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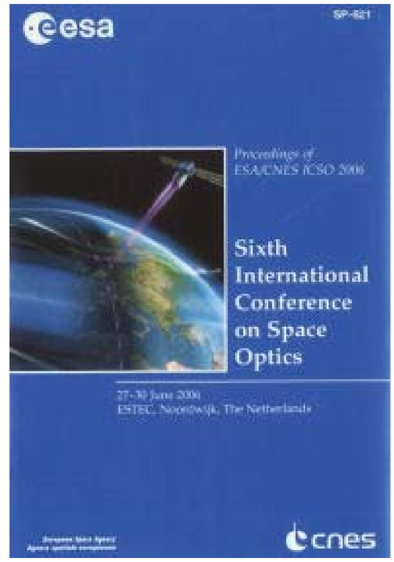

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AN INTERFEROMETER FOR HIGH-RESOLUTION OPTICAL SURVEILLANCE FROM GEOSTATIONARY ORBIT - SPACE SYSTEM STUDY

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ABSTRACT

This paper describes the study of an interferometric instrument for the high-resolution surveillance of the Earth from geostationary orbit (GEO) performed for the EUCLID CEPA 9 RTP 9.9 “High Resolution Optical Satellite Sensor” project of the WEAO Research Cell. It is an in-depth description of a part of the activities described in [1]. The instrument design, both optical and mechanical, is described; tradeoffs have been done for different restoration methods, based on an image generated using calculated point spread functions (PSF’s) for the complete FOV. Co-phasing concept for the optical interferometer has been defined together with the optical metrology needed. Design and simulation of the overall instrument control system was carried out.

1. INSTRUMENT OPTICAL DESIGN

The instrument design has been started defyning the number, size and relative position of the sub-apertures of the GEO interferometer comparing the performance of many different configurations; the most favourable interferometer concept has been chosen, the choice being between Fizeau interferometer and Michelson with Fizeau recombination interferometer; the trade-off ended with the selection of the latter one [1].
As the Michelson interferometer is composed by one external and one internal circular array of sub-telescopes lying on two different planes, two distinct optical paths are identified. The external and internal arms of the interferometer identifying the two distinct optical paths (from a sub-telescope to the focal plane, including the delay line) modeled with CODE V are shown in Fig. 1.

Each sub-telescope is an afocal Gregorian-Mersenne telescope with compression factor = 15; it produces a collimated optical beam for any planar wavefront entering in a given direction inside the telescope FOV. In this design two confocal paraboloids work at infinite conjugates. This optical configuration has been chosen in order to get an intermediate focus between primary and secondary mirror. In this focus a mask can be inserted to narrow down the telescope FOV, as needed when the external sensor for the co-phasing is used. At the output of the sub-telescope, the light is routed towards the beam combining telescope by a sequence of six flat folding mirrors, which include also the delay line (a set of two movable mirrors utilized to adjust the optical path length from the sub-telescope to the beam combining telescope). The beam-combining telescope is based on a Ritchey-Chretien configuration, both mirrors are hyperboloids. At the output of the beam combining telescope the light passes through an achromatic doublet introduced in order to minimize the residual optical aberrations and finally is focused in the focal plane, where all the beams collected by the sub-telescopes are superimposed. An interference fringe pattern is formed on the focal plane with a good visibility when the optical path difference between the interferometer arms is kept within a fraction of the coherence length. All the elements in each arm of the Michelson interferometer (from the sub-telescope to the focal plane) have been designed to get a good performance of the systems in a circular FOV of 0.05° of diameter, corresponding to an Earth surface portion of about 30 km^2 observed from GEO.
The size of the sub-telescope primary mirror (1500mm) is limited by the available volume in the payload compartment of the reference launcher (Ariane 5) for the “packing” of the whole instrument. The size of the other mirrors has been established by the optical design.
A mirror breadboarding activity has proven that the state-of-the-art technology allows us to satisfy the requirements of mirror mass and stiffness [1].

