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NEW GENERATION OF EARTH OBSERVATION OPTICAL SYSTEMS

Laure Brooker Lizon-Tati
Astrium Satellites SAS, Toulouse, France, laure.brooker@astrium.eads.net

Anthony Villien
Astrium Satellites SAS, Toulouse, France, anthony.villien@astrium.eads.net

Emmanuel Sein
Astrium Satellites SAS, Toulouse, France, emmanuel.sein@astrium.eads.net

Linda Tomasini
CNES, Toulouse, France, linda.tomasini@cnes.fr

André Laurens
CNES, Toulouse, France, andre.laurens@cnes.fr

Astrium is a key actor in European Earth Observation, accompanying users' quest for higher performances by developing ground-breaking high resolution missions (e.g. Spot family up to the newest Spot 6 and 7 satellites and the new Pléiades high-resolution satellite for CNES). The race for ever-increasing image performances is now primarily focusing on a dire improvement of either the spatial or the temporal resolution, or even both of them, targeting sub-metric spatial resolution and revisit of a few hours. Besides, requests for large acquisition capacities, extended observation durations and high reactivity are now emerging.

Facing this demand, Astrium is now exploring new concepts and innovative systems for the next generation of Earth Observation Optical Systems, by way of three studies. The first two are funded by CNES, the French Space Agency, in the frame of early mission studies.

Affordable solutions for Earth Observation optical missions offering very high spatial resolution (20cm-35cm) should overcome numerous technical constraints: the development of large telescopes with high stability or with active optics, the implementation of large focal planes and the handling of large on-board data volumes. This is the subject of the ARCTOS study funded by CNES.

Regarding temporal aspects, Astrium is exploring alternatives to classical Low Earth Orbits that are limited both in revisit intervals and persistence of observation. Through the HRT study ("Haute Revisite Temporelle") led by CNES, innovative orbits have been investigated to maximise the temporal resolution with a single satellite or a small constellation of satellites. These orbits necessarily induce constraints of their own (e.g. high radiation doses) that are assessed in this article.

Astrium is also addressing persistency of observation and high reactivity by proposing GO3S (Geostationary Observation Space Surveillance System) operated from the geostationary orbit. The satellite provides on demand video and images of any point of the area of visibility in quasi real time. This high resolution video capability combined with the persistent observation open the way to numerous new applications.

I. EXPECTED EVOLUTIONS FOR THE NEXT GENERATION OF EARTH OBSERVATION SYSTEMS

Facing the demand for ever-increasing image performances in terms of spatial or temporal resolution, future Earth Observation optical systems are challenged with the definition of either new satellite concepts or innovative orbits.

The last decade has seen an increased interest in sub-metric satellite imagery for a variety of applications including urban mapping, coastal analysis, security and defence. Systems in Low Earth Orbits, with altitudes ranging from 480 km up to 800 km are well adapted to high spatial resolutions and daily acquisitions. As can be seen in Table I, the trend is now to provide images with a resolution better than 50 cm.

	Launch	Altitude	Spatial resolution	Swath
Ikonos	1999	681km	0.82m	11.3km
Quickbird-2	2001	482km	0.65m	18km
Worldview-1	2007	496km	0.50m	17.7km
GeoEye-1	2008	681km	0.41m	15.2km
Worldview-2	2009	770km	0.46m	16.4km
Pléiades 1A/ 1B	2011/ 2012	694km	0.70m	20km

Table I: Earth Observation Optical systems survey over the last decade.

Cartography applications now require regular updates of land and urban mapping, which results in the need for satellites with large acquisition capacities. Combining high resolution with extended acquisition capacity will have a significant impact on the volume of on-board data and on the data transmission capacity as presented in section II.

A requirement for High Temporal Revisit, down to one or a few hours, has emerged for various applications such as the observation of continental surfaces, ocean colour, atmospheric chemistry, defence and security and risk management.

Classical Low Earth sun-synchronous Orbits are well suited for high spatial resolution but not for high temporal resolution. Increasing the number of satellites to form a constellation is the only solution to improve the revisit in LEO. Considering Medium Earth Orbits (MEO) or geostationary orbits can be an interesting alternative to a constellation of satellites in LEO. This is investigated and presented in section III.

