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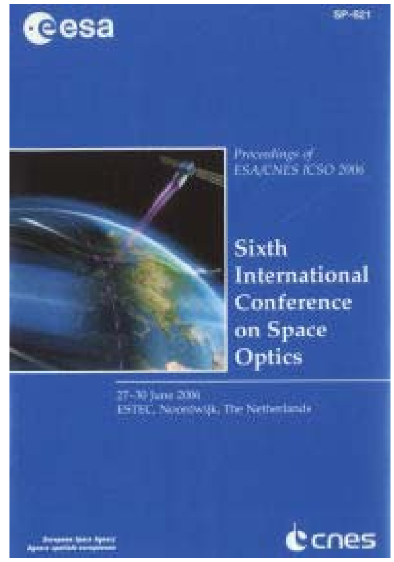

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OPTICAL APERTURE SYNTHESIS: LIMITATIONS AND INTEREST FOR THE EARTH OBSERVATION

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ABSTRACT

For very large telescope diameters, typically above 4 meters, monolithic telescopes can hardly be envisaged for space applications. Optical aperture synthesis can be envisaged in the future for improving the image resolution from high altitude orbits by co-phasing several individual telescopes of smaller size and reconstituting an aperture of large surface. The telescopes can be deployed on a single spacecraft or distributed on several spacecrafts in free flying formation. Several future projects are based on optical aperture synthesis for science or earth observation. This paper specifically discusses the limitations and interest of aperture synthesis technique for Earth observation from high altitude orbits, in particular geostationary orbit. Classical Fizeau and Michelson configurations are recalled, and system design aspects are investigated: synthesis of the Modulation Transfer Function (MTF), integration time and imaging procedure are first discussed then co-phasing strategies and instrument metrology are developed. The discussion is supported by specific designs made at EADS Astrium. As example, a telescope design is presented with a surface of only 6.6 m² for the primary mirror for an external diameter of 10.6 m allowing a theoretical resolution of 1.2 m from geostationary orbit with a surface lower than 10% of the overall surface. The impact is that the integration time is increasing leading to stringent satellite attitude requirements. Image simulation results are presented. The practical implementation of the concept is evaluated in terms of system impacts in particular spacecraft attitude control, spacecraft operations and imaging capability limitations.

1. INTRODUCTION

Earth observation from geostationary orbit is only used for meteorological missions whose sampling distance is a few hundred meters. In case of earth watching or civil security with immediate access need, the use of this orbit is necessary. But then the sampling distance is in the order of a few meters. Diffraction and altitude then impose a telescope of many meters diameter, not compatible with actual launchers and classical architectures.

Different telescope architectures are possible to cover a full range of sampling distance from this orbit:
- Classical telescope: considering a maximum diameter of ~ 3.5 m like Hershell, we have a sampling distance > 4 m
- Deployable telescope: telescope is folded for launch. Considering a full pupil, maximum diameter is around 5 m leading to a sampling distance > 2 m
- Aperture synthesis: telescope is also folded for launch with a diluted pupil. Specific image treatment might be used to recover MTF. Sampling distance is > 1 m
- Formation flying: as for aperture synthesis but the diluted pupil is spread on many satellites. With a satellite distance > 10 m for safety reason, sampling distance is < 1 m

An analysis of the geostationary orbit will help to specify the sampling distance and the maximum time to take picture. Then, dimensioning of telescope will be made based on Fizeau configuration. Specific application will be show using modified telecom satellite.

2. INTEREST & LIMITATIONS OF GEOSTATIONARY ORBIT

From this orbit, 3 satellites are necessary to cover all emerged land with latitude below 50°.

