SPACE-BASED SPACE SURVEILLANCE OPERATIONAL AND DEMONSTRATION MISSIONS

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ABSTRACT

GMV is currently leading, under ESA contract, an assessment study to define a demonstration mission for space-based space surveillance. The project team includes QinetiQ Space as responsible for the platform and RAL Space for the payload activities.

During the first phase of the study a high-level definition of a future operational mission has been carried out including the definition of user requirements for a future Space Based Space Surveillance (SBSS) service.

During the second phase of the study a precursor mission to demonstrate the SBSS operational needs has been defined.

The present paper presents the results of both phases, including architectures definition and expected performances.

1 OPERATIONAL MISSION USER REQUIREMENTS

The user requirements were derived based on the experience of the team in different SSA projects, being the starting point of the operational mission definition. The most relevant implications of the user requirements discussed and agreed with ESA were related to the priority assigned to the space surveillance in the geosynchronous orbit (GEO) region. The SBSS operational system shall be used for the observation of objects beyond low Earth orbit (LEO) both in surveillance and tracking mode, but priority shall be granted to the GEO region. That is, objects in medium Earth orbit (MEO), geosynchronous transfer orbit (GTO) and high elliptical orbits (HEO) shall be observed as well. NEO objects shall be able to be observed as well during nominal and ad-hoc observation campaigns.

In the GEO region, objects larger than 70cm shall be observed and pre catalogued in less than 72 hours. Once pre catalogued, they should become part of the full catalogue in less than 3 days. The system shall provide revisit times shorter than 72 hours for catalogued objects. In order to include a detected object in the catalogue, the accuracy envelope shall be better than 2.5km. These requirements shall be achieved by the SBSS operational system in conjunction with the ground based segment of the SST (Space Surveillance and Tracking) system that would be also available in the future.

In terms of reactiveness, the system shall be able to fulfil a tracking request for any GEO “catalogued” or “pre-catalogued” object before 48 hours after the request is issued. This requires that the space segment shall be able to be re-planned or re-programmed in less than 24 hours to accommodate the active tracking request. During planned operations, the system shall have autonomy of 7 days.

Finally, the system shall be available the 90% of the lifetime once the system becomes operational. In terms of lifetime, 50 years have been initially defined, which implies that the space segment will have to be replaced in a regular basis. Each spacecraft shall be designed for a target lifetime of 7 years.

2 SBSS OPERATIONAL MISSION

2.1. Architecture

Different architectures of operational SBSS missions have been evaluated and several trade-offs have been performed to determine which solution fulfils better the user requirements with reduced cost and minimising the technological risk. One of the key decisions to be taken in has been the selection of the number of spacecraft composing the constellation.

Different requirements and restrictions (required accuracy in the target orbit determination, need of cataloguing all objects in the GEO region, affordable telescope field of view, platform agility…) led to the definition of the system.

The proposed SBSS operational system is composed of a constellation of 4 spacecraft placed at the same dawn-dusk (local time of the ascending node at 6:00 AM) sun synchronous orbit (SSO) at 888.3 km of altitude and 98.91 degrees of inclination. Dawn dusk orbit provides

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the best illumination conditions for the detection of objects in the GEO ring while providing a stable thermal and power generation environment for the platform. The altitude is selected so that the earth does not interfere with the field of view (FOV) of the instrument in any of the observation configurations and the orbital period is such that the movement of GEO objects and the movement of the SBSS spacecraft is synchronised (integer number of orbits per day).

The satellites will be equally spaced in this orbit, separated by 90 deg in true anomaly and work in pairs separated by 180 degrees. The four satellites will be launched in a single VEGA launch using a modified VESPA multipayload adapter.

Three of the satellites will be devoted to the continuous surveillance of the GEO ring, scanning four stripes (fixed right ascension, declination between -18/18 degrees) located at +/-15 degrees and +/- 38.5 degrees with respect to the Sun-Earth direction, opposite to the Sun. The first couple of satellites, separated 180 degrees in true anomaly, will scan the stripes at +/-15 deg. The third spacecraft will scan alternatively the stripe at + and – 38.5 deg. The fourth spacecraft will share the surveillance tasks (complement the third spacecraft) with the response to active tracking requests from ground segment.

