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AN ALL-METALLIC HIGH RESOLUTION INSTRUMENT FOR EARTH OBSERVATION FROM SMALL LEO SATELLITES

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ABSTRACT

A mid-to-high resolution optical payload, named STREEGO, featuring a compact envelope, reduced mass, and competitive cost has been designed to address Earth Observation applications from low Earth orbit (LEO) small satellites. STREEGO is a fully reflective telescope designed for operation at a nominal altitude of 600 km to provide a ground sampling distance (GSD) of 2.75 m, a field of view of about 1° and a modulation transfer function (MTF) greater than 10% at Nyquist frequency (91 cy/mm) with a telescope aperture of 200 mm. A large two-dimensional CMOS sensor with a pixel size of 5.5 μm has been selected in order to obtain the requested GSD with a focal length of 1.2 m, and a signal-to-noise ratio equal to 75. A demonstration model is in the detailed design phase and will be developed, with completion planned by end of 2015. We present a detailed description of the instrument, which, by leveraging on aspheric surfaces and light-weight solutions, achieves remarkable performance in terms of compactness and image quality with less than 25 kg in mass. The optical design is based on a three mirror anastigmat (TMA) configuration whereby the mirrors are realized in metal with the same coefficient of thermal expansion of the structure in order to obtain an athermal design.

I. INTRODUCTION

In the last years the global demand for mid-to-high resolution ground images taken from low Earth orbit (LEO) satellites has constantly grown for a variety of applications: from original defence and security market, to environmental, agricultural, and geophysics applications, to more recent general public demand. The information typically targeted by these systems covers spatial, spectral, and temporal resolution. Depending on the particular task of each mission, a different balance between these three factors is required. Limiting our attention to spectral and spatial requirements, it is possible to distribute the different application fields into a two dimensional space where multi- or hyper-spectral sensors, with a wide range of resolutions, are the best choice for environmental applications, whereas panchromatic sensors up to very high resolution are more suited for topography, military, and traffic applications [1].

Imaging systems have now reached sub-meter ground sampling distance (GSD) even for commercial applications and the amount of information provided by new optical payloads is constantly increasing. Obviously, continuous improvement is expected in the future due to developments in materials, optoelectronics, signal processing, communications, and navigation. However, there are parameters or elements, such as the F/number (F/#) of the optics at a given operation wavelength, that are constrained by fundamental physics laws and are not subject to technological development. Additional constraints in the realization of space imagers come from programmatic reasons, namely related to cost, schedule, and risk management.

The trade space for the design of a new instrument is a complex balance of all of the above: state of the art of the technology, fundamental physical limitations, and programmatic constraints. In this framework, our intent is design and realize a mid-to-high resolution optical instrument, named STREEGO [2], that exploits the latest technology development on one side and dramatically relaxes the programmatic constraints in terms of cost and schedule on the other side. By leveraging on cost-effective manufacturing technologies and the availability of commercial off-the-shelf components, we are designing and manufacturing a high-resolution instrument that provides solutions to low cost, high resolution panchromatic and hyper-spectral imaging applications.

In this work, we focus on the description of the optical design and the preliminary tolerance analysis performed on the baseline 3D model of the STREEGO instrument. A trade-off between different optical designs has been performed together with a thorough optimization of the structural design to enable the integration of our cost effective solution matching the requirements of high resolution applications.

Particular emphasis is given to the description of the thermal-optical modelling that combines deterministic deformation data from the thermal and structural finite element model (FEM) of the TMA telescope together with random alignment tolerances and mirror shape errors. A Monte Carlo optical simulation of the resulting configuration allows the statistical prediction of the instrument performance in both laboratory and flight conditions. Finally, we describe the manufacturing approach that we intend to implement in order to ensure the cost and schedule benefits.