Requests for extended observation durations (up to a 1 hour or more) and high reactivity (a few hours) are now emerging. The notion of persistency (duration of observation over an area) paves the way to a new acquisition mode of the instrument: real-time video imagery.

II. HIGH SPATIAL RESOLUTION

The ARCTOS phase 0 study, led by CNES, aims at investigating affordable solutions for future Earth Observation optical missions offering very high spatial resolution (20cm-35cm). The principal applications include cartography and risk management, as well as coastal analysis and urban mapping. The horizon targeted for such mission is 2021-2022.

III.I ARCTOS mission key drivers

The 20cm-35cm spatial resolution target is definitely a key driver of the ARCTOS system and leads to several technical constraints to overcome.

Instrument sizing

Combined with the orbit altitude, the spatial resolution drives the size of the telescope, the complexity of the instrument and hence the mass and class of the satellite.

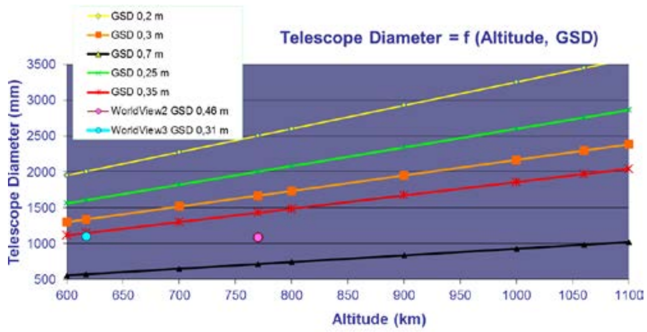

Fig. I: Telescope dimensions vs. orbit altitude and resolution (Ground Sampling Distance).

As shown in Figure I, resolutions in the range of 20-30 cm impose the development of large telescopes.

This is possible with the current Silicon Carbide (SiC) ceramic technology supported by Astrium. The development of this technology for space telescopes was started by Astrium and Boostec about 20 years ago. To date, more than 150 SiC mirrors and structural part have been manufactured and tested for space applications, including the largest worldwide space telescope developed by Astrium for the ESA Herschel mission, in orbit since 2009. The Herschel telescope is all SiC-made, with a primary mirror of 3.5m diameter.

Monolithic light weighted telescope is well suited for telescopes up to 1.5-2 meter remote sensing instrument. For larger telescopes, active optics can be implemented to compensate for in-orbit thermoelastic distortions and to alleviate the calibration and integration process (without having to develop large Optical Ground Support Equipment). The principle of active optics or active WFE (Wave Front Error) control is to use a small deformable mirror located in an intermediate pupil. Ceramic mirrors and structures have become extremely attractive for this opto-mechanical application requiring high precision and light weight.

Line of Sight Stability

Line of Sight (LOS) stability needs are directly related to the resolution-altitude ratio. Given the resolutions targeted, the LOS stability is expected to be 2 to 3 times more stringent than current system (e.g.

Pléiades). However, the knowledge of Pléiades on-board performances and prediction models is valuable and sufficient margins have been demonstrated in orbit so far to encompass greater stability needs.

Implementation of large focal planes

The ratio swath /resolution drives the number of pixels per line, hence the size of the focal plane. Aiming for resolutions below 0.35m will imply the implementation of large focal planes, especially if the system requires a large swath (see ARCTOS expectations in Table II).

This will have direct impact on the detection architecture, the layout of the focal plane and thermal aspects.

	Swath	Spatial resolution	Number of pixels/line
Pléiades 1A/ 1B	20km	0.70m	30000
SPOT 6&7	60km	2.20m	28000
Worldview-2	13.1km	0.31m	42260
Future expectations (ARCTOS)	20km	0.20m 0.35m	100000 57140

Table II: Evolution of the number of pixels per line.

Large on-board data volumes

The handling of large on-board data volumes is also a direct consequence of the high resolution. Expected volumes of a few to tens of Tbits will require both higher transmission capacity and an extended ground station network.

III.II ARCTOS system overview and performance

System overview

The spacecraft is flying on a sun synchronous orbit in the range 700-1000 km. A nadir spatial resolution in the range of 20cm-30cm and a field of view of 20km have been specified for the study. A +/- 50° off-nadir pointing capability is provided by the satellite to allow for event monitoring remote targets, as well as stereo imaging, in a single orbital pass.

In the configuration of the study, the ground segment is based on the future CNES multi-mission ground network consisting of five S-Band and X-Band ground stations.

