International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

Manufacturing and qualification of the QM mirror for the high-resolution spectrometer of the FLEX mission

Luigina Arcangeli

Giovanni Bianucci

Fabio Marioni

Ruben Mazzoleni

et al.

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111808H · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536224

Manufacturing and qualification of the QM mirror for the High-Resolution Spectrometer of the FLEX mission

Luigina Arcangeli[a], Giovanni Bianucci[a], Fabio Marioni*[a], Ruben Mazzoleni[a], Massimiliano Rossi[a], Marco Terraneo[a], Fabio E. Zocchi[a], Marco Meini[b], Francesco Galeotti[b], Riccardo Gabrieli[b], Fabio Belli[b], Matteo Taccola[c]

[a]Media Lario S.r.l., Bosisio Parini, Italy
[b]Leonardo, Avionics & Space System Division, Firenze, Italy
[c]ESTEC, European Space Agency, Noordwijk, The Netherlands

ABSTRACT

FLORIS (FLuorescence Imaging Spectrometer) is the single High-Resolution Spectrometer instrument of the FLEX (FLuorescence EXplorer) mission, currently under development by the European Space Agency as the eighth Earth Explorer Mission. The goal of the mission is the monitoring of the chlorophyll fluorescence of plants giving information about their photosynthetic activity.

Leonardo Avionics & Space System Division is the prime contractor for the FLORIS Instrument for which Media Lario is manufacturing the QM unit of the spherical mirror included in the High-Resolution Spectrometer (HRSPE), hereafter called HRM mirror.

The High-Resolution Mirror is a 250-mm diameter spherical mirror with a radius of curvature of approximately 440 mm. For the mirror substrate, Leonardo has selected the Aluminium alloy AlSi40, a special alloy with 40% Silicon content, coated with a hard polishing layer of Nickel Phosphorus (NiP), deposited by electroless chemical process. The Silicon content allows this special Aluminium alloy to have the same coefficient of thermal expansion (CTE) of the NiP layer, therefore preventing thermal deformations deriving from the bimetallic effect. The mirror structure is light-weighted to approximately 2.8 kg. The required wave-front error of the mirror is better than 0.5 fringes PV, while the surface microroughness has been specified at 0.5 nm RMS due to stringent straylight requirements of the FLORIS instrument.

Media Lario has been selected for the mirror development phase because of their experience in the design and manufacturing of AlSi/NiP mirrors demonstrated in the development of the Earth Observation optical payload for small satellites (called STREEGO), based on an AlSi40 TMA telescope. The manufacturing process includes precision diamond turning, optical figuring and super-polishing. The optical coating will be done by Leonardo at their thin-films facility of Carsoli, Italy. Since the recipe prescribes to pre-heat the mirror surface at 100 °C, Media Lario will qualify the mirror substrate with -25/+110 °C thermal cycles to ensure adequate thermal stability for the coating process.

Keywords: Aluminium mirror, Aluminum mirror, NiP coated mirror, Al/NiP mirror, AlSi40 mirror

1. INTRODUCTION

FLORIS (FLuorescence Imaging Spectrometer) is the single High-Resolution Spectrometer instrument of the FLEX (FLuorescence EXplorer) mission, currently under development by the European Space Agency as the eight Earth Explorer Mission. The goal of the mission is the monitoring of the chlorophyll fluorescence of plants giving information about their photosynthetic activity.

Leonardo Avionics & Space System Division is the prime contractor for the FLORIS Instrument [1] and has subcontracted the manufacturing of the EQM unit of the High-Resolution Mirror, hereafter called HRM mirror, to Media Lario S.r.l. The HRM mirror (Figure 1) is a concave spherical mirror with an external diameter of 250 mm and a radius of curvature of about 440 mm. The HRM mirror includes three interface pads for installation in the spectrometer.

*fabio.marioni@medialario.com; phone +39 031 867123; fax +39 031 876595; www.medialario.com

The optical requirements of this mirror include wave-front error better than 0.5 fringes PV in the operating thermal range of +20/+24 °C and surface roughness Rq of 0.5 nm RMS. The non-operational conditions are -15/+55°C, while the maximum mass requirement is 2.8 kg. Additional thermal stability requirements derive from the optical coating process that will be performed by Leonardo at their thin-films facility of Carsoli, Italy. The coating recipe prescribes to pre-heat the mirror substrate to a temperature of 100 °C. For this reason, Media Lario has been required to qualify the mirror substrate with -25/+110 °C thermal cycles to ensure there are no residual optical distortions after cycling.