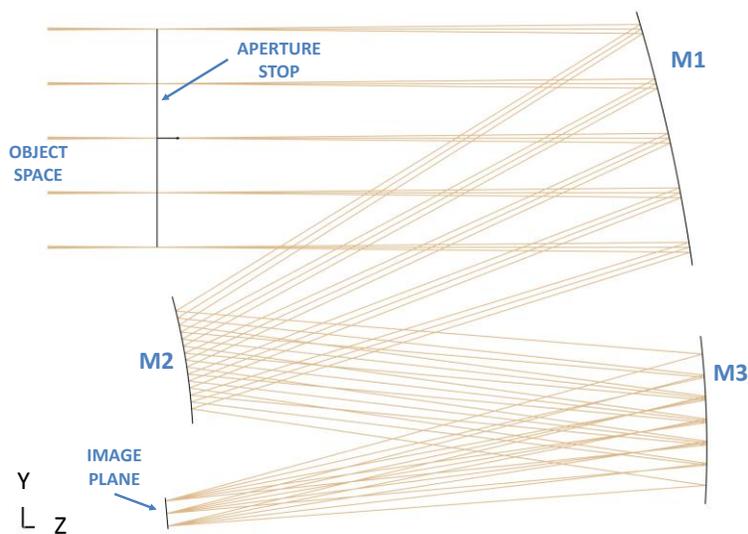


Fig. 1. Optical layout of STREEGO telescope

II. OPTICAL DESIGN

The optical design of STREEGO is based on a three mirror anastigmat (TMA) configuration [3] using off-axis aspheric, non-rotationally symmetric mirrors. The TMA allows an unobscured field of view with no chromatic aberration, greater image irradiance for a given aperture, and better modulation transfer function (MTF) at medium spatial frequencies.

The driving parameters of the optical design are related to mission requirements and include the satellite altitude, the ground sampling distance (GSD), and observable area (swath). For a system flying at 600 km from ground and a GSD of 2.75 m, the focal length must be equal to 1200 mm when the optics is coupled to the commercial CMOS detector with 5.5 μm pixel size that has been chosen as baseline solution. The required swath of about 10 km side results in an actual dimension of 11.26 km \times 9.45 km when detector size of 4096 \times 3072 pixels is taken into account, corresponding to a field of view (FOV) of $1.08^\circ \times 0.81^\circ$. Actually, the FOV is limited by the detector size, whereas the TMA itself allows larger FOV. The optical surfaces of all three mirrors have circular clear apertures with Y axis decenters and X axis tilts as shown in Fig. 1; thus the mirrors are obtained from off-axis portions of aspheric surfaces. The aperture stop is on the front opening of the telescope, thus enabling a front baffle to reject stray light and reduce the optical footprint on the primary mirror. Additional baffles may be also accommodated at the sensor plane and between M1 and M3 to further reduce possible stray light paths. The trade off analysis performed during the optical design optimization led to selecting a configuration without intermediate focus as the most robust in terms of positioning tolerances at the required focal length.

A summary of the specification of STREEGO are reported in Table 1. The nominal design has been optimized to achieve an MTF of about 64% at the Nyquist frequency of 91 cy/mm in the visible waveband. The expected performance is commensurate with what is normally expected for diffraction limited systems. Indeed, the

Table 1. STREEGO optical specifications

Parameter	Value	Unit
Focal length	1200	mm
Aperture	200	mm
FOV	1.08×0.81	$^\circ$
GSD @ 600 km	2.75	m
Nyquist frequency	91	cy/mm
As-designed TMA MTF @ Nyquist	64	%
As built MTF @ Nyquist	> 10	%
Maximum distortion	0.4	%
Minimum SNR	75	-
Mass	25	kg