Satellite overview

The instrument is based on a highly stable monolithic Silicon Carbide telescope. For resolutions of 20cm, requiring a larger telescope of the order of 2 meters, the implementation of active Wave Front Error (WFE) control is recommended. The optical solution chosen for the telescope is a Korsch type combination.

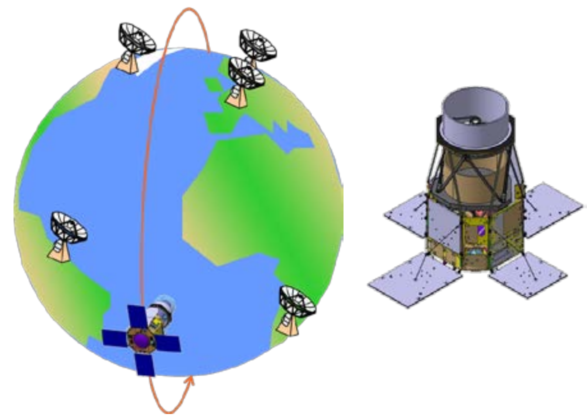

Fig. II: View of the ARCTOS system and satellite.

The spacecraft in 3-axis stabilised. Line of Sight (LOS) stability requirements (down to a few tens of µrad) are fulfilled thanks to Astrium Astrosat 250 AOCS (Attitude and Orbit Control Subsystem).

Agility performance is ensured by Astrium owned high capacity actuators.

The transmission subsystem is based on the next X-Band solution being studied by CNES, including a high gain steerable antenna, and capable of 2Gbps-downlink in dual polarisation.

Mission Performance

The ARCTOS system offers a 20-30cm Ground Sampling Distance (GSD). 30cm (at 700km) is the utmost resolution achievable with a monolithic telescope compatible with Vega launcher fairing. For a 20cm resolution, the Ariane 6 launcher is foreseen.

With its enhanced agility, the system can offer very high acquisition capacity exceeding ARCTOS' primary objective of 350 000 km² per day (corresponding to a mapping of emerged lands every 3 years).

If the satellite operates in a "paintbrush mode", i.e. sweeping back and forth to collect large areas of images in a single pass, an acquisition capacity of up to 700 000 km² per day is foreseen (for a 30cm GSD mission at 700km). For a higher resolution (e.g. 20cm), the acquisition capacity would drop to 350 000 km² per day due to the limitation of the downlink transmission which then becomes the bottleneck of the system, unless upgraded by various means to be studied.

Parameter	Performance
GSD (cm)	20 – 30
Swath (km)	20
Spectral range	Visible + SWIR
Acquisition capacity (km²/day)	350 000 – 700 000

Table III: ARCTOS performance summary

III. HIGH TEMPORAL RESOLUTION

III.I Emerging temporal mission requests

Revisit or temporal resolution

An analysis performed on a constellation of two to eight satellites at an altitude ranging from 600 km up to 10000 km showed that the revisit frequency increases with altitude up to about 5000 km. Beyond this point, the orbital period (3h20min) counterbalance the effect of the high altitude (see Figure III).

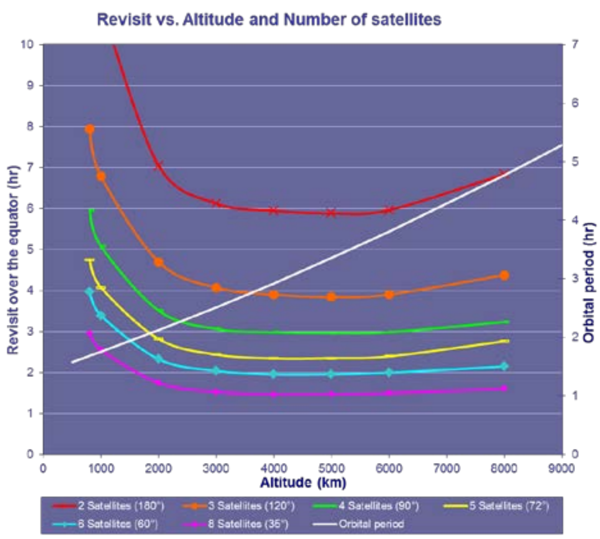

Fig. III: Revisit frequency vs. orbit altitude (the access corridor is determined by $GSD_{max}/GSD_{nadir}=2$)

Hence the benefit of flying on a Medium Earth Orbit (MEO) beyond 5000 km to improve the revisit performances is debatable. However, these orbits are appealing for the persistency of observation.