For the mirror substrate, Leonardo has selected the Aluminium alloy AlSi40, a special alloy with 40% content of Silicon, coated with a polishing layer of Nickel Phosphorus (NiP), which is deposited by electroless chemical process with a thickness of 70 µm. Electroless Nickel Phosphorus is a hard layer with an amorphous structure that is very well suited to optical finishing processes such as diamond machining and polishing, with demonstrated roughness performance down to 0.3 nm RMS. These characteristics enable applications at short wavelengths, up to the UV spectral range. At the same time, the 40% content of Silicon allows this special Aluminium alloy to have the same coefficient of thermal expansion (CTE) of the NiP layer, therefore preventing thermal deformations deriving from bimetallic effect. There are several AlSi40 alloys available on the market. For the HRM mirror, Media Lario has selected the RSA 443 alloy provided by RSP Technology, The Netherlands. RSA 443 has a density of approximately 2.5 gr/cm^3, Ultimate Tensile Strength of 215 MPa, Yield Strength of 167 MPa and Stiffness E-modulus of 99 GPa.

Media Lario has been selected for the mirror manufacturing because of its heritage and experience in the design and manufacturing of AlSi40/NiP mirrors for space applications, such as the 200 mm aperture TMA Earth Observation optical payload for small satellites, called STREEGO [2] [3], or other aspherical mirrors up to 460 mm optical aperture.

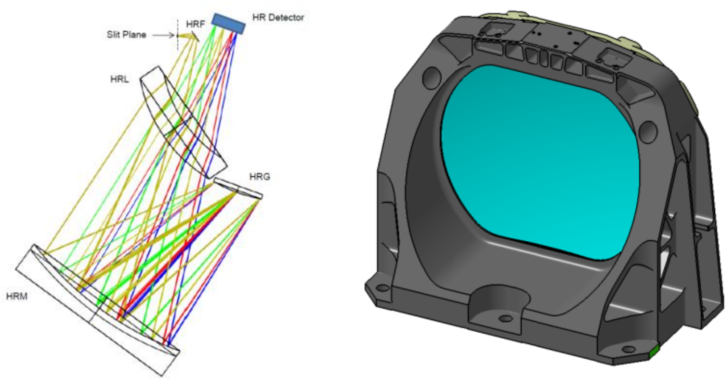

Figure 1. Optical layout of the FLORIS high-resolution spectrometer showing the HRM mirror (left) and view of the opto-mechanical assembly of the HRM mirror (right).

2. DESIGN

The design of the mirror has been done jointly by Leonardo and Media Lario in order to meet the mass requirement of 2.8 kg and, at the same time, ensure sufficient stiffness for figuring of the optical surface to WFE of 0.5 fringes PV. The mirror has diameter of 250 mm, height of 44 mm and mass of 2.094 kg achieved by a light-weighting pattern with triangular cells (Figure 2). The optical surface has a constant thickness of 12 mm to avoid any quilting artefacts during the polishing phase. The design incorporates three flanges, evenly spaced at 120°, for mechanical interface to the mirror mechanical support.

3. MANUFACTURING PROCESS

The manufacturing process consists of three main phases: CNC machining, precision diamond machining and final figuring and polishing. CNC machining includes several steps to produce the light-weighted Aluminium blank with the optical surface milled to micron level accuracy. This phase includes several heat treatment steps for thermal stabilization of the mirror. The Aluminium blank is then machined by diamond fly-cutting on the optical surface and mechanical references in order to prepare it for Nickel Phosphorus coating.