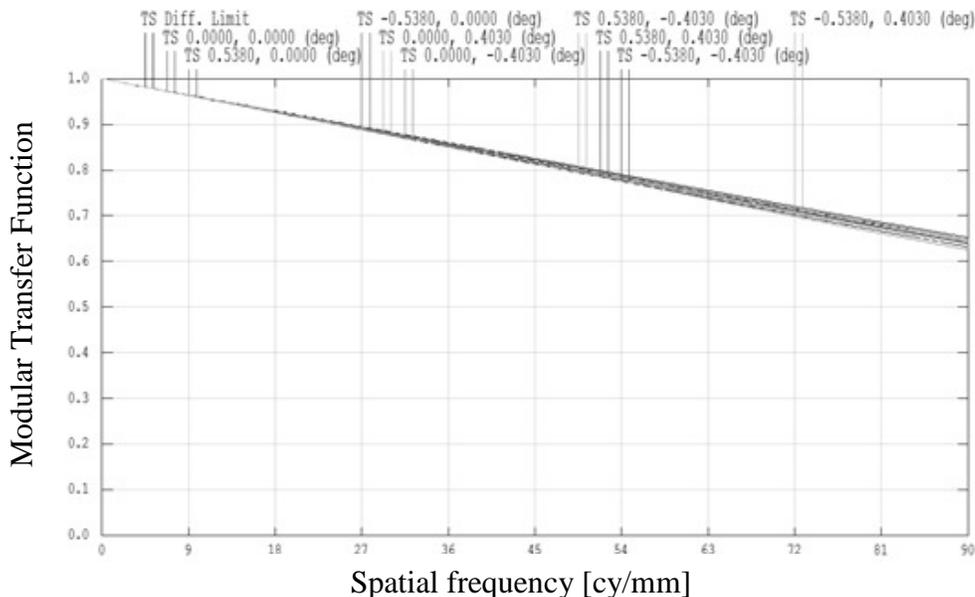


Fig. 2. Nominal MTF of the STREEGO TMA

sagittal and transversal MTF curves for all the fields coincide with the diffraction limited MTF for all practical purposes, as shown in Fig. 2. The system has an Airy disc radius of 6 μm , which means 1.2 pixel using the baseline sensor with 5.5 μm pixel size, which is a good compromise between ground resolution and image contrast. Finally, the image has a residual distortion smaller than 0.4 % and the system has acceptable telecentricity, with a maximum angle between the chief rays of the different fields of about 1°, allowing focal plane splitting for a dual-detector configuration or spectrographic applications.

In order to obtain the desired signal to noise ratio (SNR) greater than 75 over the visible spectrum, the optical design features an aperture diameter of 200 mm that, when combined with the baseline sensor with a pixel size of 5.5 μm and a quantum efficiency greater than 50%, leads to the required SNR. The resulting F/# of the optical system with 1200 mm focal length and 200 mm aperture is thus 6.

II. MONTE CARLO ANALYSIS OF LABORATORY AND OPERATIONAL PERFORMANCE

As mentioned above, the as-designed TMA exhibits an MTF equal to 64% at the Nyquist frequency, whereas the requirement for the as-built instrument under operation conditions is greater than 10% including the sensor. Moreover, the system will be obviously integrated and tested in presence of gravity and it will be necessary to correlate the measured performance in laboratory conditions to the expected performance in orbit. In order to address this goal, a detailed Monte Carlo analysis has been done including all error contributions deriving from mirror manufacturing, mechanical tolerances, system integration and alignment, and structural and thermal load cases due to laboratory or operational conditions. Smearing effects due to along-track movement and pointing error of the satellite are not included. We describe each contributor separately.

A. Mirror Manufacturing Errors

Manufacturing errors $\epsilon(\mathbf{r})$ of the optical surface of the mirrors are described by superposition of the lowest 10 Zernike polynomials $Z_i(\mathbf{r})$,

$$\epsilon(\mathbf{r}) = \sum_{i=1}^{10} a_i Z_i(\mathbf{r}), \quad (1)$$

in which the first term in the sum is defocus and tip, tilt, and piston are excluded. In each Monte Carlo run, every coefficient a_i of the expansion is considered a random variable with uniform probability density function between -30 nm and 30 nm. After a set of 10 coefficients is generated, they are normalized such that

$$\left(\sum_{i=1}^{10} a_i^2 \right)^{1/2} = 30 \text{ nm}, \quad (2)$$

Table 2. STREEGO mechanical and alignment tolerances of each mirror

Parameter	Value	Unit
Shift along X and Y axis	± 0.02	mm
Shift along Z axis	± 0.01	mm
Tilt around X and Y axis	± 0.0028	$^{\circ}$

which amounts to consider the optical surface of each mirror as a random superposition of 10 Zernike modes with an overall rms error of 30 nm.