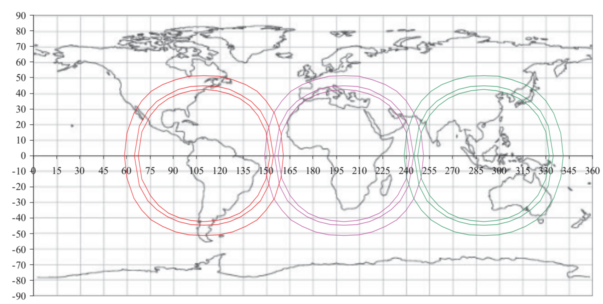

Fig. 1: Optimal positioning of 3 spacecrafts

The 3 circles correspond to a sampling distance degradation by 1.5, 1.7 and 2 from nadir sampling distance. **Then, we will consider a nadir sampling distance of 1.17 m in order to get ~ 2 m at 45°**

latitude. Above this latitude, degradation is very rapid. This will lead to a pupil diameter above 10 m. It has to be noticed that this resolution is equivalent to a resolution of 2 cm from an orbit at 700 km.

The major interest of this orbit is that we may stay over one objective and take many pictures. In the same way, we can access quickly to any point in the field of view of the instrument. **Then, we will impose the telescope to take a picture in less than 15 mn**.

The major disadvantage is that we have a constant angle of view for each objective. Furthermore, this angle of view is 60° from vertical at our latitude. This means that a distance of 1.7 time the height of an obstacle is hidden to the telescope.

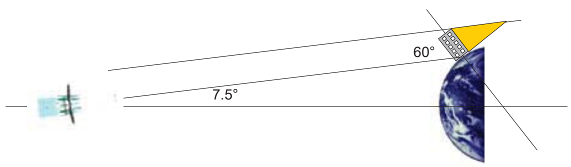

Fig. 2: Masking effect for a resolution of 2 m

The only possibility to cancel this disadvantage is to consider an inclined orbit. An orbit inclined by 45° would allow passing all over Europe

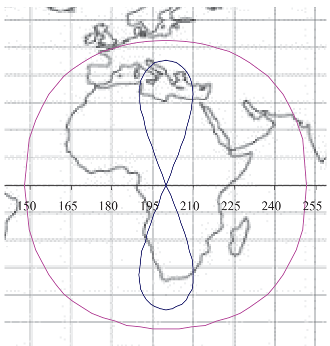

Fig. 3: Inclined orbit

But then we need 2 satellites at each position in order to be able to access the 2 hemispheres at any time. Overall, we will need to cancel the motion effect. Finally, it appears that this inclined orbit has few interests compare to its disadvantages.

3. APERTURE SYNTHESIS DIMENSIONING

3.1. Aperture synthesis specificity

For a pupil diameter greater than 10 m, a diluted pupil is necessary to be compatible with the fairing volume. Only a few part of the pupil is used. This is the aperture synthesis principal. We then have to optimise pupil shape. When the pupil is diluted, the MTF may vary in the Fourier spectrum. We then have 2 kinds of pupil shape:

- Complete configuration: there is no MTF hole within the Nyquist domain. One picture is then enough

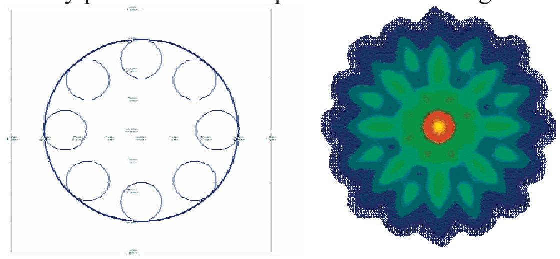

Fig. 4: MTF and associated pupil shape for a complete configuration

- Incomplete configuration: the MTF is positive only in a few part of the domain. Then, we need to combine many pictures in order to get a minimum MTF in the whole Nyquist domain. This is the case for in-line configuration: we need to turn the telescope between each picture to get a complete the MTF

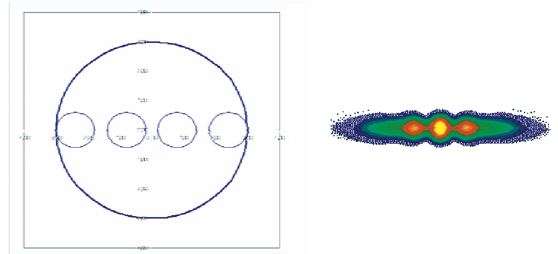

Fig. 5: MTF and associated pupil shape for an incomplete configuration

We then have 2 kinds of telescope:

- Fizeau telescope: a telescope which only a part of the pupil is used
- Michelson telescope: a telescope made of many afocal telescopes in entrance which are combined using a combining telescope or imaging telescope.