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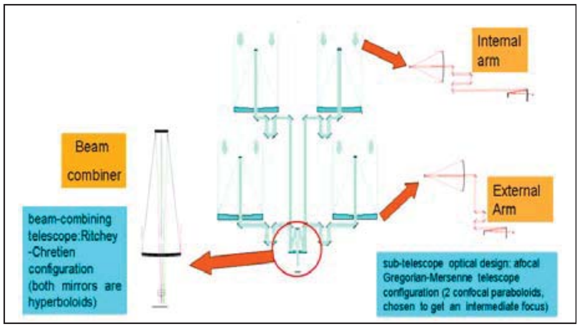
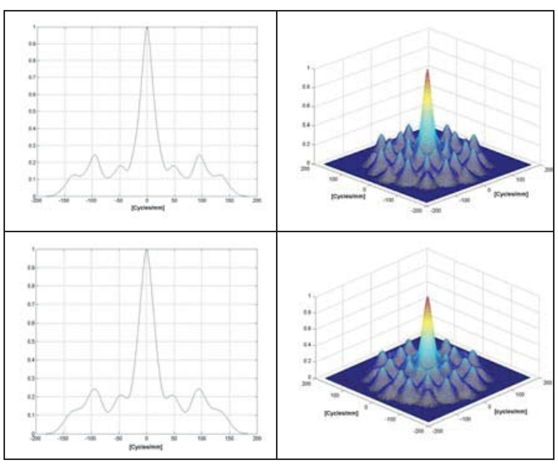


Fig. 1: interferometer optical design

In the computation of the MTF of the overall 8-arms Michelson interferometer, we had to face the limitation of the CODE V tool, which is not able to properly analyze an optical system composed by independent, parallel light path converging to a central telescope.
The problem has been overcome by exploiting the superposition property of the Fourier Transform of the pupil function calculated for each interferometer arm. The Fourier Transform of the pupil function, $h(\lambda)$, gives the complex distribution in the image and the complex square of this distribution gives the PSF. With CODE V we modelled one interferometer arm at a time and for each arm we have computed the functions $h(\lambda)$. Then the 8 Fourier Transform of the pupil function so obtained have been combined in MATLAB, to get the PSF of the whole 8-arm Michelson interferometer. Finally the polychromatic MTF of the overall 8-arms Michelson interferometer has been obtained: it is shown in Fig.2 for the field angles (0°, 0°), (0.017°, 0°), (0.025°, 0°), one field for each row.



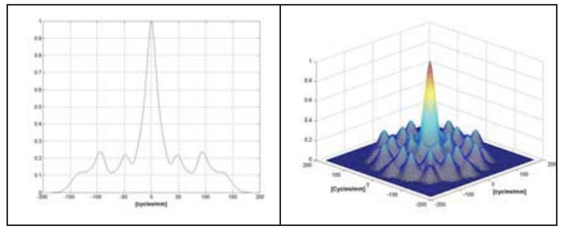


Fig. 2: Polychromatc MTF

Comparing all these polychromatic MTF, it is interesting to note a very similar shape across the FOV. This means that the instrument is optimised to provide very similar performances in the whole FOV.

2. IMAGE RESTORATION TECHNIQUES

Blur is a phenomenon that occurs whenever the intensity of a pixel depends on a average over a large area of the object space. Blur is inevitable because the resolution of a system is always finite. Blur is directly measured by the Point Spread Function (PSF) of the system, which depends on the optical architecture of the instrument, aberrations and sensor.
For space invariant systems the PSF is constant within the Field Of View (FOV), and the image can be generated by a convolution of the object distribution with a single PSF. Consequently blur can be, in principle, reduced by deconvolution. Nevertheless, for a MultiApertures Telescope (MAT) the PSF changes within the FOV and the system is space variant. Deconvolution cannot be applied to compensate PSF-related blur and other techniques must be used to restore the image and improve the resolution, provided the optical architecture of the MAT ensure that the support of the MTF is compact (no zeros within the frequency bandpass of the instrument).
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. Further PSF were computed for a complete octant of the FOV by interpolation, profiting from the symmetries of the optical configuration, and using relative distances to the points where PSF were available as weighting factors.
Two different restoration perspectives can be 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 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 use of a preconditioner P 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 of the iterative and one-step algorithms were measured by the following indicators:

i) Mean Squares Error Improvement Factor [1],
ii) Degradation Index,
iii) Subjectivity Index,
iv) Artifact Control Area.