B. Mechanical and Alignment Tolerances

Mirror positioning tolerances during integration and operational conditions has been estimated in terms of offset along the local X, Y, and Z axis and tilt around X and Y axis. Based on experience matured during the development and integration of a previous instrument [4], the position tolerances of each mirror and the detector have been defined as listed in Table 2. In the Monte Carlo analysis, each tolerance parameter is assumed to randomly varying between the two extreme values with uniform probability density function. The tolerance values listed in Table 2 should be understood to include manufacturing tolerances of the structural and reference parts and alignment and metrology tolerances during integration. When analyzing laboratory performance, M2 and the detector are considered compensators that are used to tune the system by correcting the performance in order to reach the target MTF as closer as possible during the integration phase, after which the orientation and the position of the compensators are fixed. In operational conditions, only the Z-axis refocusing of the detector is been assumed to be a free parameter to optimize the instrument performance. From this point of view, a refocusing mechanism is foreseen during operating conditions to minimize the sensitivity of the design to mirror misalignments typically induced by gradients and thermal expansions. We recognize that a refocusing mechanism is a design complication impacting on the reliability and cost of the instrument, and optimization is in progress to avoid the need of refocusing, as further discussed below.

C. Structural and Thermal Loads

A preliminary design of the payload is shown in Fig. 3 and it has been used for structural and thermo-structural simulations of the STREEGO instrument. In this preliminary design, mirrors M1 and M3 are made of electroformed Nickel [5], with 2 mm and 1.5 mm thickness, respectively. Mirror M2 and the frame of the telescope are made of Aluminum RSP (RSA-443), which has a coefficient of thermal expansion (CTE) matched to electroformed nickel. The adhesive used to integrate the mirrors to the structure is also modeled. Three 120° bipods with flexures have been assumed as interfaces to the satellite and simulated in several configurations. The mass of the entire assembly (structure and mirrors) is less than 25 kg and the envelope of the structure is 305 mm \times 525 mm \times 530 mm, as also shown in Fig. 3, excluding the baffle.

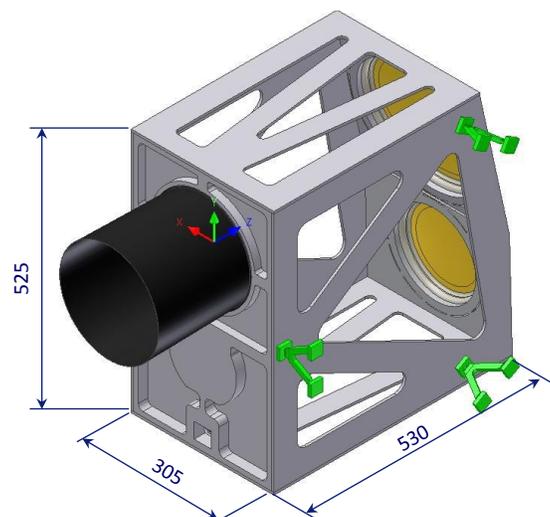


Fig. 3. Preliminary STREEGO design with volume envelope, excluding baffles
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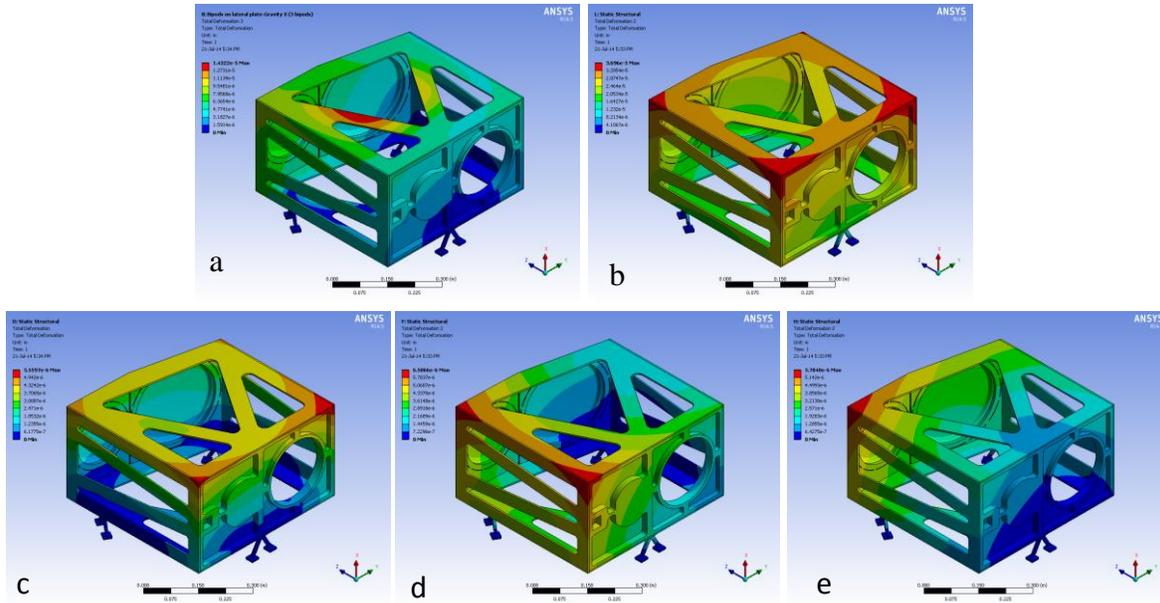


