and imposes a very different configuration, thus this possible intermediate solution is discarded and a GEO orbit is considered for the demonstrator too.

At the end of this instrument definition activity we get a possible roadmap towards the implementation of an operational surveillance mission in GEO based on a synthetic aperture telescope:

- Requirements definition, instrument design and technology development study Euclid 9.9 (years 2003 - 2005).
- Ground based demonstrator: implementation of a simple (3 apertures, possibly Golay type, 1 m class diameter) synthetic aperture telescope for proof-of-concept tests and technology development finalisation (years 2006 - 2008).
- On orbit demonstrator in GEO: implementation 5/8 meter diameter class synthetic aperture telescope, carried by a single spacecraft operating in GEO, for validation/verification of the whole system, in the same orbital environment (dynamics, thermal inputs) of the final operational mission (years 2009 - 2014).
- Operational mission in GEO: deployment of an operational system of surveillance from the GEO orbit based on one or more synthetic aperture telescopes of 40 m diameter class (years 2015 - 2020).

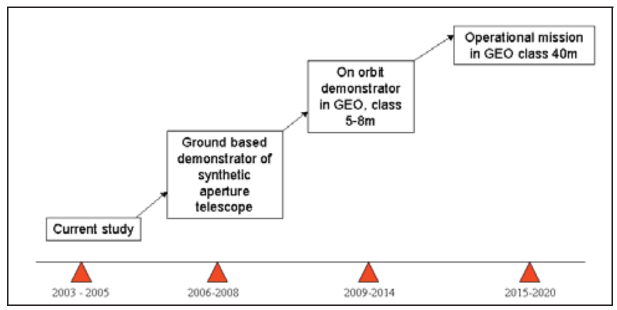



Fig. 1: possible roadmap for the implementation of an operational surveillance mission in GEO based on a synthetic aperture telescope

## 4. THE REQUIREMENTS

The current study is focused on the GEO demonstrator mission, 5-8m diameter class interferometer. Its parameters are summarized in Fig. 2.

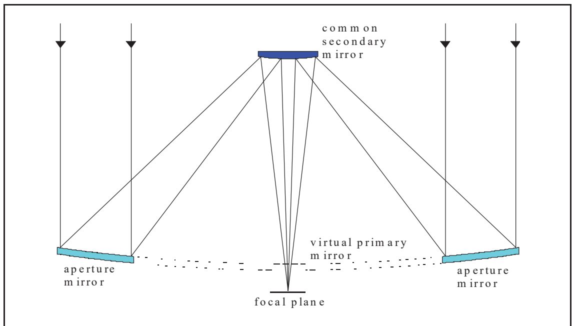
**Reference scenario for the current study activity**

- Reference mission: demonstration mission in GEO (36000 km altitude)
- Overall aperture diameter: 7 meters (Next Generation Space Telescope is 6.5 m)
- Overall satellite size: fitting in the Ariane 5 Long Fairing (telescope folded and deployed in orbit)
- Operating spectral band: 0.4 to 0.9 $\mu m$ (panchromatic mode)
- On-ground resolution: 2.2 m at 0.4 $\mu m$ wavelength, 4.9 m at 0.9 $\mu m$ wavelength
- Field of View: 5 arcmin (about 50 x 50 $km^2$ on ground)
- Aperture pattern: sized for a MTF > 0.15 for spatial frequencies below the Nyquist frequency, and optimized on the basis of the telescope implementation constraints (overall mass and size to fit the reference launcher).

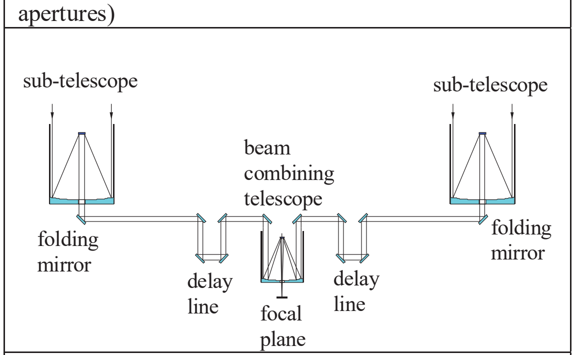
Fig. 2: parameters of the reference scenario for the current study activity

## 5. INSTRUMENT DESIGN

The selected candidate optical configurations for the GEO instrument are the Fizeau interferometer and the Michelson interferometer with Fizeau-type recombination: a trade-off has been performed to select the most suitable one. The two configurations are schematically shown in Fig. 3.