Two images, one with higher spatial frequencies and another with lower spatial frequencies were used to demonstrate the performances of the methods.

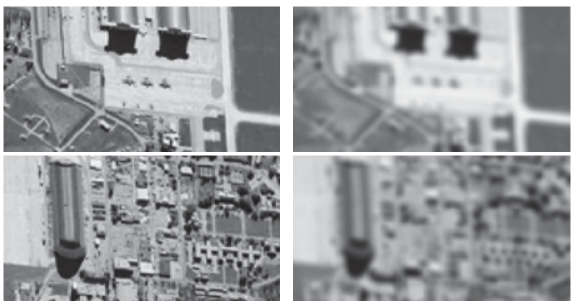


Fig. 3- Original (left) and space variant blurred (right) test images. Top – low spatial frequency content. Bottom – high spatial frequency content

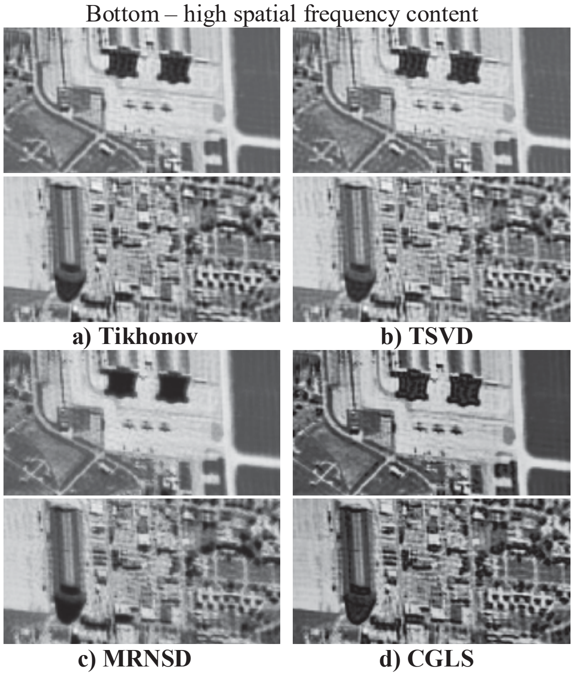


Fig. 4– Restoration with the four methodologies

The space variance of the PSF does not seem to be too relevant for the current instrument concept – 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.

3. INSTRUMENT MECHANICAL DESIGN

A reference configuration for the mechanical structure of the synthetic aperture instrument for the high-resolution remote sensing from GEO was designed to be able to fit within the long fairing of the Ariane 5 ECA version. Two suitable configurations have been identified and a trade off has been performed between them. Because of the available room in the Ariane 5 fairing, the selected configuration is based on accommodating 2 groups of four sub-telescopes on two different levels plus a smaller beam combining telescope. The upper sub-telescopes are permanently fixed; the lower sub-telescopes at launch are locked. Once in orbit, each sub-telescope in the lower platform is firstly unlocked and then deployed by means of a dedicated motorized linear actuator to its observing location. Note that such a configuration does not allow to individually provide each telescope with a pointing mechanism because, in that case, the upper telescopes would enter in the field of views of the lower ones. As a consequence, the Instrument pointing can only be achieved by moving the whole satellite.
Another configuration, always based on a 4+4 sub-telescopes concept, has also been subject of the traded-off, the "Planar" concept: lower telescopes deployable to the upper group's level .The "planar" configuration is, in principle, the most favourable, because of the symmetry and equivalence of optical paths between lower and upper sub-telescopes. It also allow to individually provide each telescope with a pointing mechanism. Such a very good optical configuration, though, is much more complicated to design an build than the "all-deployable" one; in fact, lower sub-telescopes should be mounted on a multi-mechanism capable of this steps:

- deploy the telescope outwards ;
- lift the telescope to the upper telescopes' level;
- lock the telescope in the upper location;
- provide a pointing capability.

All these functions would mean an extremely complicated mechanical design, that, with the addition of tight dynamic stability and dimensional requirements, caused to eventually discard this solution.

