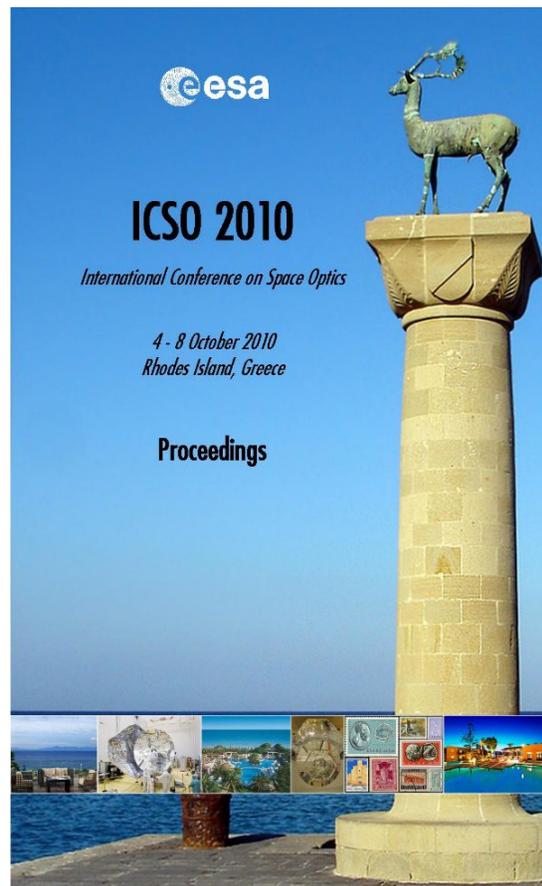


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OPTICAL DESIGN CONSTRAINTS IN TRIANGULAR SAGNAC IMAGING INTERFEROMETERS FOR EARTH OBSERVATION

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I. INTRODUCTION

The Italian Space Agency selected the imaging interferometer ALISEO (Aerospace Leap-frog Imaging Stationary interferometer for Earth Observation) as the main payload for a technological optical mission based on the small satellite MIOsat. The simple design of such an instrument, based on Sagnac configuration, makes it a promising for Earth observation missions.

The ALISEO instrument acquires an image of 10 Km by 10 Km with a spatial resolution better than 10 m and a spectral resolution of 200 cm⁻¹ (7 nm @ 0.6 μm) in the 0.4 – 1 μm spectral range.

ALISEO does not employ any moving part to generate the phase delays between the two interfering beams. The sensor acquires target images modulated by a pattern of autocorrelation functions of the energy coming from each scene pixel, and the resulting fringe pattern remains fixed with respect to the instrument's field-of-view. The complete interferogram of each target location is retrieved by introducing a relative source-observer motion, which allows any image pixels to be observed under different viewing-angles corresponding to different Optical Path Differences (OPDs).

In this paper various optical configurations are analyzed in order to meet the mission requirements. Optical configurations are discussed taking into account: detector size, spatial resolution, and entrance pupil aperture. The proposed configurations should avoid vignetting, reduce geometric and chromatic aberrations, and comply with the size and weight constraints requested by space mission. Optical configurations, based on both refractive and reflective focusing elements, are presented and discussed. Finally, some properties pertaining to the selected Sagnac configuration are discussed in conjunction with spectral estimations and data processing.

II. GEOMETRY OF THE SAGNAC INTERFEROMETER AND VIGNETTING

ALISEO is an imaging interferometer based on Sagnac configuration working in the visible and near infra red spectral range (400 – 1000 nm). ALISEO has been selected by the Italian Space Agency as main payload for the small satellite space mission MIOSAT [1].

In opposition to dispersive imaging spectrometers, in which the impinging radiance is spectrally dispersed on output focal plane, an imaging interferometer observes the autocorrelation function of the impinging radiation.

Fig. 1 shows the optical configuration for an interferometer in Sagnac configuration [2] and its possible vignetting conditions.

