HYPERSTREEGO: REACTIVE PAYLOAD

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On-board image processing is being proved with the development of HyperScout, a miniaturized hyperspectral instrument of about 1 cubic decimeter. The instrument, conceived to deliver real time L2 data thanks to the powerful on-board processing and the optimization of L2 algorithms, has a large (30°) field of view and a 80 m GSD from 600 km altitude. HyperScout is also available in quad configuration for covering larger fields and to perform cloud detection in order to identify the cloud free pixels to be used for further real time data processing. The quad configuration is PANORAMA.

PANORAMA can be used as a viewfinder in the VIS-NIR-SWIR for STREEGO, a high spatial resolution instrument in VIS-NIR and with GSD in the meters range and consequently with limited FoV. The concept proposed in this paper is to couple the two instruments on the same platform, with PANORAMA pointing approximately 45° ahead of STREEGO, a multispectral/panchromatic instrument with 2.5 m to 5 m GSD. The idea is to use PANORAMA to detect real time anomalies and to point STREEGO on these anomalies for higher resolution observations. This is possible because the hyperspectral instrument is conceived to have a pre-stored Earth map on the on-board computer that is used as comparison during observations, so that whenever the land looks different an alert is raised to the AOCS.

Detection of anomalies that are being analysed during the development of HyperScout are flooding, forest fire, volcanic eruption, landslides within minutes from their occurrence.

The paper reports the description of the architecture, the performances of the individual instruments, and the operative concept of the combined instruments, which is called HyperSTREEGO.

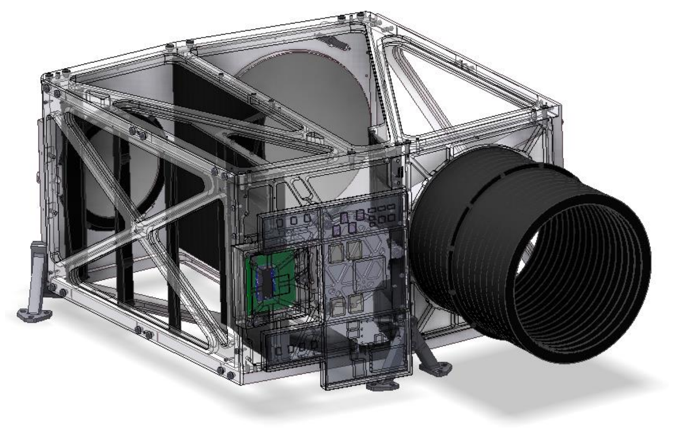
1 THE STREEGO OPTICAL PAYLOAD

STREEGO is an innovative optical payload for small satellites that has been proposed starting from a survey of existing Earth Observation instruments, and developed under an ESA GSTP contract funded by ASI. While the small satellite industry is rapidly growing [1], an interesting market segment has been identified in medium-high resolution payloads dedicated to topography, security, traffic, and urban development.

The system benefits from the adoption of pioneering technologies which have already enabled the production of small high-performance missions [2] and small satellite constellations [3]. The engineering model has now been successfully integrated and tested in laboratory conditions.

1.1 STREEGO DESIGN

STREEGO is a three mirror anastigmat (TMA) multispectral optical payload for Earth Observation small satellites, based on off-axis aspherical mirrors. Among other advantages over traditional designs, this all reflective configuration allows an unobscured field of view with no chromatic aberration, greater image irradiance for a given aperture, and better Modulation Transfer Function (MTF) performance at medium spatial frequencies.



Focal Length	1200 mm
Aperture (D)	200 mm
F/no.	6.0
FOV	1.076° x 0.807°
GSD	2.75 m
Swath	11.3 km
Active resolution	~ 4000 x 3000 px
Nominal MTF @ Nyquist	64 %
Panchromatic SNR	> 100
Mass	22 kg
Power	48 W
Volume envelope	305 x 525 x 530 mm^3
Multispectral bands	9 (VIS-NIR) + PAN

Figure 1 – STREEGO system layout and design specifications @600km

The driving parameters of the optical design were imposed by mission objectives like multispectral capability, resolution, and field of view. For a system flying at 600 km, with the selected commercial detector CMOSIS CMV12000 (5.5 μm pixel size, 4096 x 3072 pixels), the Ground Sampling Distance (GSD) is 2.75 m and the FoV 1.08° x 0.81°, for a swath larger than 11 km. In the visible waveband the nominal designed MTF is 64% at 91 cycles/mm, corresponding to approximately 30% as-built, and 10% or more in operation. The CMOS sensor features a quantum efficiency greater than 45% in the visible range, which allows the system to reach a panchromatic Signal to Noise Ratio greater than 100.

Nine wavebands have been defined as reference during the design of the system. These bands are located in the wavelength range from 450 nm to 900 nm. A thin filter integrated in front of the detector achieves the spectral selection. The filter comprises a set of 9 equally spaced areas on the same substrate together with a non-selective region for the panchromatic channel. Each channel is 3072 pixels across track and 200 pixels along track. The separation between the channels is 100 pixels, and a blocking filter based on a black Chromium mask protects the entire non-active area of the sensor.

STREEGO performances allow to cover a wide spectrum of applications and can be easily upgraded to a hyperspectral configuration by changing the focal plan filter.