The data processing will be shared between the space and the ground segment. Detection of candidates for being classified as objects will be performed on board to reduce the required communications data rate while object identification, correlation and orbit determination will be carried out on ground. The SBSS ground segment will interface directly with the SST user segment.

2.2. Observation strategy

In order to provide enough data for the orbit determination process, an object in the GEO ring shall be observed in different positions along its orbit during at least three days. A trade-off has been performed taking into account the detectability, orbit determination performances and tasking to determine the location in the orbit in which the target should be observed. Two points at +/- 15deg with respect to the anti-sun direction and a third one at +/-38.5 deg where found out to be the best compromise. A fourth measurement at +/-38.5 deg could be provided if the fourth spacecraft is not performing active tracking tasks. It is not strictly needed but if available, it will improve the system performances. In order to survey all the objects in the GEO ring, a declination stripe is defined on those locations, expanding from -18 deg to +18deg.

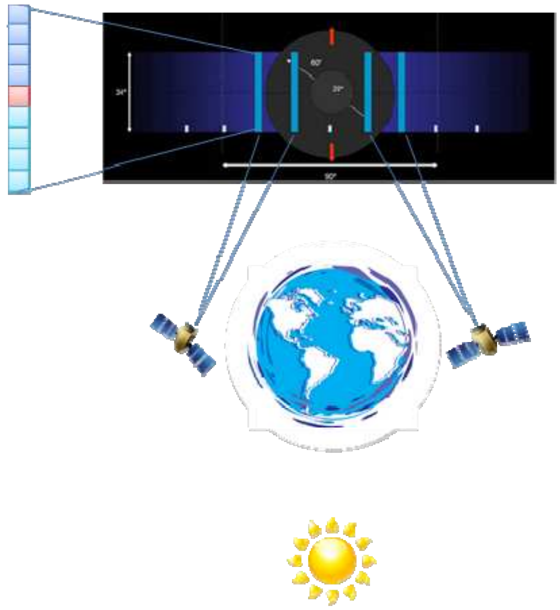

Figure 1: Observation strategy

The observation strategy consists of the quick scanning of the four declination stripes, changing the pointing of the spacecraft approximately every minute to place the FOV (4x4 degrees) at different declination. Each declination stripe is divided in 9 fields equal to the extent of the FOV. The declination stripe is covered 4 times every half orbit, changing the spacecraft the target stripe to the symmetrical one every time it crosses the polar region (so that the illumination conditions are optimised and it is avoided that the Earth enters in the FOV of the payload).

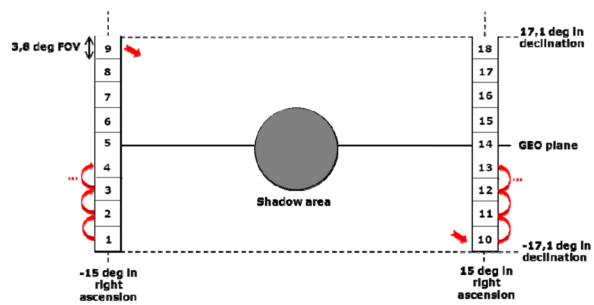

Figure 2: Strategy of pointing dividing the strip in 9 fields

This strategy has been designed to avoid that an object could be missed and cross the stripe being undetected (leak proof). The time allocated to the scanning of a stripe is set so that a GEO object will not completely cross the stripe width during the scanning period. Each field will be observed during almost one minute, which will enable the acquisition of at least 5 images.

Each spacecraft will acquire at least 360 images per orbit (over five thousand per day). This fact drives the need to perform some image processing on board to reduce the size of the required communications link with ground.

This observation strategy implies that the spacecraft will have to perform frequent pointing manoeuvres: change from field to field (4 degrees), re-scanning the declination stripe (32 degrees), changing to the symmetrical stripe (up to 77 degress+32 degrees). The manoeuvre times and tranquilisation times have been taken into account in the definition of the observation strategy. Four more manoeuvres of 90 deg around the Line of Sight (LoS) have been also defined to homogenise the thermal environment along a single orbit.