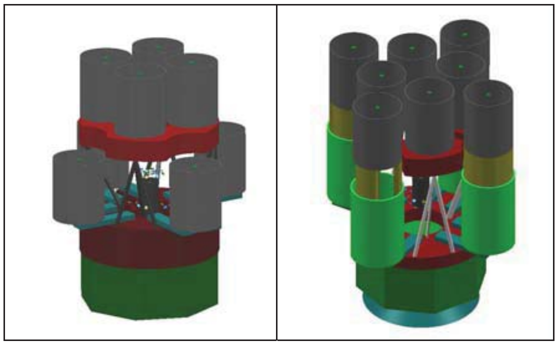


Fig. 5: left, 2 planes configuration; right, planar configuration

4. CO-PHASING CONCEPT

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.
Fig. 6 shows the description of configurations in the instrument alignment concept. To go from one configuration to another, several Metrology Modes are foreseen.

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.

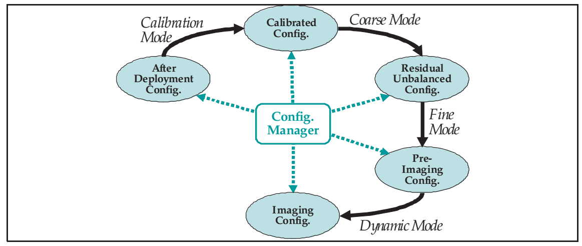


Fig. 6. Configurations and Modes of Alignment.

Fig. 7 shows the sensors selected for OPD and length measurements in relation to the metrology modes (FSI - Frequency Sweep Interferometry; MWI - Multiple Wavelength Interferometry; RI - Relative Interferometer; RBS - Retro-reflected Beam Sensor; WLFS - White Light Fringe Sensor; WLFS-VN - WLFS with Vibration Nulling), and for tilt measurement (PWS-ILS - Plane Wavefront Sensor with Internal Light Source; MRPWS-ILS - Multiple Reflection PWS with ILS - PWS-ELS - PWS with External Light Source).

Breadboards related to the selected sensor concepts have been manufactured and tested; related results are presented in [2], [3] and [4].

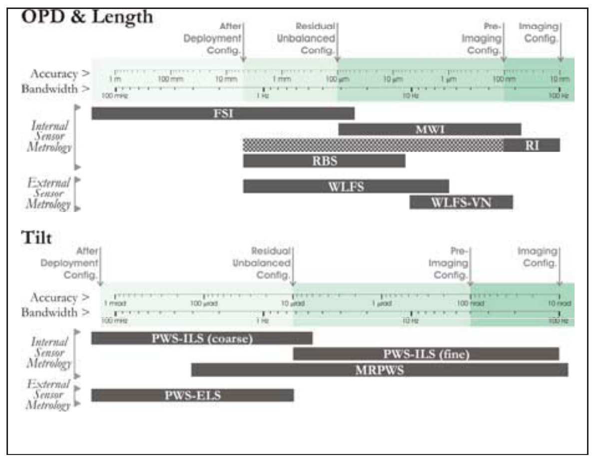


Fig. 7. Sensors for OPD and length measurements (top) and tilt measurement (bottom).

5. OVERALL INSTRUMENT CONTROL SYSTEM

The design and simulation of the overall control system was carried based on the available data concerning the GEO instrument overall metrology system specifications, the co-phasing demonstrator characteristics, including sensors and noise transmission through the bench structure, the noise-to-co-phasing transfer function characteristics for a spacecraft

structure similar to the GEO instrument, the performance requirements for the active co-phasing control loop, and the nominal parameters of the actuator mechanisms to be used by the control loop. Simulation results covered the individual OPD pair controllers, providing indications for the parameterization of the corresponding control loop, its sensors and actuators. 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.

6. RECOMMENDATIONS FOR FUTURE DEVELOPMENTS

The activity performed during this study was focused on the demonstration of the technical feasibility of an interferometer with characteristics which make it suitable for remote sensing of the Earth from geostationary orbit. As such, the study was not oriented to produce a complete preliminary S/C design.
This preliminary design has addressed the following points:

-optical design
-mechanical design
-image restoration
-detector definition
-co-phasing based on internal sensors
-co-phasing based on external sensors
-large lightweight mirror breadboarding

The 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 the following, we report a list of the main results coming out from the main activities performed and the consequent recommendations.