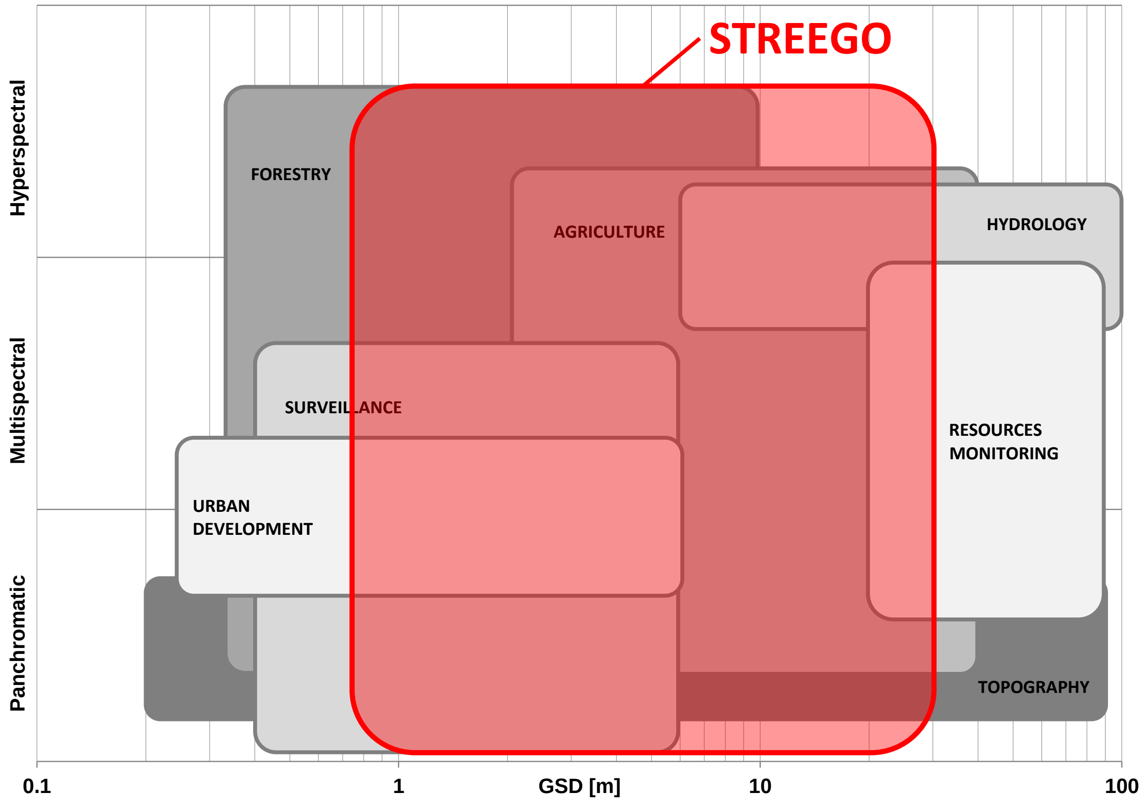


Figure 2 – STREEGO Applications domain

1.2 ELECTRONICS

STREEGO electronics consists of two connected Printed Circuit Boards (PCB), the focal plane and the main electronics. The focal plane section includes the CMOS detector and transceivers for single-ended signals. The FPGA, memories, cameralink/channel, link drivers, the input power conditioning stage and the sensor power and overcurrent protection circuits are allocated on the main electronics PCB.

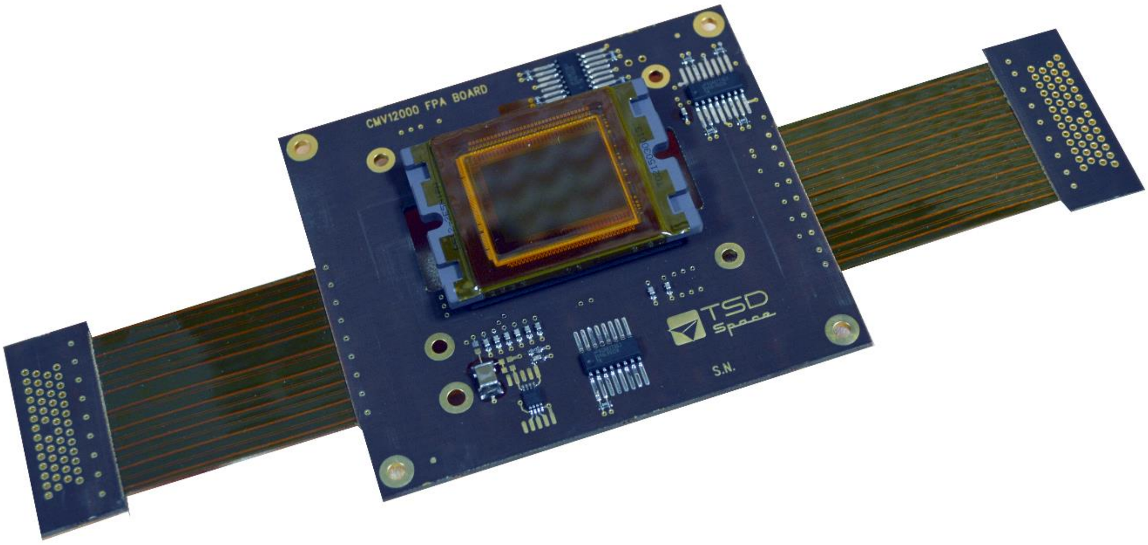


Figure 3 – STREEGO FPA

The Focal Plane PCB is composed by one main rigid PCB and two flexible PCBs ending with two small rigid PCBs that host the high density connectors of the Focal Plane Assembly (FPA).

The Focal Plane PCB and Main Electronics PCB are connected by means of those two connectors. All signals are transferred by using fully balanced lines to improve signal quality avoiding cross-talk. The flexible PCB includes a dedicated layer acting as reference plane for all differential signals, thus increasing noise immunity.

In order to offer good thermal stability of the focal plane, a thermal buffer has been placed behind the CMOS, so that the heat produced by the image sensor will be transferred away by means of a thermal strap.

Two heaters, together with three thermistors for temperature monitoring, will be attached to the thermal buffer in order to warm up the FPA in case temperatures below safe operation are detected.

Both heaters and temperature monitoring are not managed by the camera electronics itself but by the spacecraft on-board data handling system so to be activated before the camera power-on.