Collimated light selected by the input pupil P is subject to amplitude division by the beam-splitter, then the two resulting beams travel the interferometer over opposite pathways bounded by the folding mirrors. Light emerging on the output port is focused by the lens onto the output focal plane that holds the image detector. As long as a narrow FOV is imaged the instrument produces a stationary pattern of interference fringes of almost equal thickness (Fizeau fringes) on its output port. Our implementation of the Sagnac layout doesn't include any input slit, a characteristic we refer to as “Leap-frog” configuration. Due to the absence of entrance slit, the device acquires the image of an object superimposed to a stationary pattern of across-track interference fringes. Introducing a relative motion between the sensor and the object, each scene pixel crosses the entire interference pattern, hence its interferogram can be retrieved from an image sequence. Every target place is observed under several viewing angles while the sensor moves, hence a three-dimensional array of data (image stack) of varying Optical Path Difference (OPD) is collected.

The acquired physical information is the interferogram $I(x)$, that is the power of the interference pattern generated by the two rays at the position x in the focal plane of the instrument, as stated in the following relationship.

$$I(x) = C \int_0^{+\infty} S(\kappa) \| t_r(\kappa) E(\kappa) \exp(j\phi) + t_t(\kappa) E(\kappa) \exp(j\phi + 2\pi j \kappa \text{OPD}(x, \kappa)) \|^2 d\kappa. \quad (1)$$

In this equation ϕ is the initial phase of the impinging radiation field, $t_r(\kappa)$ and $t_t(\kappa)$ are the overall amplitude attenuation factors affecting the electric field amplitude $E(\kappa)$ of the reflected and transmitted rays

when passing from the input to the output port of the interferometer. The detector sensitivity, the transparency of optical components, and so on are collectively represented with the notation $S(\kappa)$. The coefficient C relates the square modulus of the field amplitude $E(\kappa)$ to the corresponding radiance $i(\kappa) = C \|E(\kappa)\|^2$ (specific intensity of the radiation field), and $OPD(x, k)$ is the optical path difference introduced by the interferometer in the considered propagation direction. In (1), the wavenumber κ corresponds to the wavelength $\lambda = 1/\kappa$, and the integration over κ takes into account the non-monochromatic light spectrum. Let us note that the OPD depends on the inclination \mathcal{G} of the entering ray, corresponding to the focal plane position x that is the projection of \mathcal{G} by the equivalent focal length of the focusing element of the instrument.

After retrieving the complete interferogram, the radiance spectrum is reconstructed by applying a Fourier-like inverse transform. The maximum OPD is also linked to the minimum detectable wavelength, being related to the geometry and the dimensions of the internal optical components of the instrument. The spectral range and resolution of the reconstructed spectrum strongly depend on the frame rate (i.e. the number of samples used for interferogram reconstruction) and the range of optical path differences, which in their turn are functions of the instrument field of view, beam splitter features (refractive index, thickness) and detector sampling.

An important characteristic of the ALISEO design is its vignetting effect which is mainly due to the common path configuration [3]: a larger entrance pupil provides a better Signal to Noise Ratio (SNR), but it demands for an increase of the beam splitter size. For a Sagnac triangular configuration the defined interferometer dimensions are related to both the length of each arm and the beamsplitter thickness (here is reported the case with a negligible beam splitter thickness).

The relation can be expressed by applying the non-vignetting condition, given by the formula:

$$\frac{B}{2} < A - \frac{D_{1,2}}{2} \quad (2)$$

where B is the beamsplitter diameter (located at 45° with respect to the optical axis), A the distance of the beamsplitter centre to the hypotenuse of the triangle defined by the beamsplitter and the mirror centers, $D_{1,2}$ the vignetting diameters of both transmitted and reflected rays taken on the continuation of A .