2.3. Payload

Table 1 below shows the key parameters of the payload. A SNR of at least 4 is required for detection of a 0.7 m object in GEO. The telescope that is defined for the mission has a square FOV of 4° x 4° and an aperture of 350 mm. It includes a detector of 4k x 4k elements, giving a plate scale of 3.5 arcsec per pixel. To avoid the sky background swamping the signal, the exposure time must be limited to the time taken for an object to cross one pixel, with the object track being reconstructed from a series of consecutive images. For a typical GEO object the pixel crossing time is 0.23 s. To meet the observation strategy, an image must be acquired every 5 seconds, implying a read-out rate of 0.8 Mpixels / s if the pixels are read out through 4 parallel ports.

Table 1: Key parameters of the payload

SNR (0.7m object in GEO)	Min 4
Entrance pupil diameter	350 mm
Field of view	4° x 4° (square, full angle)
No. pixels	4k x 4k
Exposure time	0.23 s (= one pixel crossing)
Plate scale	3.5 “/pixel
Read out rate	0.8 M pix / s (one image / 5s)

A radiometric model has been developed to estimate signal and noise levels, accounting for contributions from the sky background (mainly Zodical light), detector read and dark noise, stray light noise (with contributions from celestial objects and the Earth) and shot noise.

Figure 3 below shows how the noise sources and SNR vary with telescope aperture. Each of the noise sources is estimated in terms of the number of signal electrons per pixel per 0.23 s exposure. An aperture of 350 mm is selected as being the smallest aperture still giving an SNR greater than 4.

The telescope optical design, selected after an extensive trade-off, is a Ritchey–Chrétien telescope with a three-element refractive field flattener. Figure 4 shows a cross section through the telescope. A baffle arrangement has been developed and analysed for stray light performance, with the results feeding into the SNR model.

The telescope structure is made from carbon fibre re-enforced plastic in order to maximise stability while minimising mass. The mirrors are made from Zerodur and light-weighting techniques are applied to reduce their mass. The telescope is equipped with a door in order to maintain cleanliness; in the open position the door also acts as baffle for stray light from the Earth. A piezo-electrically driven focus mechanism, actuating the detector, is included to allow re-focussing on orbit.

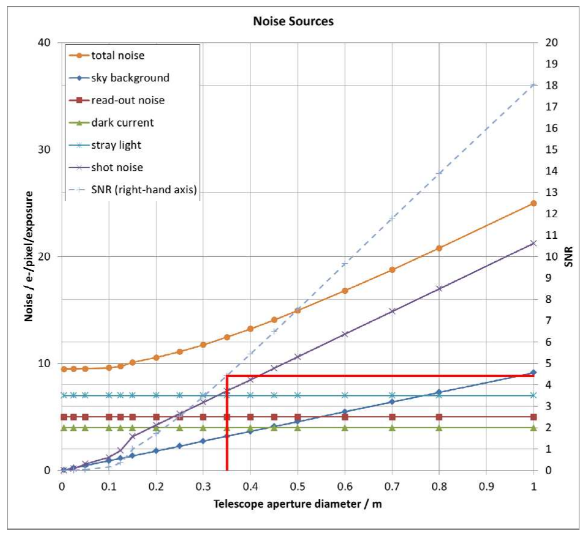

Figure 3: SNR and noise sources versus telescope aperture. The bold red line shows the SNR at an aperture of 350 mm.

The thermal design uses passive cooling via a radiator to maintain the detectors at the required temperature of about -40°C. The whole telescope is allowed to ‘run cold’ (i.e. no attempt is made to warm it to close to room temperature) in order to minimise heater power. A small amount of operational heating is applied as required to minimise thermal gradients across the diameter of the telescope tube, which would otherwise tilt the mirrors. The operational temperature of the structure is around -50°C, and the refocus mechanism is used to compensate for the resulting focus shift between on-ground room-temperature alignment and operation. Heaters are also provided for survival and decontamination.

The detector is a custom CMOS detector. CMOS is chosen over a CCD because of the absence of frameshift smear, its greater radiation tolerance, its lower power consumption and simpler read-out electronics. A CMOS detector can provide the required noise performance as long as some dynamic range is sacrificed compared to a CCD. Given that, even for a debris object of 10m, the signal is no more than about 10,000 electrons, this is an acceptable trade. The detector front end electronics, housed in a separate electronics box, drive the detector and read out the image data, passing it to a SpaceWire interface, over which the payload is also commanded.