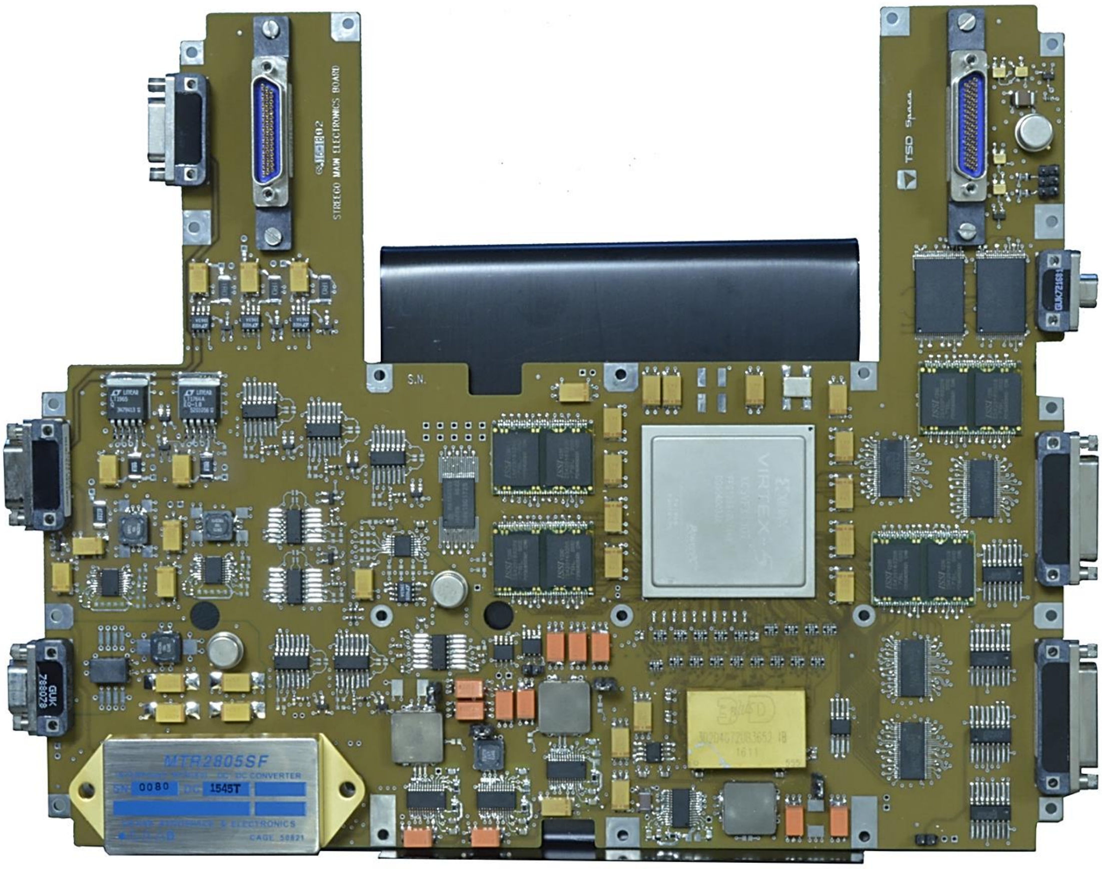


Figure 4 – STREEGO main electronics

The Main Electronic section allows a maximum data rate of 155 megapixel/s at 10 bits per pixel and 125 megapixel/s at 12 bits per pixel.

The design of the STREEGO electronics is based on radiation tolerant components available in two qualification grades, one at 10Krad, the other at 100 Krad. All components are mounted on a high density PCB designed and manufactured according to the ECSS standards.

1.3 STREEGO PRODUCTION

The manufacturing process adopted for the aspherical mirrors of STREEGO is based on a combination of diamond turning machining and CNC bonnet polishing of an amorphous Nickel-Phosphorous coated Aluminum mirror, a similar approach to what successfully adopted for other metallic payloads [4].

This processes has been extensively used in Media Lario over the past years for the production of X-ray mandrels [5]. As the thermal design of the payload is essentially passive, the need to guarantee the best performance of the optical surfaces in the harsh space environment leads to the choice of a thermal treated and CTE-matched substrate, like Aluminum RSA443.

Starting from an athermal design approach for the optical bench, the same material has also been selected for the entire structure, as already done by Media Lario for another TMA payload [6].

The deposition of a Silver enhanced coating is also mandatory to increase reflectivity and provide better SNR in the panchromatic and multispectral channels.

Figure 5 – Polished M1 mirror (238 mm outer diameter) with drawing of its light-weighting and IRP 600 polishing machine

The bonnet polishing process is based on the control of a 7 axes CNC machine, with an air inflated pad that contacts the surface and physically performs the polishing action in combination with a polishing slurry.

MLT has two deterministic polishing machines, Zeeko IRP600X and IRP 1200Xcapable to process up to 1 m class substrates.

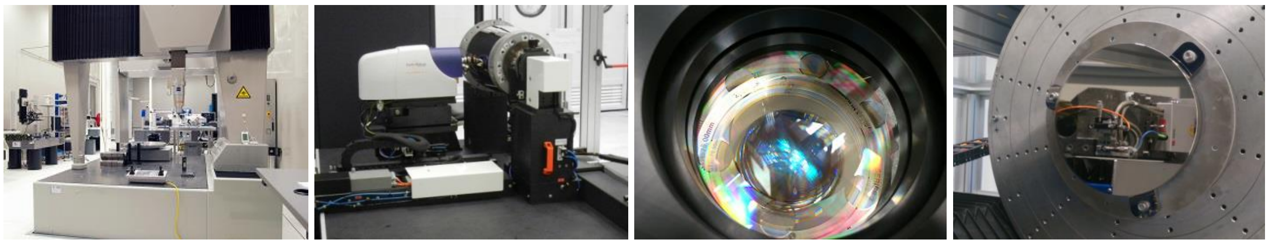


Figure 6 – Some of the metrology tools adopted during manufacturing (left to right: UPMC 3D CMM, CCI Lite White Light Interferometer, CGH and reflection of the MPR700 on the first M1 prototype).

The shape error of the three mirrors is well below the required specifications, in particular for M1 is 12 nm RMS, and for M2 is 7 nm RMS. M3 was stopped just below 20 nm RMS due to schedule constraints, being this mirror the least sensitive to shape accuracy errors.

1.4 STREEGO INTEGRATION AND TEST

The STREEGO integration has been performed in only three days and the procedure has been experimentally tested on a breadboard model of the system which features all the relevant interfaces for the alignment of the mirrors.

The distortions induced by mechanical fixation of the mirrors to the Optical Telescope Assembly (OTA) have been assessed by interferometric measurements, and the alignment errors have been measured by CMM. The results are in line with, and well within, the system error budget.