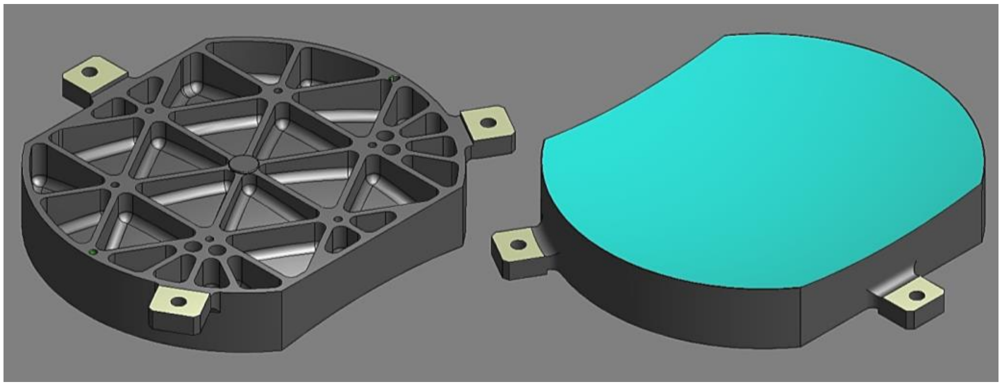

Figure 2. Mechanical design of the FLEX HRM Mirror.

This electroless coating process contains approximately 12% of Phosphorus and ensures constant thickness over the entire surface of the mirror, including the backside light-weighting structure. The Nickel Phosphorus coating has a hardness of about 550 HV and an amorphous structure that makes it very suitable for the diamond turning and polishing processes, particularly with respect to surface roughness.

The NiP coated blank is then diamond machined on the optical surface and mechanical references. Additional heat treatment steps are included in this phase to complete the thermal stabilization process. Figure 3 shows two HRM mirrors blanks after NiP coating and one HRM mirror after final diamond machining. At the time of submission of this publication, also the second HRM mirror unit is in final diamond machining phase, planning to begin the figuring and polishing phase in early September for delivery to the customer within October 2018.

Precision diamond machining ensures shape accuracy of about 0.5 µm PV on the optical surface, radius of curvature within 0.1 ‰ of the nominal value and surface roughness of approximately 3 nm RMS, which form an excellent substrate for the final figuring and polishing phases. Diamond fly-cutting also ensures precise machining of the three flat interface pads of the mirror, with flatness and parallelism within 1 µm PV. This performance ensures that the mechanical references are accurately aligned within 0.02 mm to the optical spherical surface, against a specification of 0.1 mm, thus facilitating the integration of the HR mirror in the instrument.

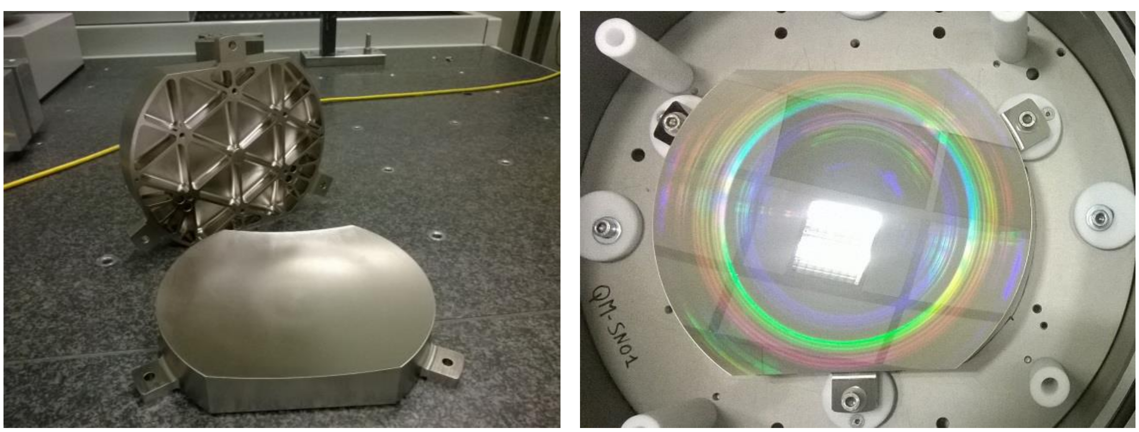

Figure 3. Two HRM mirror blanks after NiP coating (left) and one in the transportation container after final diamond machining (right).

4. RESULTS OF THE BREADBOARD MIRROR

While the EQM unit of the HRM mirror is in its completion phase, we report the results achieved on a representative HRM Breadboard mirror, which has already been produced to setup and verify the entire manufacturing process, particularly the polishing and figuring and thermal stabilization. For convenient and timely utilization of an existing blank of RSA 443

Aluminium alloy, the HRM Breadboard mirror is 20 mm shorter (i.e. 184 mm vs. 204 mm) and without interface pads, while the optical surface is exactly the same as the nominal design.