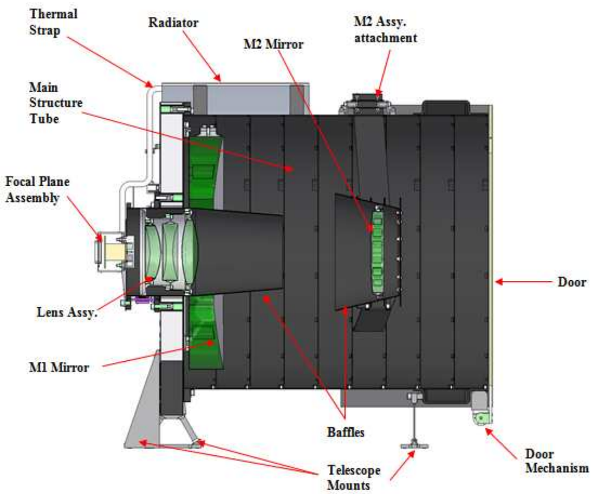

Figure 4: Cross section through the payload

2.4. Platform

The platform design is based on heritage from ESA's PROBA family [1-4], developed by QinetiQ Space. Some adaptations are necessary to accommodate the relatively large payload.

The PROBA1 and PROBA-V (Vegetation) spacecraft are earth imaging satellites, while PROBA2 is observing the sun. In terms of orbit and attitude, the SBSS spacecraft will be closest to PROBA2. PROBA1 and PROBA2 are in operation for respectively 12 and 3 years and are still working perfectly. PROBA-V is to be launched in Q2 2013.

Such as its predecessors, the SBSS will be an accurate and agile platform, allowing to meet the pointing requirements and to perform frequent scanning manoeuvres needed to change the FOV declination. During each observation period, the telescope will be pointing to the same point on the GEO region, minimising at the same time the rotation of the FOV around the LOS direction. Four 90° manoeuvres per orbit (two of them matching the polar manoeuvres above mentioned) will be performed to improve the S/C thermal conditions and to avoid star tracker blinding by the earth (see Figure 5).

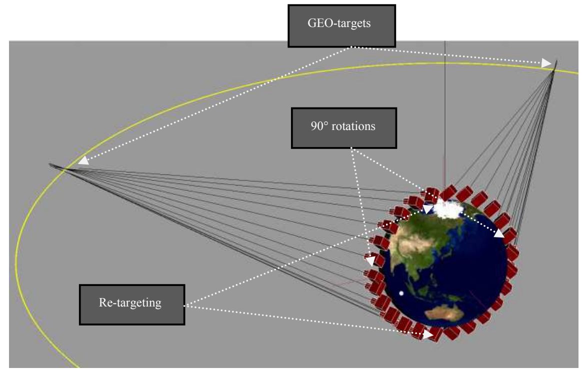

Figure 5: S/C attitude over one orbit, with GEO targets at 38.5° sun illumination

The SBSS platform is represented in Figure 6 and Figure 7. It has a mass of about 170kg for dimensions of about 1.4mx0.9mx0.9m. Three body-mounted solar panels will provide power to the bus and the payload, while the Advanced Data and Power Management System (ADPMS), will take care of the power conditioning and distribution. Depending on the observed GEO-target and the presence of eclipses (in Winter time) the platform will deliver between 160W and 200W average power. The ADPMS, developed by QinetiQ Space, also serves as on-board computer, it hosts a LEON2-processor. The ADPMS will host the mission software and be in charge of main operations, but a dedicated electronic unit will be implemented to perform the on board image processing tasks and interface between the payload and the computer.

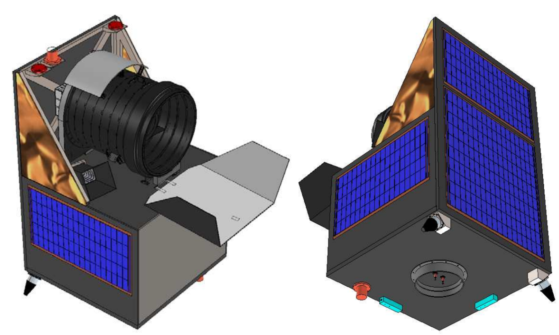

Figure 6: SBSS platform with telescope (external view)

The on-board attitude estimation is based on the use of a star tracker and an extended attitude Kalman filter (i.e. it is gyroless). Two star tracker heads are used to guarantee high performance along all directions. In order to achieve the high pointing accuracy and stability, a perturbation observer is implemented, which allows to estimate and compensate the effect of the spacecraft's remanent magnetic moment. The attitude control is performed by means of reaction wheels. Four wheels are accommodated in a tetrahedron configuration to provide redundancy. Two attitude controllers are used: a sliding mode controller for large manoeuvres and a state-feedback controller for the fine pointing. In order to avoid saturation of the reaction wheels by environmental perturbations, a momentum management controller is added based on magnetotorquers and magnetometers.