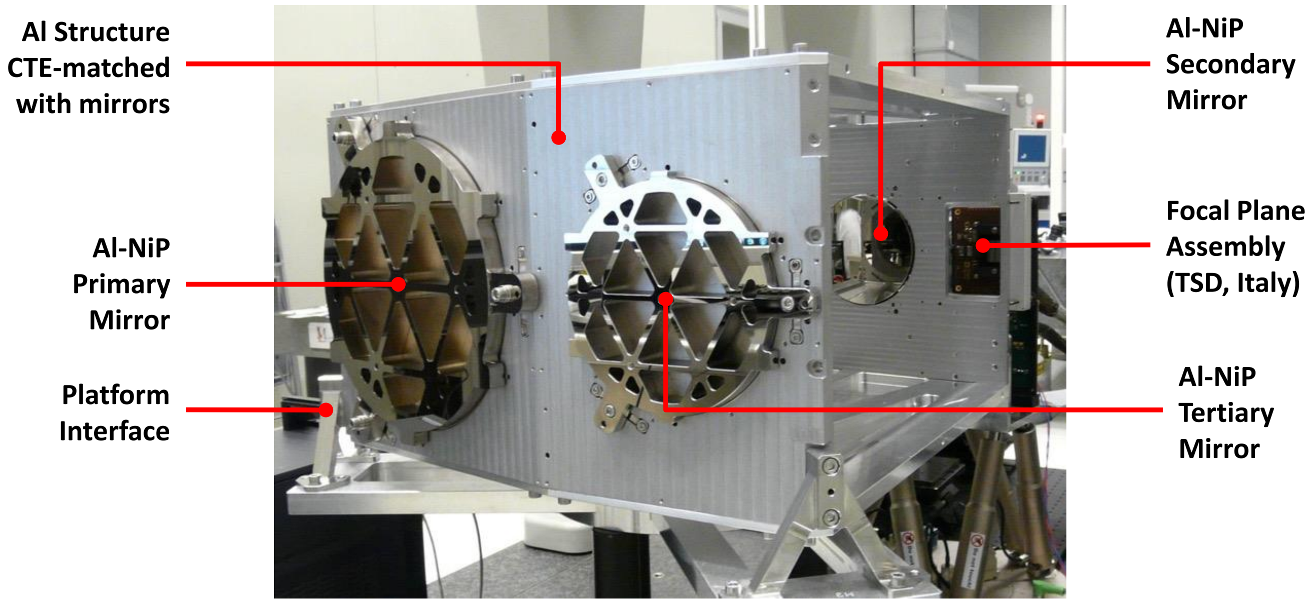


Figure 7 –Mirrors mounted on STREEGO EM on Test Bench (side panel removed to show internal parts)

The integration sequence was the following:

- The multispectral filter was installed on the sensor ceramic packaging.
- M1 and M3 have been mounted on their common plate within the specified mechanical tolerances and verified via 3D CMM measurements of the mirrors reference cubes.
- The adjustable M2 has been installed by reference pins and 3D CMM measurements close to its nominal position.
- In order to verify the system wavefront error after integration, MLT performed an interferometric test in reverse configuration with the TMA in auto-collimation on a flat mirror.
- M2 has been then used as a compensator minimizing the double pass wavefront distortion by tilting and shifting and then fixed in the optimal position.
- The FPA and the Camera Electronics have been mounted on the optical bench and the FPA optimized by means of a wide angle collimator optimizing the image of the collimator target recorded by the payload sensor.

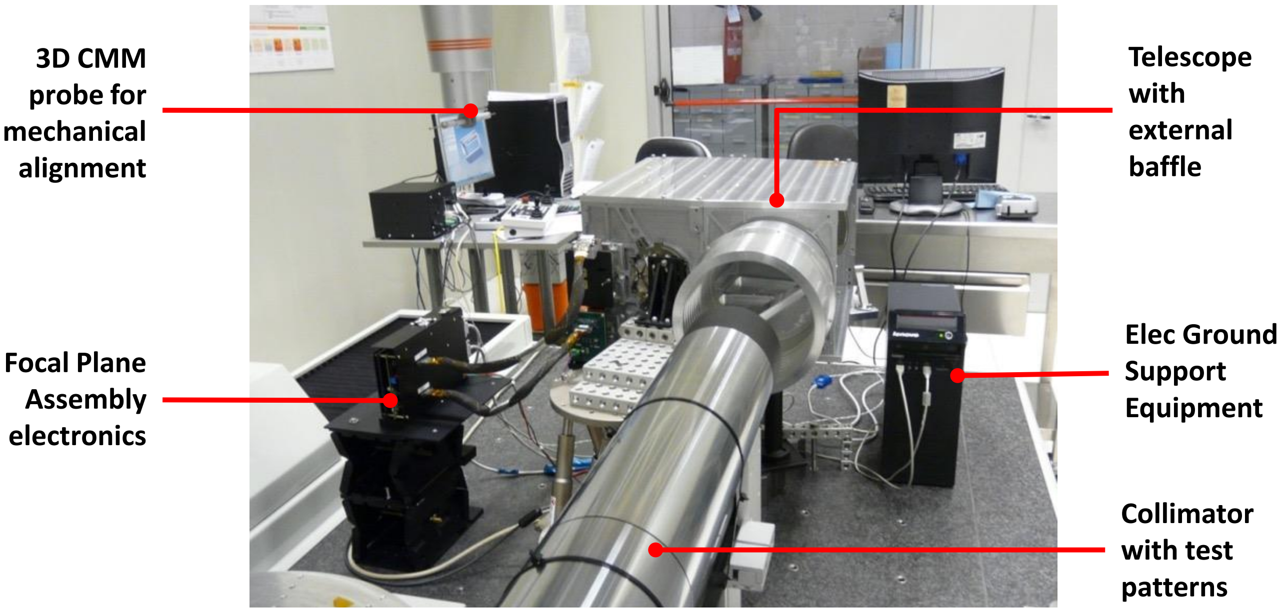


Figure 8 – Telescope aperture on STREEGO EM Assembly

The performed payload verifications showed a final integrated system Wave-Front Error (WFE) of 44.8 nm RMS.