Fizeau interferometer concept (shown with 2 apertures)




Michelson interferometer with Fizeau-type combination concept (shown with 2 sub-telescopes)

Fig. 3: the two optical configurations candidate of the trade-off

At the end of the comparative analysis, the Michelson interferometer with Fizeau-type combination has been chosen as the reference optical configuration for the GEO instrument.

The first step to be accomplished for a space interferometer development is the finalisation of the choice of the aperture configuration. The choice made for this study is based on an initial criterion (compatibility with launcher fairing dimensions) that provided the maximum apertures number and the maximum diameter for each aperture; then the final configuration has been found considering various types and calculating their MTF (Fig.4), then comparing them and choosing the most performing one.

The interferometer detectors type and characteristics have been identified too. Indeed CCD Mosaic detectors of 28 Mpixels and more are suited for the application from the point of view of acquistion time, SNR and datarate.

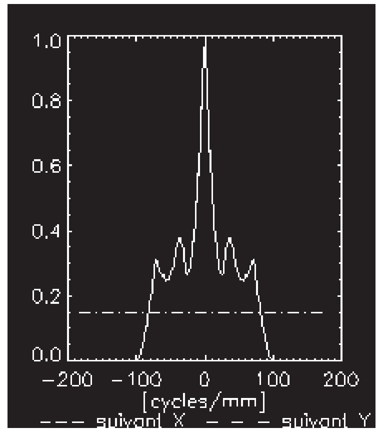



Fig. 4 Typical MTF of the aperture configuration shown in Fig. 5

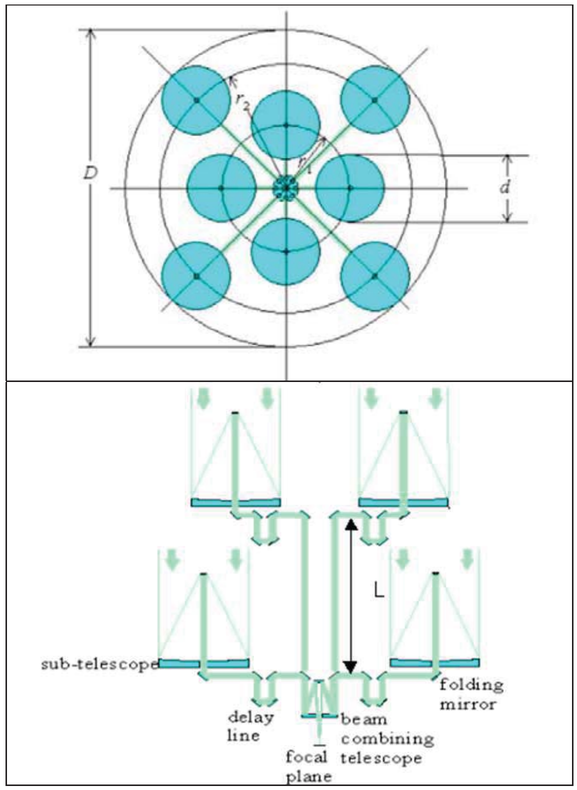



Fig. 5: sub-apertures configuration and interferometer optical concept

The mechanical reference configuration has been designed to be able to fit within the long fairing of the

Ariane 5 ECA version, operative since 2002 and able to launch a total mass of up to a 10050 kg into GTO (Fig. 6).

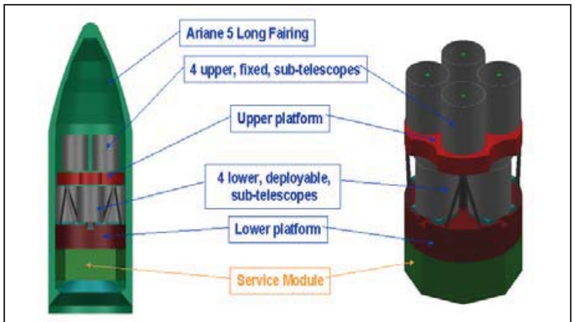



Fig. 6: instrument inside Ariane 5 long fairing (left) and in folded configuration (right)

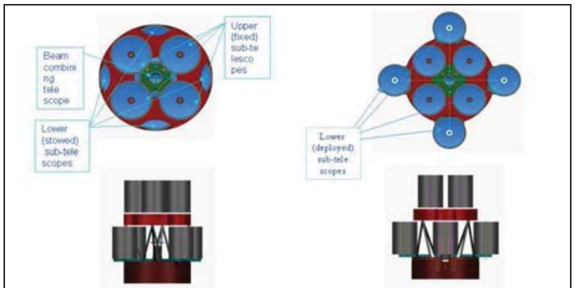



Fig. 7: upper and side view of the folded (left) and unfolded (right) configuration