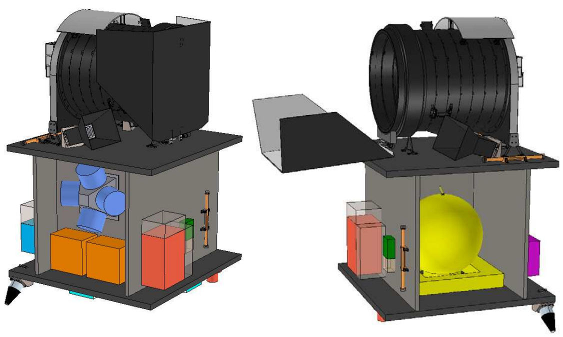

Figure 7: SBSS platform with telescope (internal view)

The AOCS software adds much flexibility for the execution of large manoeuvres, which is especially useful for tracking NEO. The guidance module indeed offers the possibility to autonomously determine attitude profiles that will avoid star tracker blinding by earth and moon.

The SBSS platform also accommodates a 1N (HPGP) propulsion system. About 140m/s of propellant will be needed in order to correct for launch injection errors, to perform orbit maintenance, for collision avoidance and finally to de-orbit the spacecraft at end-of-life (which requires over 75% of the total ΔV capabilities of the spacecraft).

An S-band communication system is used for uplink to the spacecraft and for downlink of housekeeping telemetry. The S-band antennas are accommodated such as to guarantee omni-directional coverage throughout the mission. Payload data is downlinked via X-band, at a rate of 33Mbps.

The thermal design is mainly passive. The payload is radiatively and conductively decoupled from the platform. Survival heaters are installed for the critical components, such as the battery, the propulsion system and payload.

A summary of the main platform characteristics is given in Table 2.

Table 2: Platform characteristics

	SBSS platform
Avionics	ADPMS (Advanced Data and Power Management System) Processor: LEON2-E (SPARC V8) Mass Memory Module : 16 Gbit (baseline), 11 GByte available Interfaces: RS422, TTC-B-01, analogue and digital status lines, Packetwire, compact PCI
Power	Solar panels: body-mounted GaAs solar cells with 28 % efficiency Battery: Li-ion, 28V, 12Ah Bus: 28V battery regulated voltage
Structure	Aluminium inner H-structure Aluminium milled bottom board CFRP outer panels with solar arrays Aluminium payload and anti-sun panels
AOCS	3-axis stabilised satellite Actuators: • 3 magnetotorquers (internally redundant) • 4 reaction wheels • 1N HPGP propulsion system Sensors: • 2 magnetometers • 2 star tracker (with 2 camera head units) • 2 GPS receivers Pointing performances: • AKE (Absolute Knowledge Error) – 4 arcsec • APE (Absolute Pointing Error) – 27 arcsec • RPE (Relative Pointing Error) – 1 arcsec over 1.5s – 5 arcsec over 60s
Communication	S-band downlink: 1Msps S-band uplink: 64ksps X-band downlink: 33Mbit/s
Software	Operating system: RTEMS Data handling/application software: based on PROBA OBSW
Thermal	Mainly passive thermal control, heaters for the battery and the payload

The spacecraft reliability is maximized by taking into account the following three drivers at all levels of the design:

- Use of redundant units & components for crucial parts of the platform (resulting in single point failure tolerant bus)
- Unit selection based on in-flight heritage
- Component selection using MIL standard components, components with flight heritage or space qualified components

The SBSS spacecraft is completely redundant spacecraft with the exception of the payload. The spacecraft bus is single point failure safe. Hot redundancy is foreseen for the S-band receivers, the star tracker cameras and certain parts of the power management in ADPMS. Cold redundancy is foreseen for the transmitters, the on-board computer and the AOCS sensors and actuators.