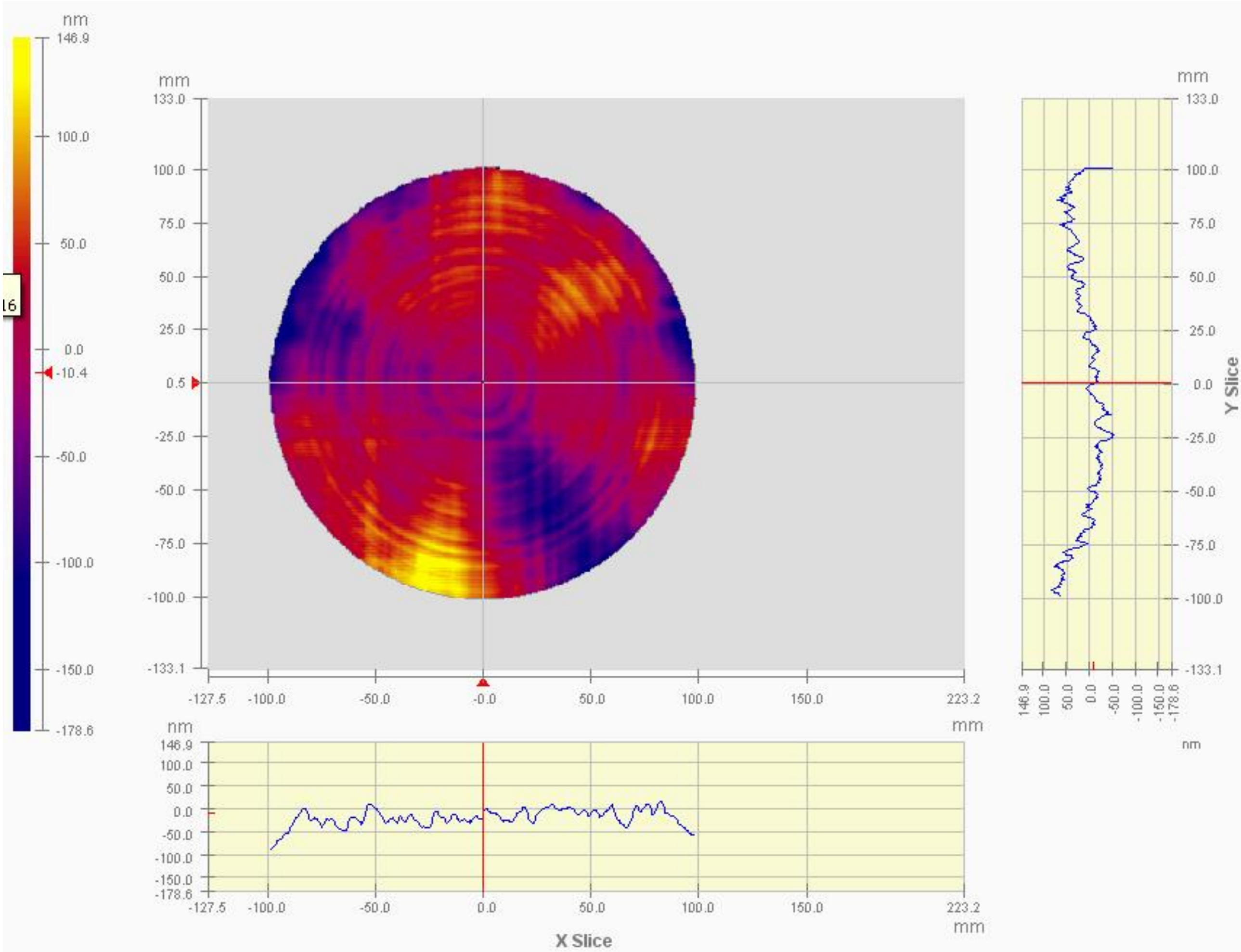


Figure 9 – Telescope WFE measurement: 44.8 nm RMS

2 HYPERSCOUT AND PANORAMA

2.1 HyperScout

HyperScout is a miniaturized hyperspectral imager developed by cosine measurements systems BV. The Engineering Model has been successfully manufactured and tested under the course of a European Space Agency funded project. HyperScout is the first ever miniaturized hyperspectral imager with its own brain. It is designed to be operated upon nano, micro and larger satellites. The extremely compact reflective telescope ensures high optical quality in the VNIR range.

The on-board data handling system is made for real-time data processing, enabling Level-2 generation on-board and therefore drastically reducing the amount of data to be downloaded and processed.

If used on board larger satellites, the wide swath, the Level-2 real-time data processing, and the minimal impact at system level, make the HyperScout attractive as an ancillary instrument providing real time phenomena information either to the larger primary payload, or to a ground control room.

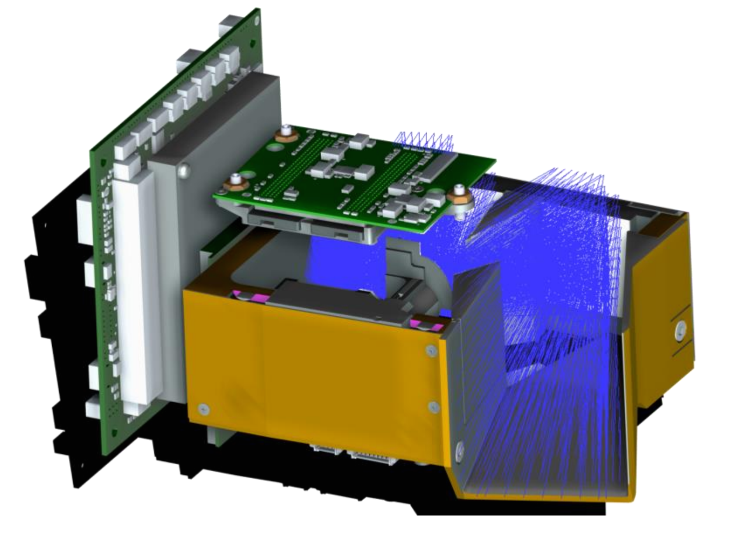
Figure 10: The HyperScout fully assembled.

This enables smart operational planning for large payloads. HyperScout, being a small, cost-effective and highly reconfigurable payload, can be effectively used in a large variety of missions, ranging from large-scale, as support instrument to larger payloads, to small scale, providing commercially valuable data products to a broad end-user community. The applications for which the real-time processing has been developed are listed in the following:

- Land survey and management, e.g. monitoring of vegetation conditions, crop water requirements, illegal dumps
- Early warning, e.g. flooding, forest fire, landslides

- Land cover and land use classification
- Monitoring of vegetation conditions (drought)

The on-board processing time is expected to be below the minutes for most of the applications of the envisaged applications.



FOV	31° x 16°
GSD	80m
Swath	350km
Active resolution	~ 4000x2000 px
Spectral range / resolution (high res)	470 – 900 nm / 5 nm
Spectral range/ resolution (ext range)	400 – 1000 nm / 12 nm
SNR	~100
Mass	0.7 kg
Volume	1 L
Average power	10 W

Figure 11 – HyperScout system layout and design specifications @600 km

A more detailed description of the instrument can be found in [7], [8] and [9].

2.2 Panorama

Panorama is a quad configuration of HyperScout.