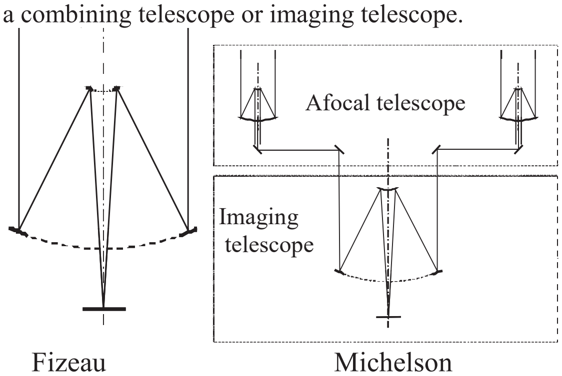

Fig. 6: Fizeau and Michelson telescope

3.2. Imaging simulations

The major parameter for pupil sizing is the MTF. Imaging simulations where performed with complete and incomplete configurations and different MTF and SNR in order to determine the minimum acceptable MTF with the constraint that the MTF is greater to this minimum on all the Nyquist domain. For incomplete configurations, the Wiener method is used to combine the pictures. This method determines the optimal filter for the whole picture by minimising an error function. Before applying the Wiener filter, denoising is performed with wavelet.

Around 20 simulations for each configuration where performed. For incomplete configuration, we limited the number of requested elementary images to 20 to be compatible with the limited time duration of 15 mn in orbit. For simulation, the following methodology is applied:

- WFE is modelled by Zernike polynomials
- Autocorrelation of the pupil shape
- MTF in Fourier domain including system MTF
- Application of radiometric model (photonic noise, reading, quantification)
- Denoising using wavelet
- Generalised Wiener deconvolution

$$G(u,v)=\frac{H^{*}(u,v)}{|H(u,v)|^{2}+\beta}$$

β parameter is set to get an optimal picture
H : optical transfer function estimation
G : Wiener filter

Images where analysed and compared by one photo interpret to images with same quality criteria as Pleiades for reference. The comparison was performed on images after processing. It appears that incomplete configuration gives better final image since it is a combination of many images: the final MTF is higher for low spatial frequency.

Finally, a MTF of 2% and a SNR of 150 where selected. With those parameters, quality is comparable to this reference with incomplete configuration.

For incomplete configuration, we consider that at Nyquist, MTF is the root mean square of all pictures.

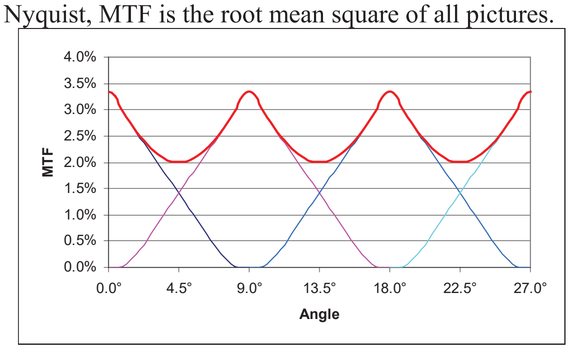

Fig. 7: MTF criterion at Nyquist for incomplete configuration considering 20 pictures

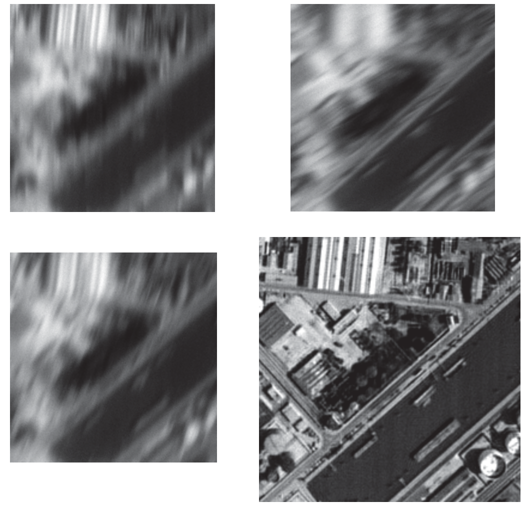

Fig. 8: Example of image from incomplete configuration before and after combining