The HRM Breadboard mirror followed the same manufacturing process explained in section 3. The CNC machining, NiP coating and precision diamond machining performed as expected from previous heritage and experience on similar mirrors. The main purpose of the HRM Breadboard mirror was to setup and validate the final shape correction and polishing steps. In fact, the roughness requirement of Rq 0.5 nm RMS requires a final super-polishing phase that may conflict with the preceding shape correction step. As such, the HRM Breadboard mirror was an early development vehicle to prove the two optical specifications of the mirror, that is wave-front error and surface roughness.

The wave-front error requirement of 0.5 fringes PV is well within Media Lario's capability but it is more difficult to achieve on the elongated, not circular, shape of this mirror. In fact, standard consolidated polishing practices with pitch lap and alumina slurry are well suited for round mirrors, while create astigmatic errors on elongated shapes. While this issue has been addressed with dedicated shapes of the pitch lap, this workaround departs from the best practices of sub-nanometre polishing, which is based on large and regular pitch laps and decanted alumina slurries.

For this reason, the HRM Breadboard mirror was further processed on Media Lario's ZEEKO IRP 1200X polishing machine (Figure 4). This 7-axis CNC system uses a rotating inflated membrane bonnet, covered with a polishing cloth that is constantly irrigated with a liquid slurry. This deterministic process corrects the shape of the mirror starting from the interferometric metrology data of the mirror, so that the IRP system is programmed to selectively correct the surface of the substrate and iteratively converge to the final optical specifications. Media Lario has developed such deterministic figuring and polishing processes for any optical designs, including off-axis aspheric shapes, and for different substrate materials, including NiP coated Aluminium, Fused Silica, and standard and low-thermal expansion glass, such as ZERODUR®.

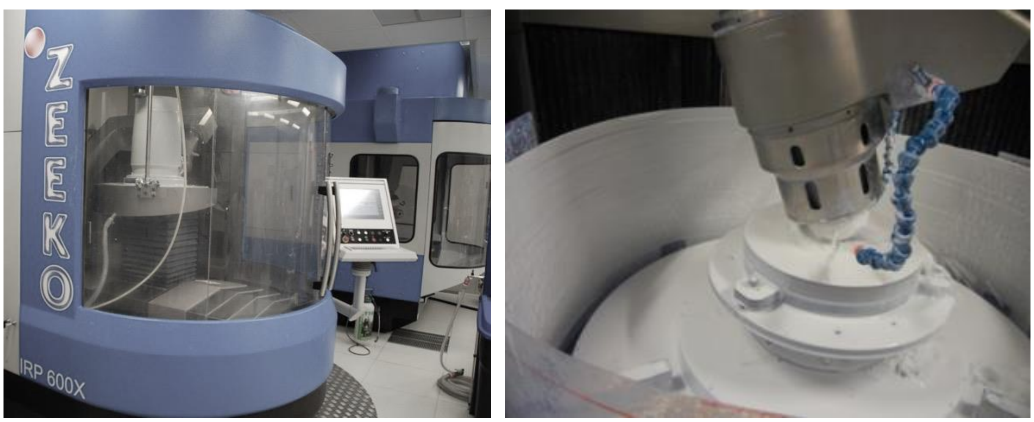

Figure 4. ZEEKO IRP 600X (left, foreground) and IRP 1200X (left, background) installed in Media Lario and example of off-axis aspheric Al/NiP mirror in figuring and polishing process (right).

The HRM Breadboard mirror was polished with seven IRP converging polishing runs (Figure 5), achieving a wave-front error of 0.48 fringes PV (Figure 6), which is better than the specification of 0.5 fringes, and a surface roughness Rq of 0.58 nm RMS, marginal higher than the specification of 0.5 nm RMS. Table 1 summarizes the full set of measurements performed on the HRM Breadboard mirror, while Figure 7 shows the surface roughness measurement of the HRM Breadboard mirror with Sq value of approximately 1 nm RMS and Rq values of 0.58 nm RMS. Sq is the Root Mean Square evaluated over the complete 3D surface, while Rq is the Root Mean Square evaluated over 2D profiles.