Two HyperScouts in the VNIR range are used to enlarge the FOV ACT from which to derive level 2 geophysical information in real time. Two HyperScouts in the SWIR are used to identify the cloud free pixel to be used for the processing.

Figure 12: the CAD model of PANORAMA showing the 4 HyperScouts. The first 2 HyperScouts on the left are

in the SWIR. The two on the right are 2 VNIR

In this configuration the total FoV is 62° x 16°, with a swath of around 700 km. Due to its very large field of view the extreme areas of the instrument will provide a highly deformed image so a more conservative FoV is considered to be no more than 58° across track.

3 HYPERSTREEGO

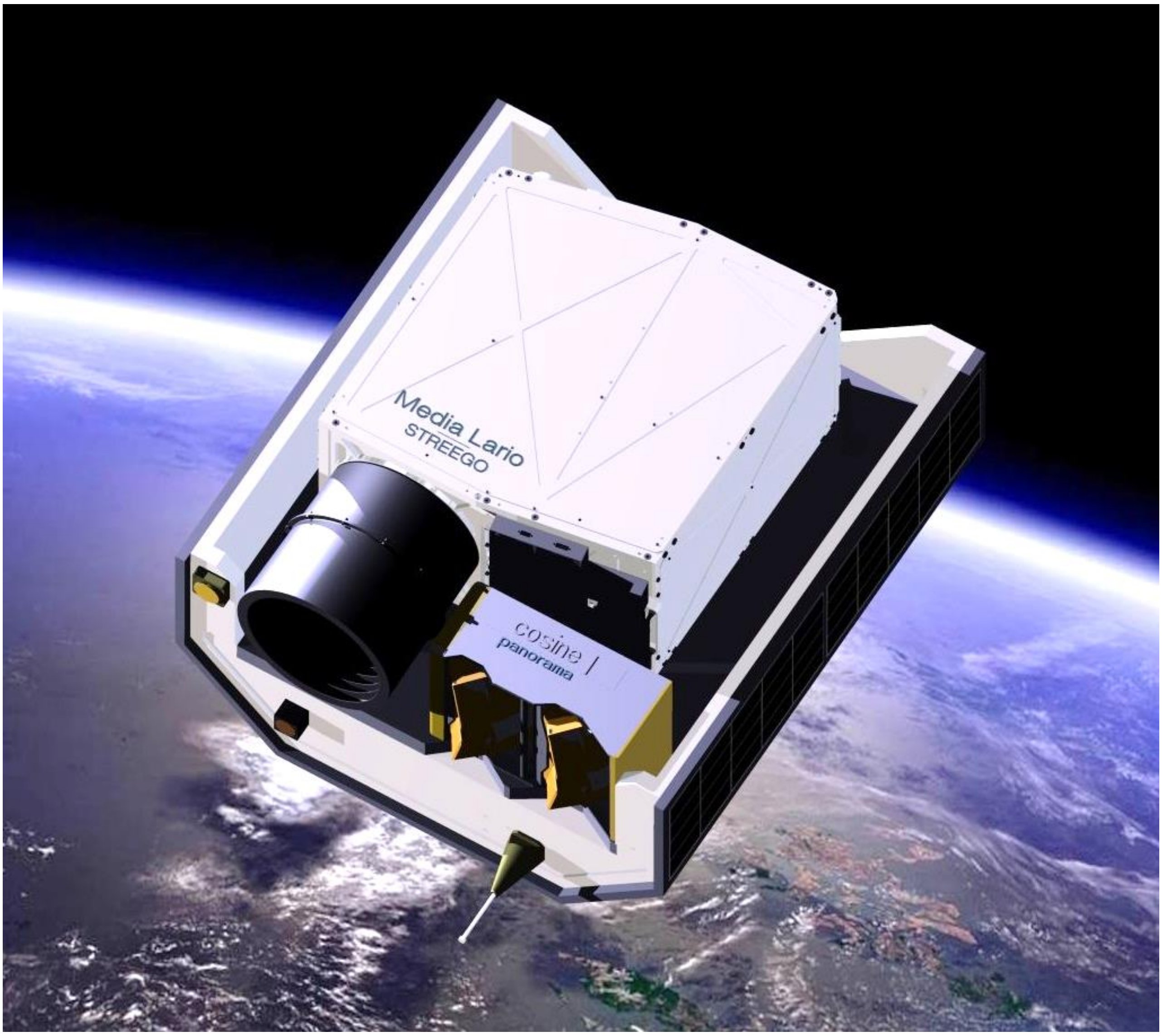


Figure 13 – HyperSTREEGO artist's impression

The HyperSTREEGO payload concept is composed of the two separate systems, Panorama and STREEGO, with a total mass of 23 kg and a total power of 58 W, which can be integrated on a single small satellite platform.

The Panorama instrument will be pointing at 45° along track, ram-facing, whereas the STREEGO instrument will be pointing nadir so that the first will autonomously identify changes or anomalies in the covered area which will then be imaged at high resolution by the second.

The following picture shows the FoV's and pointing directions of the two instruments, red and 45°

forward looking for Panorama, blue and nadir pointing for STREEGO. The huge difference in ground area coverage of the two instruments is evident from the illustration.

Figure 14 – HyperSTREEGO fields of view and pointing

The two electronics subsystems would work as separate units and would interface with the On Board Data Handling (OBDH) system, which would take care of repointing the satellite and operate both instruments. This approach would allow minimal redesign, if any, of the two payloads.

The system is highly autonomous in its operations due to the HyperScout capability of identifying any ground anomaly and trigger an alert which would be sent to the OBDH with the relevant coordinates and data. This will in turn repoint the satellite so that the STREEGO field of view covers the anomaly area and acquires the multispectral images at high resolution to be downloaded.

Since the two payloads have been designed in separate development projects, there is room for future optimization of the mechanical and thermal design.

The first order analyses performed show that at 600 km altitude the time needed for the STREEGO nadir pointing field of view to enter the HyperScout coverage is about one minute, as highlighted in the following figure.

This means that within one minute the HyperScout needs to process the entire observed region, detect any anomaly and the satellite has to repoint STREEGO in the required direction. In the worst case, the satellite has to be repointed by ±30° across track, therefore, assuming a standard small-sats platform with a repointing capability of about 1°/s, this leaves 30 s for the on-board HyperScout processing and anomaly detection.

This is a challenging requirement which currently cannot be met because the HyperScout takes a couple of minutes to process the entire FoV.