Persistency

The persistency is closely linked to the type and altitude of the orbit. Classical LEOs can only provide up to 10 minutes of persistency, but increasing the altitude of observation will extend the duration of observation. At 8000 km, a1-hour duration of observation is possible. On the high end, the geostationary orbit offers up to 12-14 hours of persistency.

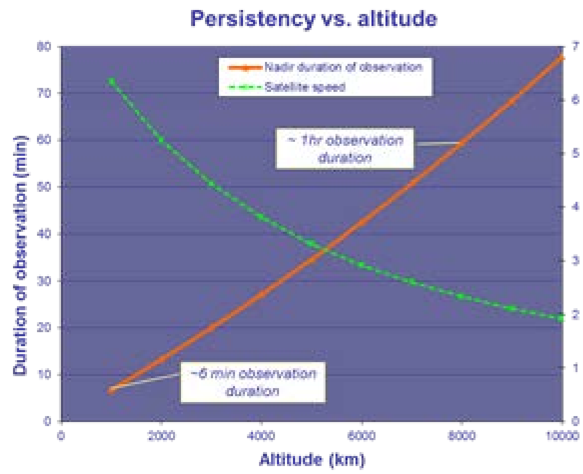

Fig. IV: Duration of observation vs. orbit altitude.

III.II HRT System

Mission description

The HRT mission (Haute Revisite Temporelle) will investigate innovative orbits providing high temporal resolutions in the 2020-2025 horizon. The system consists in one or a pair of metric imager(s) on an elliptical sun synchronous orbit (see characteristics in Table IV).

Parameter	Value
Apogee	6353 km
Perigee	1261 km
Inclination	115°
Argument of perigee	202°

Table IV: HRT orbit key parameters

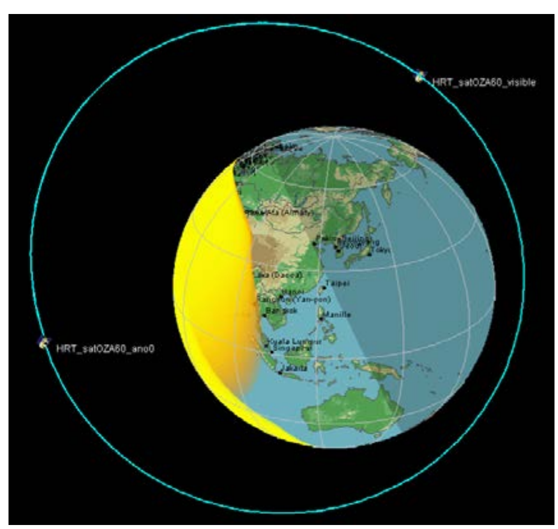

Fig. V: The HRT 2-satellite system on elliptical sun-synchronous orbit

The access corridor used to determine the temporal performance of the system is defined by an Observation Zenithal Angle (OZA) smaller than 60°.

This orbit offers an extended persistency of observation below the apogee (~20°N) and a high temporal revisit around mid-latitude regions (latitude band centered over 20°N).

One of the singular features of this orbit is the altitude and satellite velocity variation along the orbit (implies a variation of the ground sampling distance and of the field of view). An orbital section of 90 minutes (about half of the orbital period) can be dedicated to image acquisition. This segment is determined by the OZA constraint, the satellite pointing capacity and the acceptable range of altitude/velocity variation for the instrument.

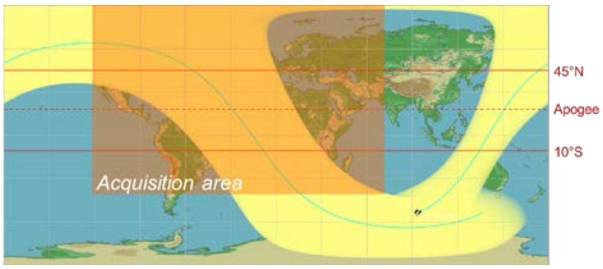

Fig. VI: Orbital section used for acquisition.