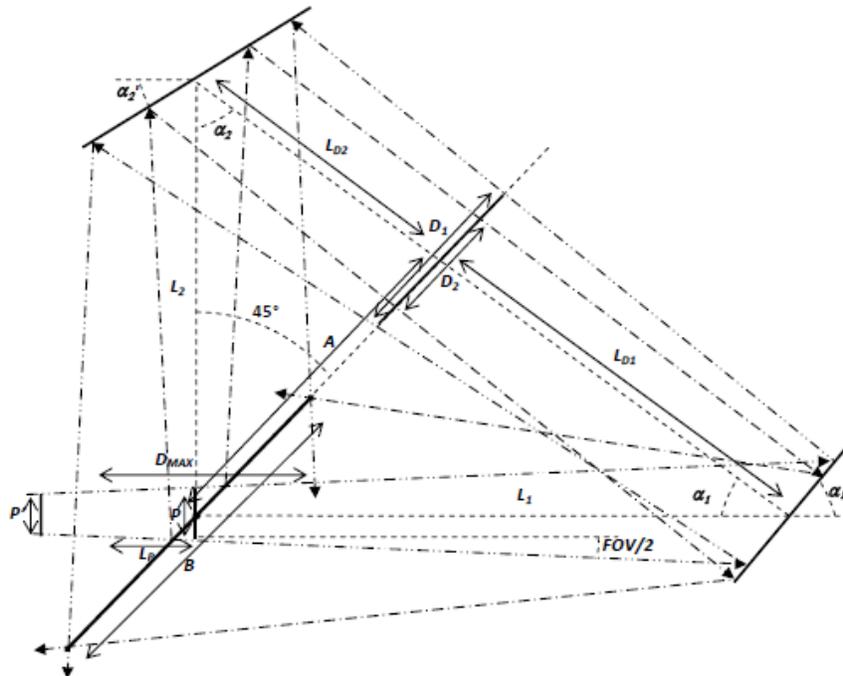


Fig. 1. ALISEO interferometer in Sagnac common path triangular configuration with its vignetting conditions.

In Fig. 2 the quasi-linear behaviour of the entrance pupil with changing FOV is shown for different lengths of each interferometer arm. Interferometer arm dimensions fix the non-vignetting condition between the entrance pupil diameter and field of view (FOV) angle.

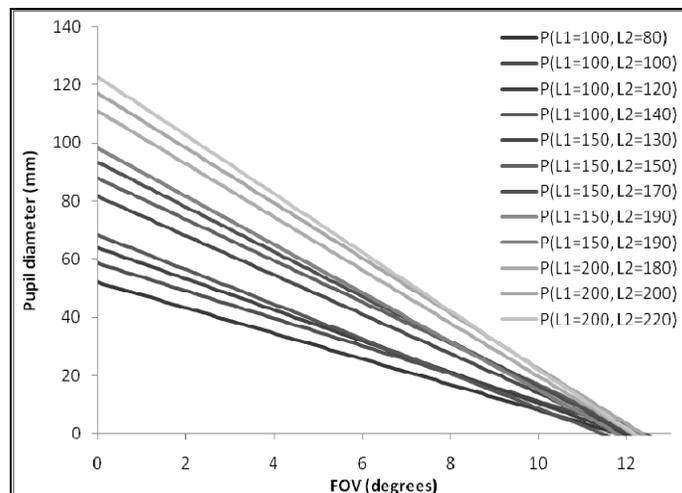


Fig. 2. Quasi-linear relation between FOV and entrance pupil for different interferometer arms lengths.

III. FOCUSING OPTICS

Since the rays exiting the interferometer are collimated, a focusing system is used for observing the scene image and the relative pattern of interference fringes.

The focus length of the optical system is fixed by detector size which also determines the spatial resolution of the imaging interferometer. Moreover, the entrance pupil, that affects the number of photons impinging on the detector, must ensure a high, but not saturated physical signal. Finally, the imaging optics must reduce geometric and chromatic aberrations which lower the image quality. In the following both transmission and reflection optical configurations are analyzed and discussed for a detector of 1024 pixel x 1024 pixel, with a pixel size of 14 μm .

A. Lens Based Optics

In this paragraph a lens based configuration is presented. Lenses material and curvature radius (see Fig. 3a) have been selected for minimizing chromatic and geometric aberrations.

The optical system in Fig. 3a has been designed using Zemax software. It is diffraction limited with an Airy disk with mean radius of $\sim 7\mu\text{m}$. The spot radius diagram (the image of collimated rays with different entrance angles) is plotted in Fig. 3b. The diagram shows the image of collimated rays entering with different angles for different wavelengths (represented in different colors).