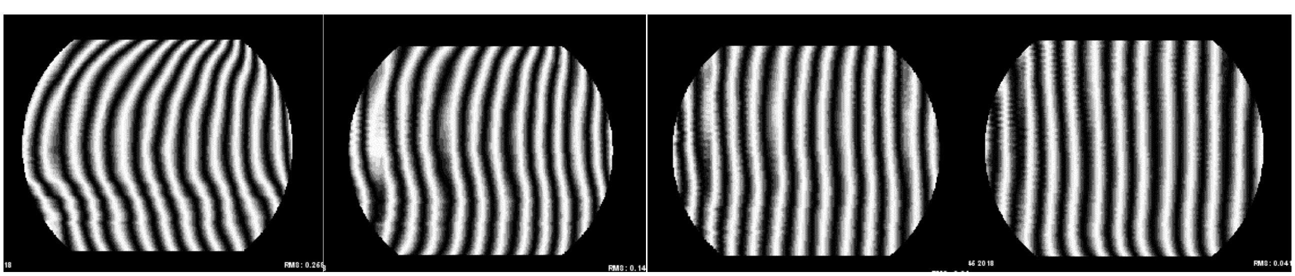

Figure 5. Evolution of the surface accuracy of the HR Mirror Breadboard during the IRP figuring and polishing runs.

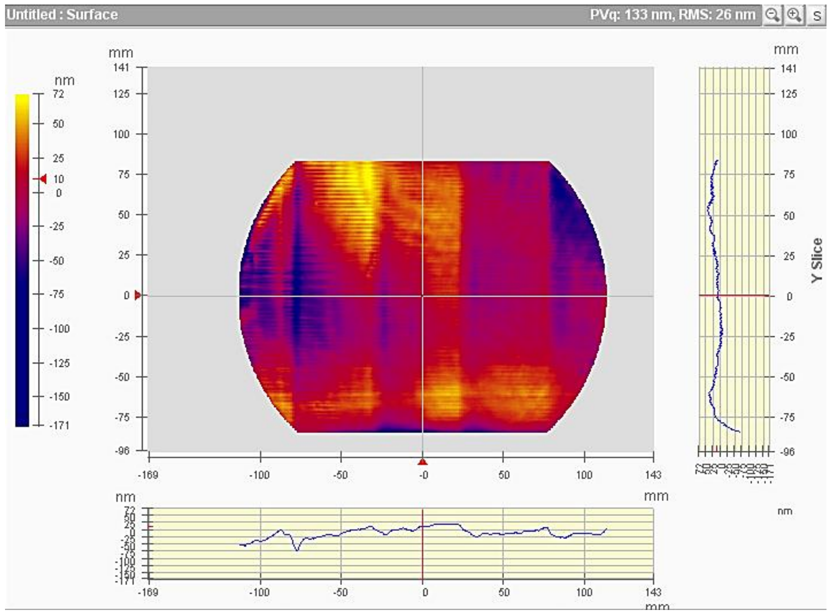

Figure 6. Surface shape accuracy of 133 nm PV achieved on the HR Mirror Breadboard, corresponding to a wave front error of 048 fringes PV.

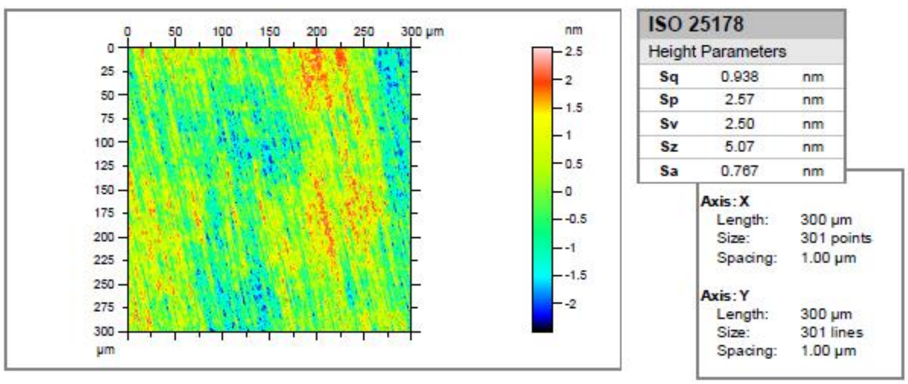

Figure 7. WLI surface roughness measurement of the HR Mirror Breadboard after iterative figuring and polishing on Media Lario's ZEEKO IRP 1200X.