Fig. 4. Thermo-structural deformations of the selected load cases: a) gravity along X axis, b) 5 °C uniform temperature change, 6 °C/m thermal gradient along c) X axis, d) Y axis, and e) Z axis

Five FEM analyses have been done to cover both laboratory and operational condition. In the former case, the instrument will be tested with the X-axis along the vertical direction, and the corresponding load case consists of 1g gravity in the same direction. For operational conditions, we assumed a uniform temperature variation of the payload of 5 °C, which may lead to a performance degradation due to a possible mismatch of $0.5 \cdot 10^{-6} \text{ K}^{-1}$ between electroformed nickel and aluminum RSP, and three thermal gradient of 6 °C/m along the three axes X, Y, and Z, which amounts to about 3 °C along the Z and Y axes and about 2 °C along the X axis. It must be underlined that the thermal gradient of 6 °C/m is considered extremely demanding and is preliminarily assumed as pessimistic worst case in order to be compliant with the most severe environmental requirements.

The results of the FEM analysis in terms of deformation are shown in Fig. 4, whereas the MTFs corresponding to each of the load cases considered separately are shown in Fig. 5. It should be noticed that in the Monte Carlo analysis of the operational condition, a combined load case is considered that is the superposition of the 5 °C uniform temperature change and the worst thermal gradient, which happens to be along the Y direction. The resulting combined MTF, practically overlapping the Y-axis thermal gradient, is also shown in Fig. 5.

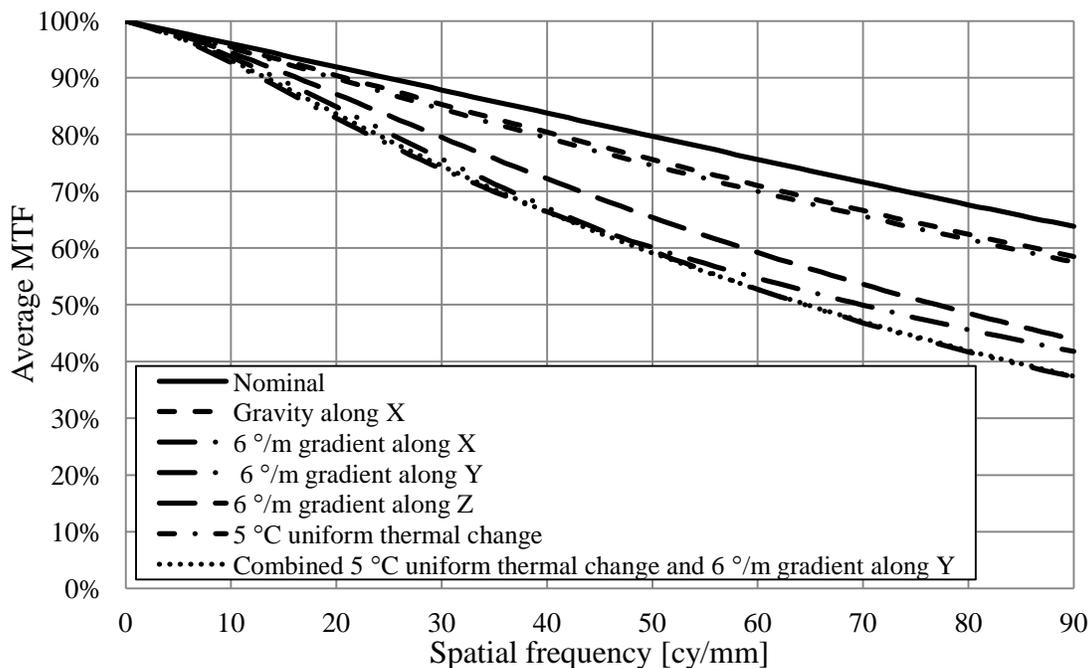


Fig. 5. MTF of the selected FEM load cases
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D. Results of Monte Carlo Analysis