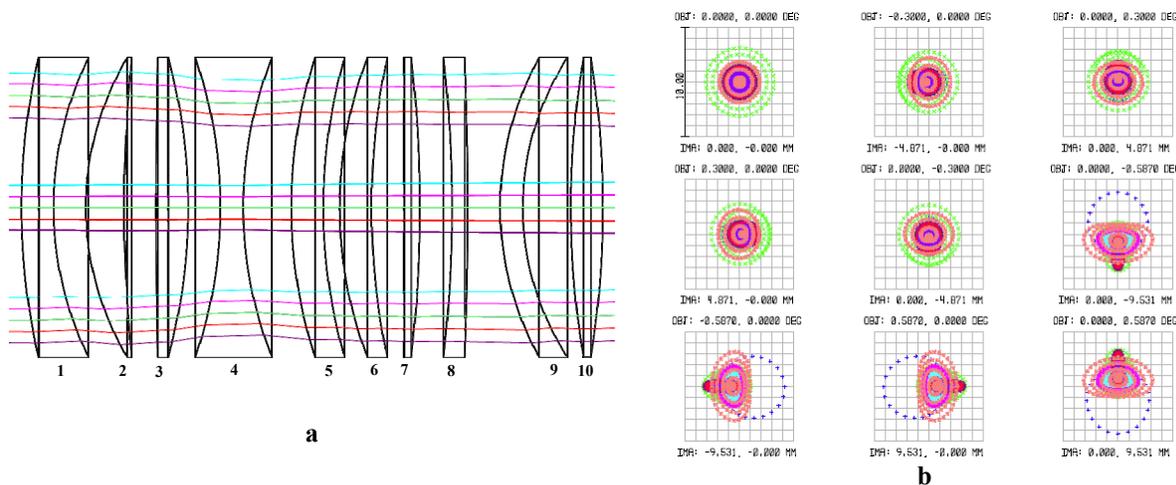


Fig. 3. Lens based focusing system (a). Spot radius diagram for the lens based system (b).

A more compact solution which does not affect the above mentioned optical properties has been analyzed. Example of different versions obtained by the use of folding mirrors are presented in Fig. 4

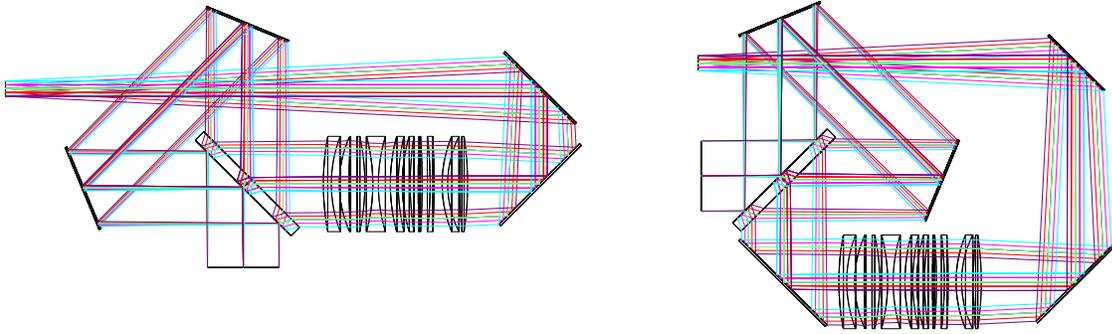


Fig. 4. Different configurations of the lens based version of ALISEO

B. Mirror Based Optics

In order to reduce the chromatic aberration due to lenses, a focusing element based on aspheric mirrors has been considered. In Fig. 5a and Fig. 5b the layout and the three dimensional model of a mirror based configuration are presented. At the exit port of the interferometer, two aspheric plus a spherical mirrors have been combined. In the mirror-based approach the main problems are related to keep the various optical elements aligned. The off-axis approach increases the geometric aberrations, although the spot radius diagram (Fig. 6) remains comparable to the lens based version.