Table 1. Summary of the manufacturing results achieved on the HR Mirror Breadboard.

Parameter	Specifications	Results	Measurement method
Mass	2000 g	1951.6 g	Scale
Diameter	250 ± 0.05 mm	249.95 mm	CMM
Width	184 ± 0.1 mm	183.94 mm	CMM
Centring	≤ 0.03 mm	0.03 mm	CMM
Height of vertex	23 ± 0.02 mm	22.963 mm	CMM
Radius of Curvature	439.8 ± 0.3 mm	439.76 mm	CMM
WFE	≤ 0.5 fringes PV	0.48 fringes PV	Interferometer
Roughness Rq	< 0.5 nm RMS	0.58 nm RMS	White Light Interferometer

5. CONCLUSIONS AND FURTHER WORK

FLORIS (FLuorescence Imaging Spectrometer) is the single High-Resolution Spectrometer instrument of the FLEX (FLuorescence EXplorer) mission, currently under development by the European Space Agency as the eighth Earth Explorer Mission. The goal of the mission is the monitoring of the chlorophyll fluorescence of plants giving information about their photosynthetic activity.

Leonardo Avionics & Space System Division is the prime contractor for the FLORIS Instrument for which Media Lario is manufacturing the QM unit of the spherical mirror of the High-Resolution Spectrometer (HRSPE), called HRM mirror.

For the mirror substrate, Leonardo has selected the Aluminium alloy AlSi40, a special alloy with 40% content of Silicon, coated with an amorphous layer of Nickel Phosphorus (NiP), which is well suited for diamond machining and polishing. The 40% content of Silicon allows this alloy to have the same coefficient of thermal expansion (CTE) of the NiP layer, therefore preventing thermal deformations deriving from bimetallic effect.

The results achieved on the HRM Breadboard Mirror meet the requirements sets by Leonardo and have validated the manufacturing process. The CNC machining, NiP coating and diamond machining steps have confirmed the performance capability already demonstrated in previous mirrors of similar shape and quality. The conventional polishing process has shown limited applicability to the elongated shape of the HRM mirror, which resulted in residual astigmatism error. This required to include an additional process step with deterministic figuring and polishing process on Media Lario's ZEEKO IRP machine. Seven runs were enough to converge to final wave-front error performance of 0.48 fringes PV (spec 0.5 fringes) and surface roughness Rq of 0.58 nm RMS (spec 0.5 nm). The radius of curvature was within 0.1 ‰ of the nominal value, therefore well within the specification value.

The QM unit of the FLEX HRM mirror is now in its final manufacturing diamond machining step, planning to start the shape correction and surface polishing phases in early September. The mirror will then be thermal cycled in -25/+110 °C range to confirm the thermal stability for the subsequent coating step at Leonardo's thin-films facility of Carsoli, Italy.

ACKNOWLEDGEMENTS

The work presented was done in the framework of FLEX Mission for ESA Eight Earth Explorer Mission. Media Lario thanks ESA and Leonardo for selection and cooperation during the development.

REFERENCES

[1] Coppo, P., Taiti, A., Pettinato, L., Francois, M., Taccola, M., Drusch, M., "Fluorescence Imaging Spectrometer (FLORIS) for ESA FLEX Mission," Remote, Sens. 9(7), 649, 2017.
[2] I, Ferrario, R. Ghislanzoni, L. Maersi, M. Rossi, M. Taccola, P. Zago, F. E. Zocchi, "An all-metallic high resolution instrument for earth observation from small leo satellites" ICSO 2014, Tenerife, Canary Islands, Spain 7-10 October 2014.
[3] Rossi, M., Arcangeli, L., Bianucci, G., Capuano, G., Formicola, G., Longobardi, P., Maresi, L., Mazzoleni, R., Spinelli, S. M., Taccola, M., Terraneo, M., Zocchi, F.E., "Design and qualification of the STREEGO multispectral payload" Proc. SPIE 10402, Earth Observing Systems XXII, 104020B (5 September 2017); doi: 10.1117/12.2275323