3.3. Pupil shape optimization

Then, we need to select between complete and incomplete configuration. For this we consider a pupil composed of circular elementary pupils with same diameter. With Golay or circular configuration and with previous hypothesis – MTF greater than 2% on all Nyquist domain – a minimum number of 12 elementary pupils with 2 m diameter is requested: Golay configuration has MTF hole inside Nyquist domain and circular configuration tends to an annular pupil.

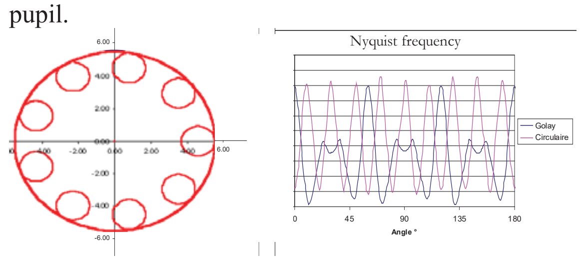

Fig. 9: MTF performances at Nyquist for Golay and circular configuration

This high number of pupils leads to a volume which is not compatible with Ariane 5 short fairing. **Then, we consider in-line configuration.** This configuration is optimised by considering square elementary pupils or segments.

3.4. Telescope selection

We now have to select between Fizeau and Michelson. When considering Michelson telescope, one important impact is to have a constant optical patch length between all telescopes to the imaging telescope. This requests a high number of mirrors which needs to be deployed with the elementary pupils. Each pupil corresponds to one telescope. Then, we need to integrate 6 + 1 telescope leading to a more stringent

WFE budget. Furthermore, this kind of telescope is more difficult to align in orbit – no compensation between axes - and request more mechanisms. **Then, a Fizeau configuration is selected.**

4. APPLICATION & SYSTEM IMPACTS

We now have to design a Fizeau telescope with a ground sampling of 1.17 m from geostationary orbit. Final performances are MTF of 2% and SNR of 150.
We consider the use of E3000 telecom spacecraft in order to have realistic interfaces hypothesis.

4.1. Optical design

The pupil shape optimisation concluded to the use of 6 square pupils - or segments - of 1.1 m side. A Korsch optical combination is used to minimised stray light impact since it is not possible to have baffle for this size of instrument. The objective was to minimise primary mirror-secondary mirror distance which is still around 11 m.
The focal length of the telescope is 360 m. The most constraint mirror is the secondary mirror with a DY of 11 µm.
To take the requested 20 pictures, the satellite is in rotation. Then, we have to compensate the motion effect for each image. This is done by using 2 folding mirrors in the optical path. Another solution was to use an anti-rotating device but its size and the associated mechanism would have been too important. This also needs to have a telecentric optical combination.
The final WFE of this optical combination in a field of view of 20000 x 20000 pixels is below 4 nm after motion effect compensation.

4.2. WFE budget & Telescope alignment tolerances

The telescope must be aligned when in orbit: deployment mechanisms can not have a precision of a few nm or nrad, therefore alignment mechanisms are necessary. We will consider only rigid motions of primary and secondary mirrors; adding deformation mechanism on primary mirrors needs more mass and more sophisticated wavefront sensor. We then have 6 degrees of freedom for each segment + temperature and 6 degrees of freedom for secondary mirror + temperature. All folding mirrors, tertiary mirror and focal plane are located on a stable optical bench which also support all alignment sensors. This is the reference, and then no additional degree of freedom is to be considered. For fine tuning of the segments, only 3 axes out of 6 are necessary for each of them.
By considering a WFE of 6 nm for each degree of freedom, we obtain the following allowable tolerances after correction by the 3 selected axes Translation z, Rotation x and Rotation y – see Fig. 9

In the WFE budget, we also need to consider the focal length variation between all segments. With a WFE budget of 6 nm, we obtain a tolerance on the focal length of ΔF/F = 2 E-6. By using interferometric measurement between all segments, we may obtain a precision of 2 E-5 after polishing. Then, a different temperature setting for each segment allows getting the final accuracy.
The final WFE budget including polishing, mechanism tolerances, 0 gravity … is of 50 nm including some margin for thermal control tolerances.