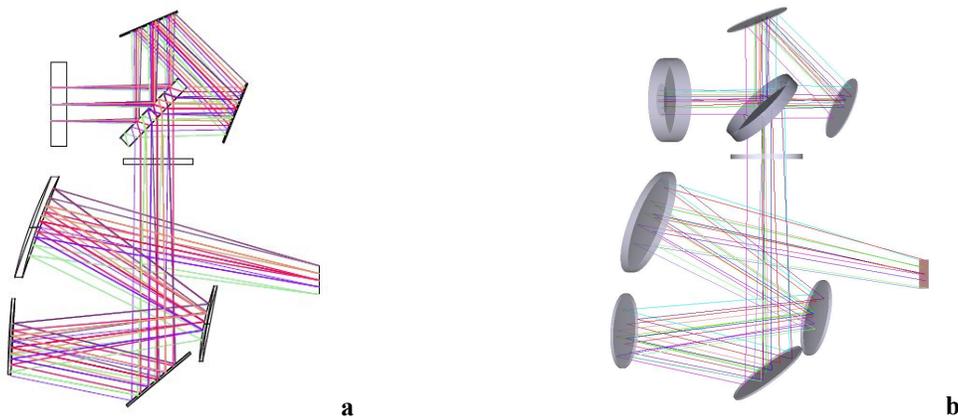


Fig. 5. Layout (a) and 3-dim model (b) of mirror based version of ALISEO

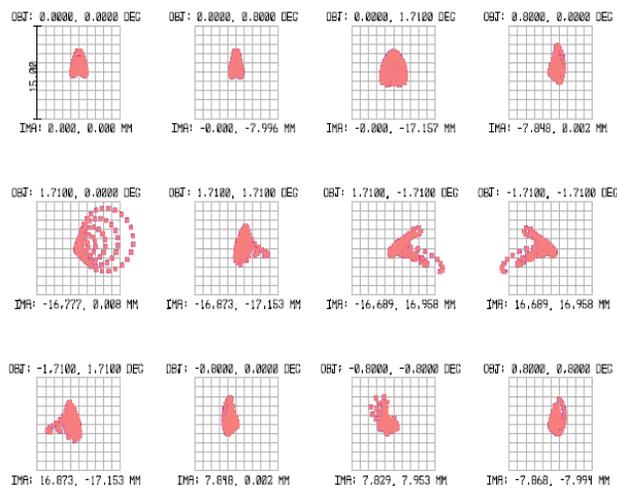


Fig. 6. Spot diagram for mirror based configuration

IV. DISCUSSION

The analysis performed in previous chapters demonstrates that vignetting can easily affect common path imaging interferometers. This effect can be avoided with a careful balance between the need of a large entrance pupil and the constraints related to instrument's dimensions. At the same time, the analysis performed on focusing optics put in evidence that mirror based configurations show problems related to geometric aberrations, but the one based on lenses need a large number of elements to be realised.

Some advantages are implicit in using imaging interferometers, due to their high signal (Jacquinot's effect), and the option to adjust the sampled spectral range and resolution by changing the sensor sampling step and the instrument Field-Of-View (FOV). Other critical points are also connected with the high data-rate requested, and the heavy data pre-processing for compensating instrument response and possible acquisition phase errors.

Regarding to Fellgett's advantage for imaging interferometer, an analytical comparison of system performance (estimation of amplitude of the effective signal and Signal-to-Noise ratio) between the interferometric technique and the traditional dispersive spectrometers performed in a previous paper [4], brought to a new interpretation of it, concluding that in the past Fellgett's advantage has been not well understood. In fact the informative tail of the acquired interferogram to be resolved requires a radiometric resolution much finer (depending on the illumination source's bandwidth) than that is needed for a dispersive spectrometer operating at the same high spectral resolution [4].

V. CONCLUSIONS

Possible solutions for the ALISEO optical layout have been presented. The problem of vignetting and of the focusing system have been discussed and the characteristics and difficulties related to both lens based and mirror based solutions have been illustrated.

Starting from the performed analysis, improvements in ALISEO optical layout will may regard the combined use of mirror and refractive systems, in order to efficiently reduce both geometric and chromatic aberrations.

REFERENCES

- [1] A. Barducci, F. Castagnoli, G. Castellini, D. Guzzi, P. Marcoionni and I. Pippi, "ALISEO on MIOSAT: an Imaging Interferometer for Earth Observation", International Conference on Space Optics ICSO 2008, Toulouse, France, 14-17 October 2008.
- [2] M. J. Persky, "A review of spaceborne infrared Fourier transform spectrometers for remote sensing", *Review of Scientific Instruments*, Vol. 66 (10), pp. 4763 – 4797, 1995.
- [3] Y. Ferrec, J. Taboury, H. Sauer, and P. Chavel, "Optimal geometry for Sagnac and Michelson interferometers used as spectral imagers", *Optical Engineering*, Vol. 45 (11), 115601-1 – 115601-6, 2006
- [4] A. Barducci, D. Guzzi, C. Lastri, P. Marcoionni, V. Nardino, and I. Pippi, "Theoretical Aspects of Fourier Transform Spectrometry and Common Path Triangular Interferometers", *Optics Express*, Vol. 18 (11), pp. 11622 -11649, 2010.