We have performed a trade-off among some possible mechanical configurations on the basis of the requirements related to the Ariane 5 long fairing, to the reference optical configuration, to the possible concepts for the choice of deployment mechanism of the mirrors system. We have selected a mechanical configuration based on two groups of four sub-telescopes on two different levels plus a (smaller) beam combining telescope ("2 planes" configuration, Fig. 7). The upper group is constituted by fixed units, i.e. the upper sub-telescopes are permanently fixed; the lower sub-telescopes are locked at launch. Once in orbit, each sub-telescope in the lower platform is firstly unlocked and then deployed by means of a dedicated motorised linear actuator to its observing location.

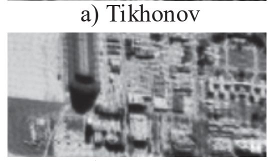
For a MultiAperture Telescope the PSF changes within the FOV and the system is space variant. The interferometer images were simulated using real optical satellite images (ground resolution: 2.8 m) and a set of PSFs that characterize the behavior of the imaging system in seven points within the FOV, obtained by design using CODE V, and by interpolation for the other points (Fig. 8). Two different restoration perspectives where envisaged:

i) a single PSF is used to restore the image globally;
ii) block restoration, by sectioning the image in blocks, and using the average PSF over the block.

Four restoration approaches have been retained: two make use of iterative algorithms - Conjugate Gradient Least-Squares (CGLS) method and Modified Residual Norm Steepest Descent (MRNSD) method - and two direct procedures that rely on regularization techniques - Tikhonov Least-Squares (Tikhonov) and Truncated Singular Value Decomposition (TSVD). The restoration effects with the four methodologies are shown in Fig. 9.
The use of a preconditioner applied to the PSF accelerates the rate of convergence in the iterative case. Different image boundary conditions (periodic, zero and reflexive) were implemented and compared.
The performances were measured by four indicators: Mean Squares Error Improvement Factor, Degradation Index, Subjectivity Index and Artifact Control Area.

Fig. 8- Original (left) and space variant blurred (right) test images.


a) Tikhonov b) TSVD




c) MRNSD d) CGLS

Fig. 9– Restoration with the four methodologies

We may conclude that a single overall PSF has the best performance in both iterative and non-iterative modes. CGLS iterative method can be used for both high and low spatial frequency image contents; Tikhonov minimizes artefacts when restoring homogeneous areas; MRNSD is a very good compromise for high variability regions.

In parallel, the optical metrology needed to ensure the stability of the optical configuration has been defined. An interferometric instrument based on the synthetic aperture technique requires a complex metrology system to ensure the stability of the optical configuration and the knowledge of its state. To perform co-phasing, two complementary methods are needed: an external sensor metrology and an internal sensor metrology. While the external sensor makes use of information available within the Field of View, the internal metrology makes

use of laser light fed into a metrology interferometer and other non-interferometric sensors. The external sensor metrology is based on a wavefront sensor. To achieve co-phasing, the relative phase between the wavefronts (from the various telescopes) which are combined together must be constant within a fraction of the wavelength. The basic principle is to work with the observed scene: one bright point is extracted (image plane filtering) and used as point source. The internal sensor metrology will be based on interferometers, wavefront type sensors and retro-reflection measurement sensors, all using internal laser light. These technologies will allow both absolute and relative measurements of Optical Path Differences (OPD), Optical Path Lengths (OPL), and angles.
From deployment to observation, the instrument will pass trough different configurations, corresponding to different levels of correction of perturbations.
In addition to the measurement of the absolute value of OPD and variations in time, it will be necessary to measure the distance between planes and lateral and longitudinal deviations in the pupil positioning, to cope with pupil geometry requirements.
The design and simulation of the overall control system was carried on based on the available data. Two possible strategies for controlling the overall instrument were suggested: simulations have shown that it is possible to adjust the OPD for all sub-telescopes (ST) pairs under the current or other similar configuration of the ST, for both proposed strategies. Strategy 1 (decentralized control) is more robust to failures and more accurate. However, it is less robust to mismatches between the commanded ODL and its actual value. Strategy 2 (Master-Slaves control) is a centralized solution, therefore simpler to implement. However, it is less robust to failures of the master arm, and was shown to be less accurate.
Both internal and external metrology sensors have been breadboarded and are presented in other papers of this conference ([2], [3]).