As already mentioned, the Monte Carlo analysis was run for both laboratory and operational conditions. In the former case, the random contributions due to mirror manufacturing and mechanical and alignment tolerances are summed up together with the deterministic contribution due to gravity as calculated by FEM analysis. In the operational scenario, the gravity contribution is replaced by the combined load case of uniform temperature variation and the worst thermal gradient, which happens to be along the Y axis (see Fig. 5).

For both laboratory and operational conditions, up to 2000 optical simulations were run and the MTF at the Nyquist frequency were calculated over 17 fields as the average of sagittal and tangential direction values. In order to summarize the results, we took the lowest of the 17 MTF; in other words, we chose the lowest value of the MTF at Nyquist frequency over the entire field of view as representative metrics of each Monte Carlo run.

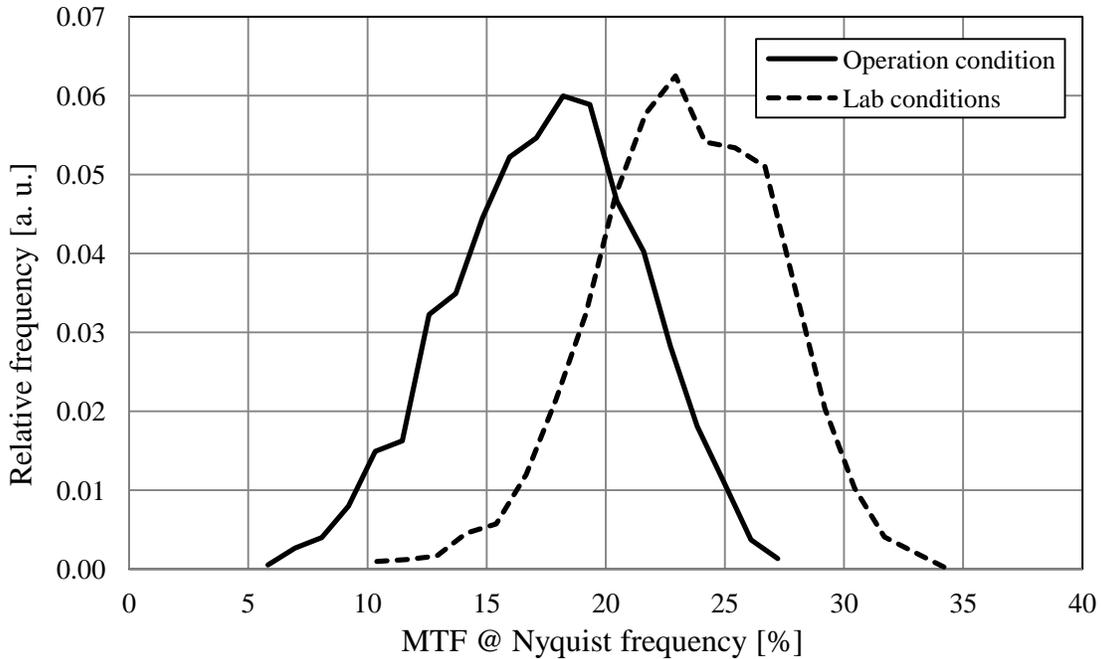


Fig. 6. Histogram of the MTF value at Nyquist frequency as obtained from the Monte Carlo analysis