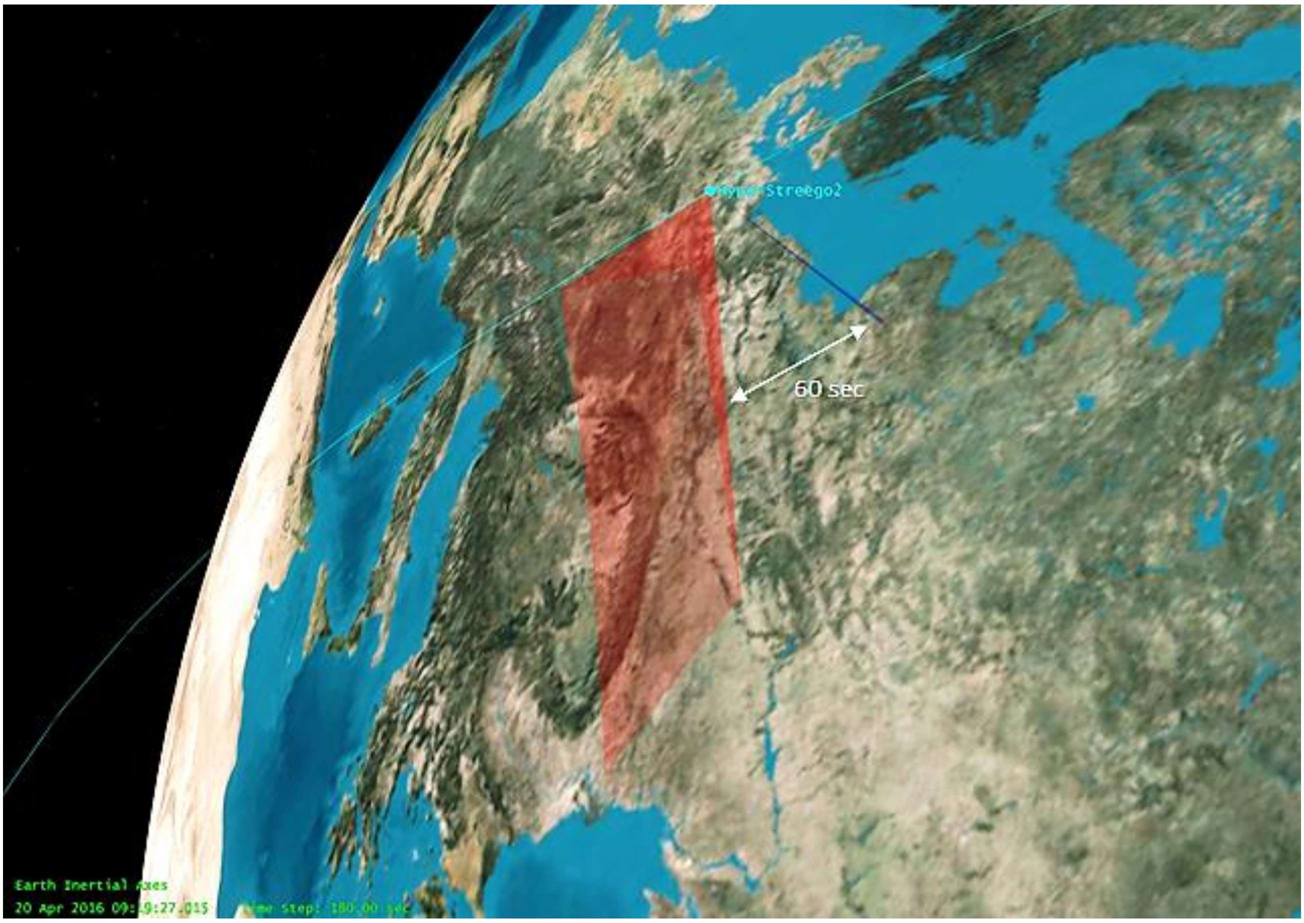


Figure 15 – Panorama half FoV (in red) and STREEGO FoV (in blue)

However, it must be noted that the HyperScout development roadmap is targeting reduction of the processing time to only 40 s. The remaining 10s reduction could be easily achieved by a better satellite repointing performance of only 1.5°/s or, for example, using a smaller region of interest for the anomalies detection and thus reducing the processing time which is, as a first approximation, almost linear with the number of pixels to be processed.

An alternative and more flexible, albeit more expensive and complex, solution would be to fly a constellation of HyperSTREEGO. As an example, it has been considered a constellation composed of two satellites on the same orbit and a bigger constellation of four satellites with two satellites per orbit and the two orbits at 90° to each other.

The wide field of view of the PANORAMA configuration allows to overlap the ground tracks of two satellites on the same orbit.