Fig. 10: Tolerance after fine tuning

Segment	1	2	3	M2
Tx µm	68	84	85	2.5
Ty µm	220	276	292	19
Tz µm	**0.008**	**0.008**	**0.008**	19
Rx µrad	**0.024**	**0.024**	**0.024**	2
Ry µrad	**0.020**	**0.022**	**0.022**	17
ΔT	0.5°	0.5°	0.5°	

4.3. Mechanism definition

The 6 segments are deployed 3 by 3 using deployment mechanisms as used for telecom antennas. This mechanism has also 2 rotation axes for in orbit alignment. To determine the necessary mechanisms with associated performances – precision and range – we consider a maximum range for each mechanism of +/- 5000 steps.
We finally need 47 mechanisms: some are "low" accuracy - µm or µrad- the ones used for fine tuning are in the range of nm or nrad.

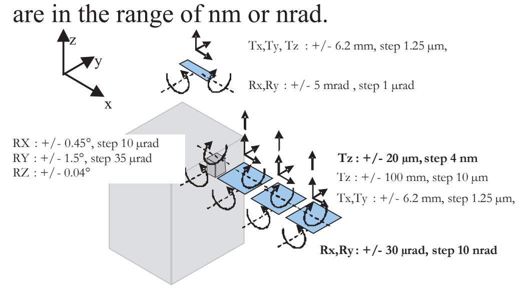

Fig. 11: synthesis of needed mechanisms

4.4. Alignment strategy

To be able to perform in-orbit alignment, we need wavefront sensors. By using external source – star of ground beacon– we need to modify the orientation of the satellite for each alignment and then to assess that this alignment will not be modified. This will require many analyses with the risk that alignment is needed before each picture and this will add delay on the time to get the picture. Then, we designed a completely internal wavefront sensor which is able to keep the alignment even during pictures. This sensor measures the alignment of each segment and of the secondary mirror. After deployment, a reference alignment needs to be performed with beacon on ground. Then this alignment is kept as a reference using only the internal wavefront sensor. The following sequence is proposed for this first alignment:

- A referenced segment is first aligned using the wavefront sensor
- Alignment of the secondary mirror
- Rough alignment of the others segments: 20 µm in focus
- Rough phasing: 0.5 µm in focus
- Final tuning

4.5. Thermal control

We need to be able to take picture during whole day. Due to the big size of this instrument, we will not consider baffle. We have analysed that it is possible to have a thermal control of the primary mirror - which is the most critical part - without baffle at ~ 25°C with an average thermal power of only 520 W during day and night.
For the secondary mirror, specific baffling is needed to avoid illumination while taking picture.
The thermal flux variation due to a modification of the orientation of the telescope is completely negligible compared to the solar flux variation. Since the thermal control is able to compensate the solar flux variation, any orientation is allowed to take picture.
With this thermal control, it would be even possible to consider an infrared mission during night. We just need to avoid pictures too close to the sun mainly for straylight impact.

4.6. Mechanical architecture

For the mechanical architecture, segments are deployed 3 by 3 using 2 arms which are folded on the sides of the spacecraft during launch. An optical bench is located at the top of the spacecraft. It supports the tertiary and folding mirrors, the filter wheel for color pictures, the detector and the wavefront sensor. This is a stable support that is used as the reference for the alignment.
For all structure and mirrors, we will consider Silicon Carbide. This material has a high specific stiffness E/ρ and a high conductivity. This helps to minimise mass and to improve thermal control.
For deployment of the secondary mirror, we consider the use of Collapsible Tube Mast. This is a bi-convex tube that is rolled after being flat. This mechanism was developed for a solar sail.