Another main characteristic is the high level of radiation doses due to the Van Allen belts, with an environment particularly severe around 6000 km for trapped protons. This will principally affect unshielded parts such as solar arrays, mirrors, lenses, etc.

Satellite overview

The instrument is based on a 3m monolithic Silicon Carbide main reflector with active optics implemented. The optical solution chosen for the telescope is a Korsch type combination.

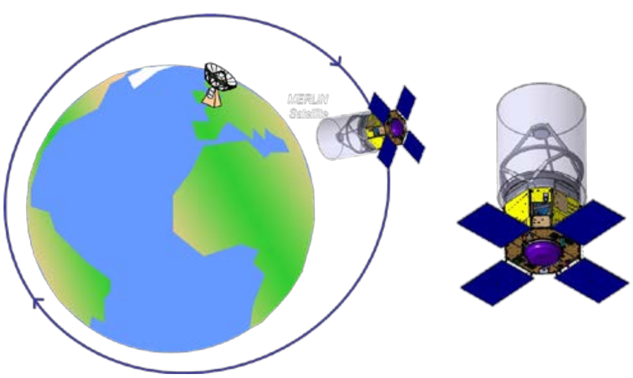

Fig. VII: View of the HRT system and satellite.

The spacecraft is 3-axis stabilised and has two acquisition modes:

- Static mode: multispectral pushbroom imagery
- Dynamic mode: step and stare video imagery

Line of Sight (LOS) stability requirements are quite stringent (down to ~10 µrad) but can be fulfilled thanks to an upgraded Astrium AOCS (Attitude and Orbit Control Subsystem). Agility performance is ensured by Astrium owned high capacity actuators.

The severity of the environment regarding radiation doses has a significant impact on the design of the satellite. Aluminium shielding is recommended on some detectors and components. Solar arrays are substantially oversized, as no shielding solution can be envisaged. The impact on the mass and satellite inertias is important.

Mission Performance

The HRT system offers a 1-meter Ground Sampling Distance (GSD), which is achievable with a monolithic reflector compatible with Ariane-6 launcher fairing.

Revisit performances over the geographical area of interest are the following:

- 3 hours (mean)/ 6 hours (max) for a single satellite
- 1h30 (mean)/ 3h30 (max.) with two satellites

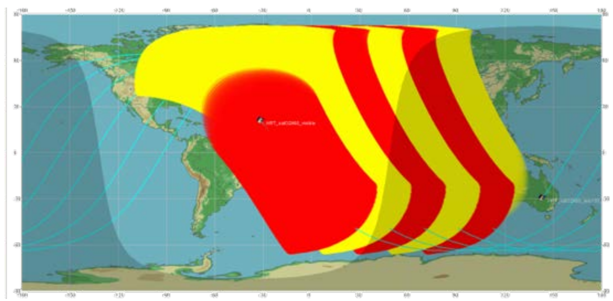

Fig. VIII: HRT 2-spacecraft system with both satellites on the same orbital plane (LTAN: 13h30), 180° apart

Persistency over the area of interest is expected to reach 30 to 45 minutes. This drives the maximum duration of a video.

The table V below summarises the HRT mission key performances.

Parameter	Performance
GSD (m)	1 (static) / 3 (video)
Swath (km)	50 (static) / 10 (video)
Spectral range	Visible
Mean revisit interval (hr)	3 (1 S/L) / 1h30 (2 S/L)
Persistency (min)	30 to 45

Table V: HRT performance summary

Besides the severe radiation environment, one difficulty of the mission is the launch cost of such system, which has to be deployed on a critical inclination orbit (116°).

III.III GEO3S System

System overview

Realising that the user demand and market need is evolving towards flexible, dynamic, real-time observation, Astrium has studied GO3S, the Geostationary Orbit Space Surveillance System, a concept based on optical telescope operating in a geostationary orbit, to provide global, real-time, video imagery.

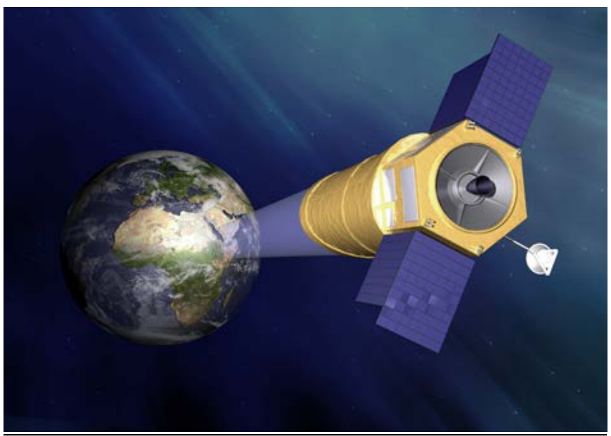

Fig. IX: GO3S artist view.