Concerning the choice of the aperture configuration, from the literature we see that various studies in this field seem to indicate that the use of a mathematical criterion to optimise the interferometer sub-apertures spatial configuration (using the MTF as merit function) may allow a better definition of the final configuration, capable of considering all the possible options for the mirrors configurations and not only an arbitrary subset (Ref.5). This is the rule to follow for the aperture configuration choice of the GEO satellite. Moreover, the final optimal interferometer sub-apertures configuration choice should be made with the analysis of the complete optical chain (from collecting optics to focal plane) that includes the optimisation of the compression ratio and the analysis of the beam disposition on the combiner (includes tolerancing of longitudinal and lateral pupil homothety) [6].

Concerning general instrument design, the initial effort must be oriented to find an as-simple-as-possible instrument & metrology configuration, as this kind of instrument is characterised by an high complexity level that needs to be reduced as much as possible. This effort must be oriented also to the minimisation of mass, volume, number of active elements needed, number of custom elements needed. In the frame of this design activity also the maximisation of the use of off-the-shelf items (if possible, already suitable for space use) plays an important role, as it impacts e.g. on the reduction of testing activities and cost.

An help to reduce mass and complexity will probably come from the use of fiber optics and integrated optical circuits when possible, especially in the routing of the beams for internal and external co-phasing metrology. Usually they not only are of help for simplifying design but also are small and robust. For example, a bulk optical chain performing phase-modulation (electro-optic), beam merging (interference) and grating can be compacted in one single integrated circuit, reducing number of elements, mass, dimensions, alignment problems. Unfortunately often these integrated optical devices are not off the shelf components. They require a specific design and specific space qualification process.

Concerning the laser, particular attention is to be paid to new developments in this field.
Solid-state lasers are currently the “natural” candidates for spatial applications, in particular diode pumped Nd:YAG ones. The reason is that in 2007 the first European space-qualified laser (made by Galileo Avionica) will fly in the AEOLUS mission as part of the ALADIN instrument (Atmospheric Laser Doppler Lidar Instrument) and moreover this type of laser is also being qualified for the future LISA (Laser Interferometer Space Antenna) mission. But, if the project schedule allows further effort in the field of laser space qualification, it may be possible to take into consideration also other possible options, like e.g. fiber integrated lasers, which would have many advantages, such as reduced weight and dimensions, increased ruggedness. The use of such a kind of laser is an objective to be considered carefully at the beginning of the Phase A.
In parallel to the study phase, also partial breadboarding activities focused on critical aspects must be foreseen

(e.g. concerning the use of particular detectors, of fiber optics technology, of integrated optical devices, of internal metrology tilt sensors…)

In the frame of a complete Phase A study, it is important to highlight that thermomechanical aspects are fundamental for this kind of instrument and require a particular effort; the use of materials suitable to solve problems related to mass, stiffness and dimensions variations due to thermal reasons is to be investigated. A special attention shall be made to those materials that can be used both for optics and for structure (e.g. SiC, well known for both uses) so to reduce the problem of different thermal expansion coefficients between optical and structural parts, thus reducing thermal deformation problems that are particularly serious for optical interferometers. It is fundamental also to estimate precisely the possible deviations from the nominal configuration, to determine the maximum range of the metrology sensors and avoid possible over-dimensioning that would lead to useless increase of technology complexity. Similarly, the behaviour of the instrument in term of vibrations (amplitude and frequency) is to be studied in depth to allow an exact specification of the dynamic performances of the sensors.

The design and development of a space qualified version of interferometer must include the study of the environmental effects experienced during the travel and then the orbiting in GEO. The foreseen environments that the instrument will experience must be completely characterised to allow design the various interferometer components with sufficient security margins; a suitable test campaign must be foreseen for those devices / materials that are not space qualified. The fundamental aspects to be defined are the vibration levels, temperature ranges, radiative levels. Tests to check survival to particular thermomechanical environments (in vacuum or not) are common practice in space technology. What is a bit less common is the testing of radiation effects, for which it is necessary to refer to particular facilities.

The current study and breadboarding phase has provided us plenty of information, indications and recommendations concerning how to plan and direct in an effective way the following activities aimed at performing a complete Phase A study of the interferometer for remote sensing of the Earth from geostationary orbit.

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