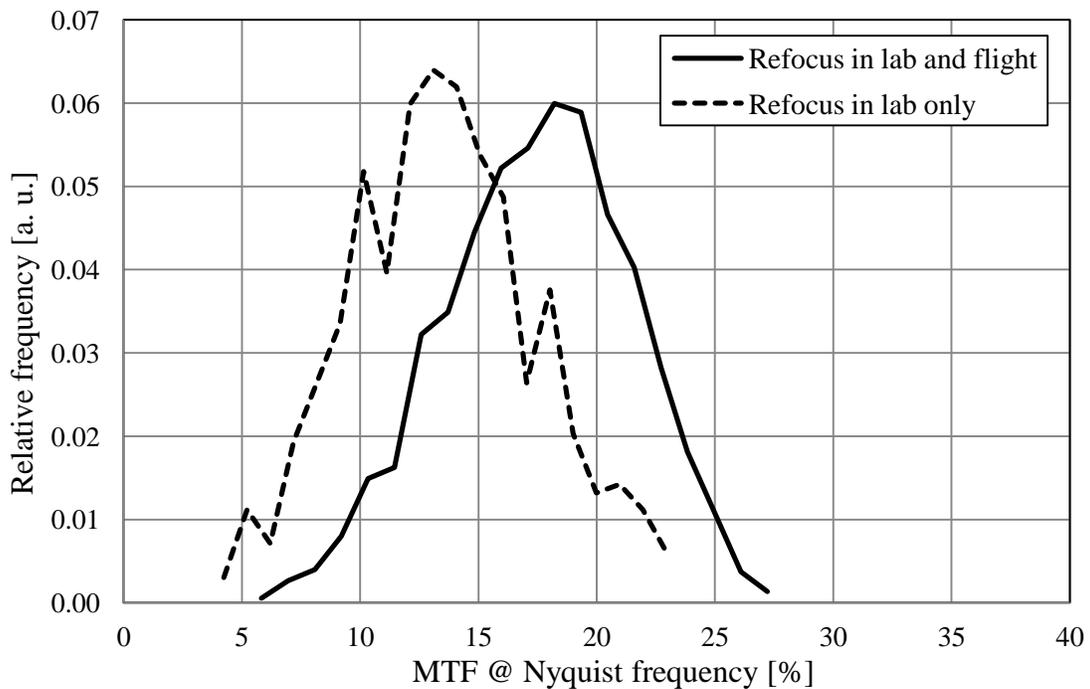


Fig. 7. Histogram of the MTF at Nyquist frequency with and without in-flight refocusing

A histogram of the 2000 values so obtained is plotted in Fig. 6 after having multiplied each MTF value by 0.6, whereby 60% is assumed to be the contribution of the detector MTF to the instrument MTF at Nyquist frequency. It is apparent from Fig. 6, that the performance of STREEGO is well above the 10% MTF goal in laboratory condition, whereas there is a 3.5% probability of performance below specification in operational condition, with an absolute minimum MTF of 6%.

As mentioned in section II.B, the analysis in operational condition is done assuming the possibility of detector refocusing during both integration and in-flight operation. However, since an onboard refocusing mechanism adds complexity and reliability issues to the instrument, we are currently exploring if and how it can be avoided. Fig. 7 shows the histograms of the Monte Carlo analysis performed with and without in-flight refocusing. In the former case the solid curve in Fig. 7 is the same as the solid trace in Fig. 6, whereas in the latter case, the MTF value at Nyquist frequency (dashed curve) shows a decrease of about 5% absolute on average, with a consequent increase to 20% of the probability of performance below 10% MTF target. Activity is in progress to further optimize the thermal and structural design in order to mitigate this effect and definitely avoiding the onboard refocusing mechanism.

III. MANUFACTURING APPROACH

Media Lario Technologies' proprietary manufacturing technology consists of replication of mirror substrates from high precision mandrels by means of an electroforming process [4], [5]. The mandrel is machined and polished to the shape accuracy and surface roughness requirements of the final mirror substrate. During the electroforming process the mandrel is immersed in an electrolytic bath in which the mandrel itself is the cathode. By means of a controlled electrochemical process, Nickel ions are released from the anodes and deposit onto the mandrel (cathode), thus creating a low-stress Nickel deposition on the mandrel. Once the deposit has reached the desired thickness, the mandrel is removed from the electroforming bath and the mirror is separated from the mandrel. The mandrel is then qualified for the next electroforming cycle, where another mirror is replicated from the same mandrel. Therefore our "high-accuracy replication by electroforming" technology is intrinsically cost-effective for series production of precision mirrors.