GO3S aims at offering maximum persistency and reactivity to earth observation users:

- **Persistency**: From the geostationary orbit, the system will offers permanent real-time access to any zone in its area of visibility and will be able to acquire dynamic scenes or videos over the selected zone for as long as needed.

- **Reactivity**: With high agility, real time programming and downlink capacities, GO3S is freed from the time dependence that constrained the traditional Low Earth Orbit optical system and any zone in its area of visibility can be observed with very short notice.

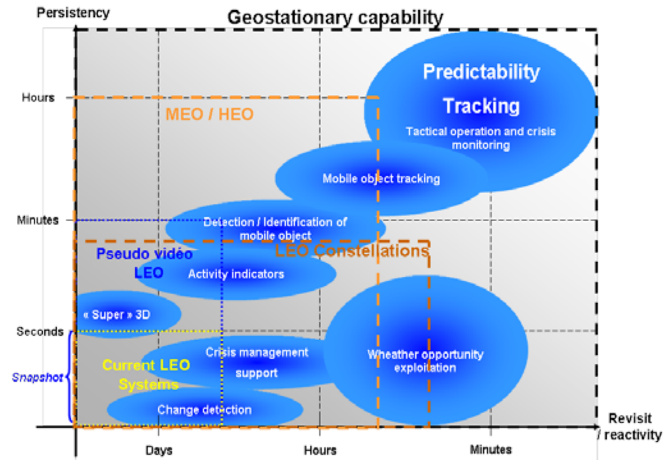

Fig. X: Comparison of Low Earth, Medium Earth, Highly elliptical and geostationary orbits. Geostationary orbit offers maximum persistency and reactivity.

The GO3S concept is a system bringing new capacity on the market, to complement existing data available from traditional low Earth orbiting satellites, with four types of products:

- Sustained video: Flexible duration live video at 5Hz.

- Time Lapse : Repetitive acquisitions at the desired frequency of a scene for change detection or activity monitoring

- Burst: Dynamic image of a scene combining background and moving target detection with mobile size and kinetic properties assessment (velocity, heading).

- Mosaics: Large area fast mapping with dynamic image acquisition.

Innovative applications

With these products and based on a flexible operational concept including real time system programming, GO3S meets a wide range of civilian, military and security needs:

- Strategic and economic Intelligence with on demand and flexible revisit capabilities of the points of interests.

- Disaster management with active, real-time monitoring. System strong reactivity allows any event to be monitored from its very first stage which is a key asset for disaster management. Dynamics and video information bring a significant add-value versus static imagery. They improve situation knowledge and can directly be used to support operation.

- Hot spot monitoring. Advanced applications such as automatic target tracking, or specific area monitoring (Fencing) are possible thanks to moving target detection.

- Maritime surveillance with both coastal and deep-sea monitoring. A silent radar-like mode is available thanks to moving target detection and kinematics estimation. Deep sea monitoring will benefit from the wide acquisition capacities through mosaics products.

- Military operations for strategic and dynamic support. Thanks to its instantaneous access and its sustainable and real-time sensing capability, GO3S will enable operations support not only for operation preparation but also during and after execution through real time monitoring.

- Media, web-based with live coverage on demand.

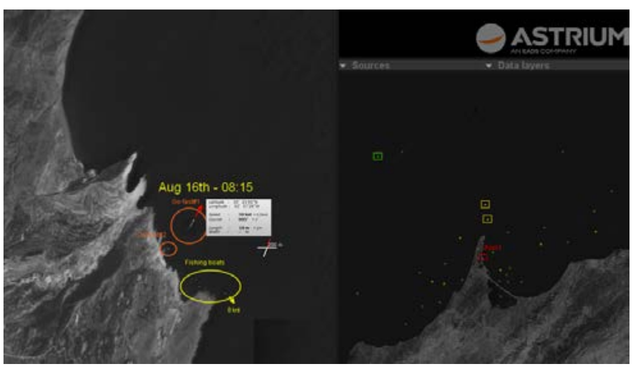

Fig. XI: Maritime surveillance. Automatic moving target tracking. Velocity and heading estimation (full field of view right and zoom left).