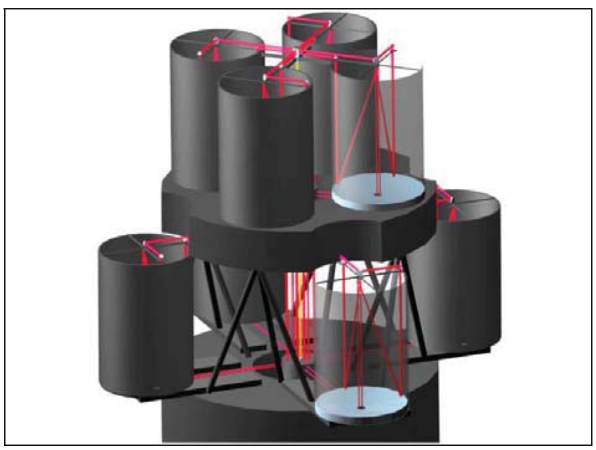


Fig. 10: optical metrology concept

## 6. MIRROR TECHNOLOGY DEVELOPMENT AND VALIDATION

The mirror breadboarding activity has proven that the state-of-the-art technology allows us to satisfy the requirements of mirror mass and stiffness (eigen frequency). Current lightweighting technology and mirror materials are well developed to produce large lightweighted mirrors for space applications. The requirements concerning the tolerance on the radius of curvature and on the optical quality (wavefront error) are more critical from the point of view of the feasibility (although the first requirement is almost achieved): taking them into account it will be possible to refine the optical design of the instrument to make it compliant to achievable figures.

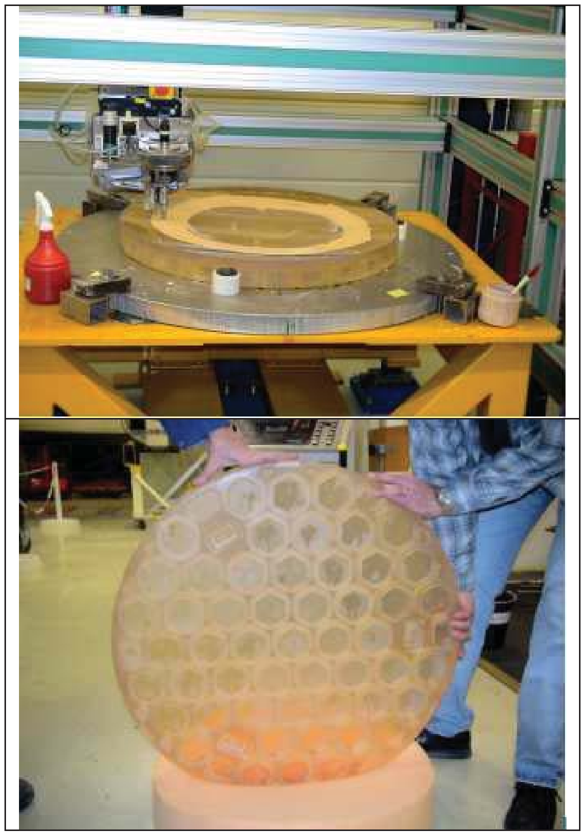


Fig. 11: mirror breadboard in some manufacturing steps

## 7. CONCLUSIONS

We can conclude that this technological research shows the feasibility of a Michelson-Fizeau interferometer with characteristics which make it suitable for remote sensing of the Earth from geostationary orbit.

This project has finally covered:
-Mission analysis
-Instrument optical and mechanical design [1]
-Image Restoration [1]
In parallel: one breadboard of large aperture mirror technology
-Internal co-phasing technology [2]
-External co-phasing Technology [3]

Good results have been obtained both with the interferometer design and with the laboratory breadboard tests, that show the suitability of metrologies to keep the instrument in cophasing conditions in presence of a noisy environment.
Technological maturity and feasibility have been demonstrated by external sensor breadboard, internal sensor breadboard (concerning both absolute and relative internal metrology), mirror breadboard.

Now that technical feasibility is fully demonstrated, next step is to perform a complete Phase A study to deeply evaluate all the matters related to a real S/C design and manufacturing, in parallel with the breadboard of a simple synthetic aperture telescope for proof-of-concept tests and technology development finalisation.

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