Nickel electroformed optics have been adopted for many years in some of the most renown X-ray space observatory missions [5], and they are now proposed as a feasible solution for imaging optics systems. A prototype imaging sensor based on a TMA design has recently been realized by Media Lario Technologies for the Italian Space Agency (ASI) [4]. Electroforming aims at reducing the manufacturing complexity of aspheric surfaces by leveraging on the 1:1 shape and roughness replication of the mandrel surface, which is machined only once with traditional techniques, therefore allowing the production of many mirrors at reduced cost and cycle time. Moreover, electroformed mirrors have typical thickness of the order of 1 mm, thus significantly contributing to mass reduction. We believe this innovative approach can change the way cost-effective high-performance optics will be produced for future missions. Particularly, we anticipate that the production lead-time of the Streego telescope, after the qualification phase, will be as short as 6 months.

Moreover, we have developed deterministic figuring and polishing processes on metal and glass substrates for aspheric, non-rotationally symmetric optics. This technology is enabled by two in-house Intelligent Robot Polisher (IRP) machines for 600 mm and 1,200 mm substrates, supported by optical interferometry and profilometry. Not only this conventional optics manufacturing technology is synergistic to our replication by electroforming technology for the one-off production of the mandrel, but it is also complementary for the fabrication of aspheric optics on NiP coated aluminum substrates, as required for M2 of STREEGO.

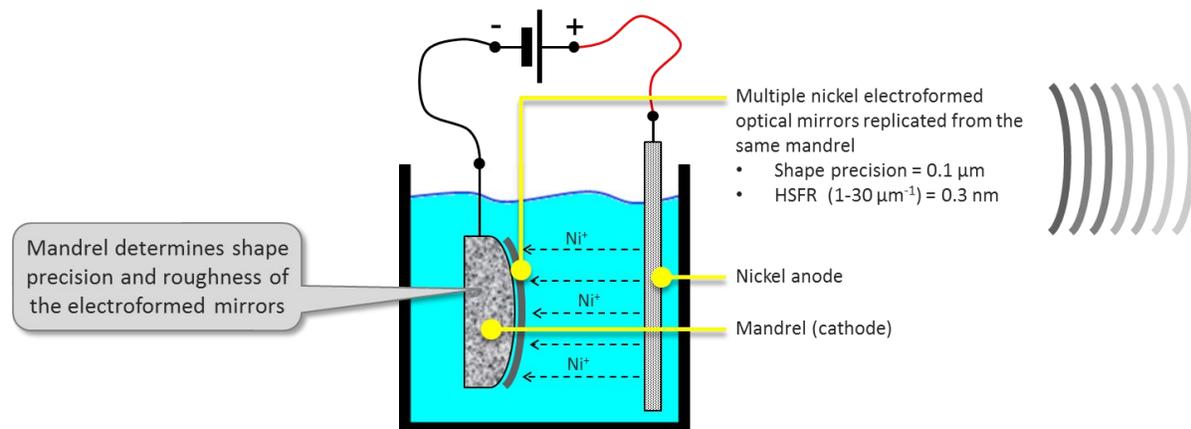


Fig. 8. Illustrative representation of high-precision replication by electroforming technology

IV. CONCLUSIONS AND NEXT STEPS

Streego is an innovative cost-effective optical payload that Media Lario Technologies is developing for the small-satellite Earth observation market. The design tradeoff has led to a 200 mm aperture TMA optical configuration. The system includes the optical telescope assembly and focal plane assembly (FPA) electronics providing a ground sampling distance of 2.75 m from 600 km orbit, a swath of about 10 km, and a target as-built MTF greater than 10% at the Nyquist frequency of the specified GSD.

From the preliminary assessment conducted so far, the performance of the STREEGO instrument in both laboratory and operational conditions are compliant with the target specifications even assuming very severe environmental conditions. Further work on the thermal and structural design is in progress with the goal of defining a reference mission and satellite platform in order to better estimate the thermal operational condition on one side, and further improving the optical stability in order to avoid the need of an in-flight refocusing mechanism on the other side.

The opto-mechanical design of STREEGO is also fully compatible with multi- or hyper-spectral applications and preliminary system analysis shows that the addition of an adequate filter bank on the detector would already enable 10-bands capability with 5.5 m GSD using the baseline FPA electronics.

The STREEGO program is entering the detailed design phase with the final goal of manufacturing a demonstration model by the end of 2015.

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