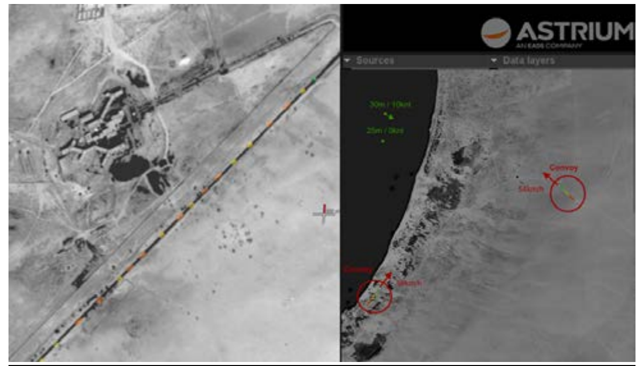

Fig. XII: Military operation support: Convoy detection and air strike real time monitoring (full field of view right and zoom left).

System performances

The GO3S system offers a 3m Ground Sampling Distance (GSD). It is the ultimate resolution that can be achieved with a monolithic telescope compatible with the current largest launcher fairing such as Ariane 5. Such a resolution is necessary to ensure efficient terrestrial moving target detection for middle latitude scene.

The accessible zone, for a maximum degradation of the mean GSD by a factor 2, correspond to 28% of the earth surface and extend up to 64° of the Sub-Satellite point.

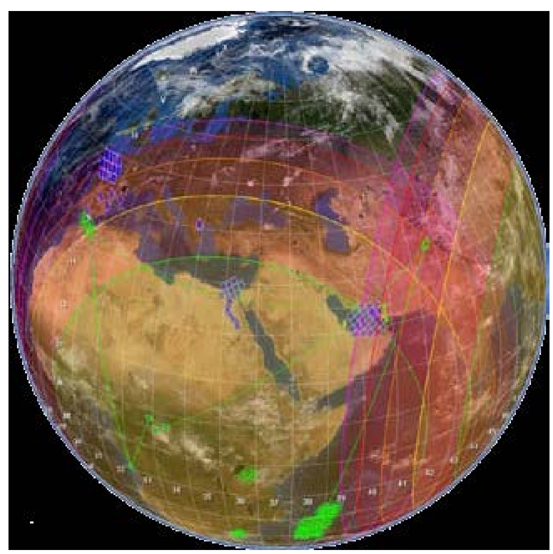

Fig. XIII: Ground Coverage of the GO3S system.

Combining a large 100km x 100km Field of View, a long daily observation period (up to 14h) and an optimised agility (average repositioning time below 3mn), the system offers very high acquisition capacity.

The system will, for instance, be able to map France in less than 45mm or the whole Africa in less than 2 days.

Parameter	Performance
GSD (m)	3
Swath (km^2)	100 x 100
Spectral range	Visible
Video rate (Hz)	5
Background merit factor	32 @ $60 W/m^2/st/\mu m$

Table VI: GO3S performance summary

Satellite overview

GO3S satellite benefits form the last innovations in the space-borne optical observation domain. It takes advantage of advanced technologies developed by Astrium for past and on-going science missions like the Herschel telescope, Gaia or Euclid as well as from Astrium's internal research and development dedicated programs carried out over almost 10 years [1].

The instrument is based on a 4-meter monolithic Silicon Carbide reflector, implementing active Wave Front Error (WFE) control and CMOS ultra wide detectors matrixes.

Line of Sight (LOS) stringent stability requirements (down to a few tens of nanorad) are fulfilled thanks to embedded LOS correlation sensing and proportional cold gas actuators.

Agility performance is ensured by Astrium owned high capacity actuators

Mobiles detection, image quality enhancement and data reduction is achieved with advanced on board video algorithms performing real time registration, fusion, moving target detection and compression.

Astrium's system and prime contractor experience in large Earth observation and scientific missions is key for the technical realisation of the GO3S system. The combination of Astrium agile platforms used for the latest low Earth observation systems, new generation detectors and large silicon carbide mirror expertise developed in the frame of scientific missions makes the GO3S system development possible within short time frame, and an operational system can be envisaged from 2022.