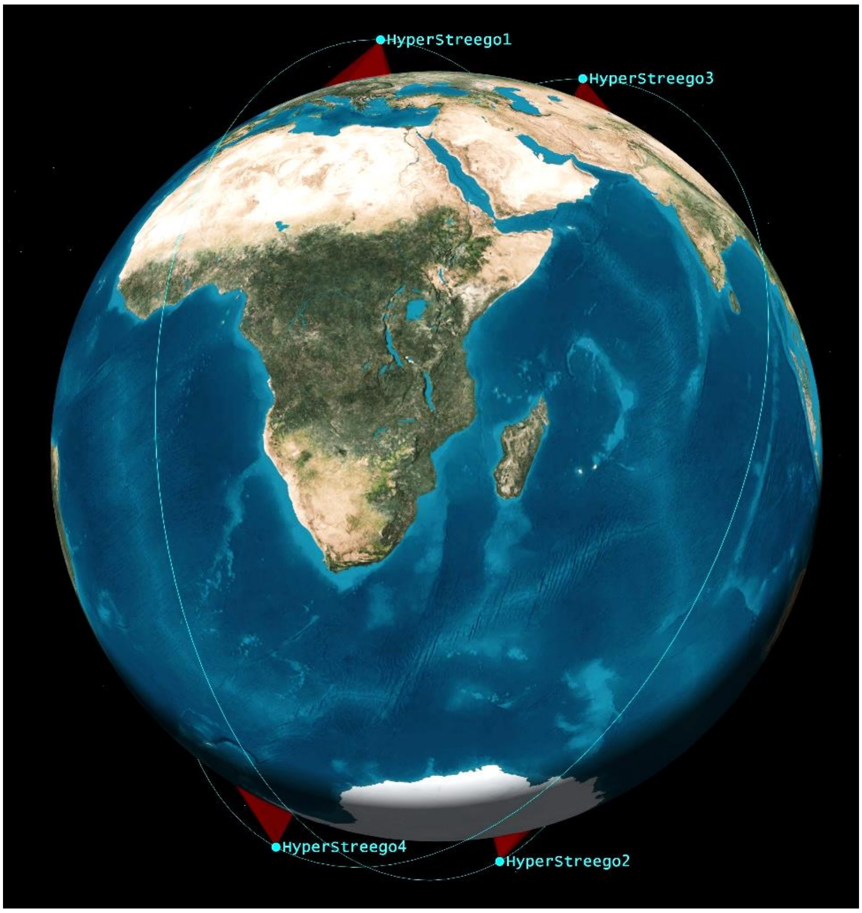


Figure 16 – HyperSTREEGO four satellites configuration

The analyses show that in the first case it's possible to achieve the complete coverage of an area like the entire Europe in around four hours and in the second it's possible to cover the same area twice a day. The first coverage happens from 8:30 AM to 12:30 PM, whereas the second coverage from 12:30 PM to 17:30.

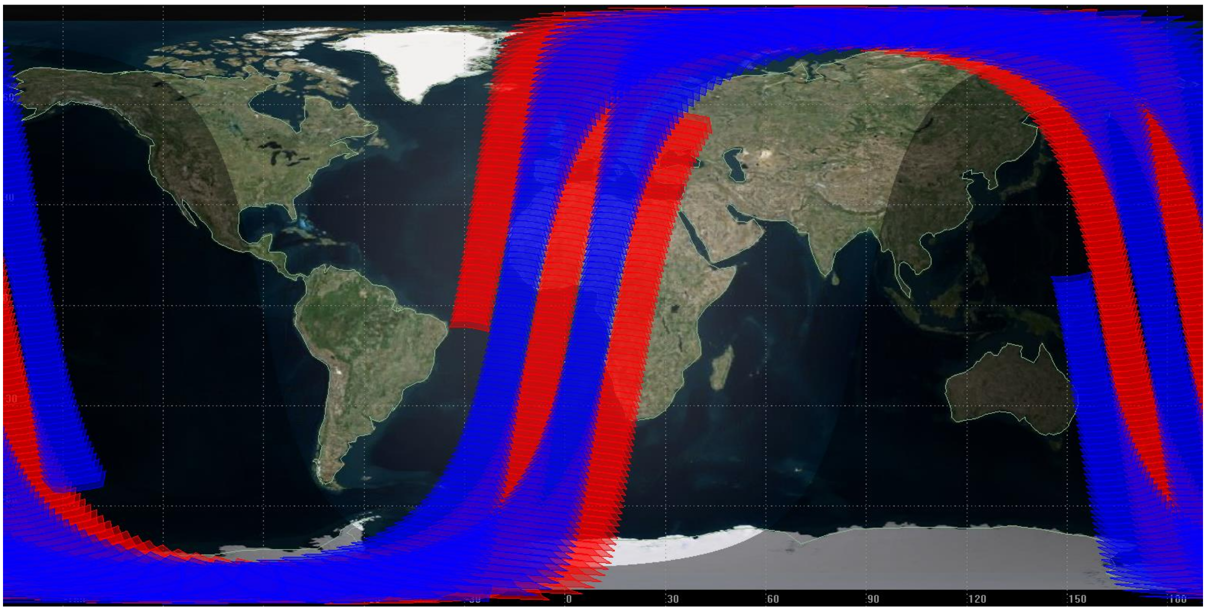


Figure 17 – Ground track of a two satellites on the same orbit configuration

4 CONCLUSIONS

We have presented an integrated instrument, called HyperSTREEGO, comprising one Panorama instrument, which could act as fast reacting anomaly detector and imager, and one STREEGO instrument, which would be used to acquire high resolution images of the anomalies.

Anomalies that could be detected and analysed by HyperSTREEGO within minutes from their occurrence are floods, forest fires, volcanic eruptions, and landslides.

Although the current design of the HyperScout cannot perform the required changes detection in the required time, an improved design of the instrument is already foreseen. This new design and performances will enable the integrated HyperSTREEGO to take high resolution images of detected changes in almost real time.

Alternative solutions which require multiple satellites in order to overcome the current performances limitations have been presented.

5 REFERENCES

[1] Villain, R., “Small Satellites, Earth Observation & New Space, a new chapter in space history,” 10th Symposium on Small Satellites for EO, Berlin (2015).

[2] Maresi, L., Taccola, M., Moelans, W., Moreau, V., Vermeiren, J. "Compact Optical Payload for Daily Survey of Vegetation from Small Satellites," 23rd Annual AIAA/USU Conference on Small Satellites (2009).

[3] Risse, S. et al, “Novel TMA telescope based on ultra precise metal mirrors,” *Proc. SPIE 7010*, Space Telescopes and Instrumentation 2008: Optical, Infrared, and Millimeter, 701016 (2008).

[4] Steinkopf, R., Gebhardt, A., Scheiding, S., Rohde, M., Stenzel, O., Gliech, S., Giggel, V., et al. "Metal mirrors with excellent figure and roughness," in Optical Systems Design, pp. 71020C-71020C, International Society for Optics and Photonics, 2008.

[5] Arcangeli, L., Borghi, G., Bräuninger, H., Citterio, O., Ferrario, I., Friedrich, P., Grisoni, G. et al. "The eROSITA X-ray mirrors-technology and qualification aspects of the production of mandrels, shells and mirror modules," ICSO, vol. 4, p. 8. 2010.

[6] Rossi, M., Borghi, G., Neil, I. A., Valsecchi, G., Zago, P. et al. "Electroformed off-axis toroidal aspheric three-mirror anastigmat multispectral imaging system," *Opt. Eng.* 53(3), 031308 (Jan 09, 2014).

[7] Esposito, M. et al, “HyperScout - The intelligent hyperspectral imager,” 2015 IEEE International Workshop on Metrology for Aerospace, Benevento, Volume: CFP1532W-USB.

[8] Conticello et al, “Hyperspectral Imaging for Real Time Land and Vegetation Inspection,” Proc. 4S conference 2016, Malta.

[9] Soukup et al, “HyperScout: Onboard Processing of Hyperspectral Imaging Data on a Nanosatellite,” Proc. 4S conference 2016, Malta.