High levels of reliability and autonomy are also achieved by implementation of an advanced Failure Detection, Isolation and Recovery (FDIR) approach. Anomalies are handled on-board without need for ground intervention.

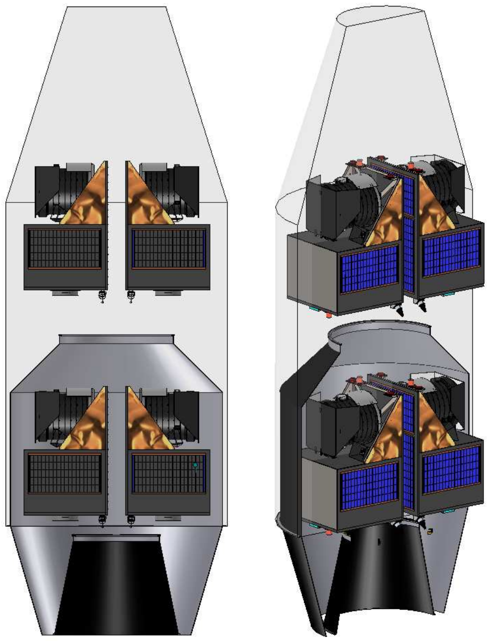

Figure 8: SBSS constellation in one VEGA launcher with adapted VESPA adapter

As mentioned earlier, the four SBSS spacecraft that would be needed to perform the mission could be launched together on one single VEGA-launcher. The VEGA Secondary Payload Adapter (VESPA) would then need some modifications to host the two bottom spacecraft cylindrical part shall be enlarged or spacecraft height reduced). But in terms of mass, VEGA will be capable of launching the 4 spacecraft in a single launch.

2.5. Data processing

Each of the satellites of the SBSS system will generate a large amount of images per orbit, at least 360 images with a size of 32Mb each. In order avoid the implementation of unnecessary high performance communication subsystems, some data processing will be performed on-board. In this way, exposure data tables and calibration images will be downloaded. Data reduction process will be performed at two different levels:

- At Exposure Level: A single scientific, time-tagged exposure is processed in order to remove instrument-dependent issues affecting the data and to provide precise and calibrated information.
- At Observation Level: The set of calibrated exposures related to an Observation Task are processed in order to identify earth orbiting objects and to provide accurate information about the position and magnitude of the identified objects.

Processing steps performed on board will be restricted to those strictly necessary to assure a fast near-real time processing of the continuous acquisition schema, and to reduce the volume of scientific data to be downlinked to the Ground Segment. The rest of the processing will be performed on ground in order to reduce the on-board computation needs (hardware), to ease the maintenance (corrective, perfective) of the processing software, to allow the supervision of the processing (if necessary), and to permit the reprocessing of the data in case new improved algorithms are available.

The image processing activities to be done on-board will cover the following tasks:

- Basic Data Reduction, including Bias Subtraction, Dark Current Subtraction and Flat Field correction.
- Cosmetic Processing, including bad pixels masking and cosmic rays removal (TBC)
- Detection process, in which candidate targets will be identified (both stars and actual targets). The detection will be based on thresholding.
- Packing and cleaning observation task data, generation of the Exposure Data Table containing a pre-defined set of data for each possible target (identifier, centroid in image coordinates, flux above the sky, …)

The Exposure data table will be downloaded to ground for further processing. This processing will include the astrometric and photometric processing (providing accurate location of each element using an Astrometric Catalogue and also providing the associated apparent magnitude). A first correlation of possible objects will also be carried out to reduce the false alarm rate, as an object should appear in at least 3 (TBC) consecutive images taken in the same field. Finally, an identification/classification process will be run prior to the generation of the data processing output to be sent to the SST user segment.

2.6. Ground Segment

The SBSS operational mission will reuse the user segment of the SSA system, offering the same final interface to the user. Therefore the products of the SBSS operational mission will be the detection products. These products will be fed to the SSA user segment for correlation and final build up and maintenance of the catalogue. The SBSS mission will also interface with the SSA system to accept active tracing request.

The main components of the SBSS operational mission ground segment will be:

- Ground station, preliminarily selected at Kiruna. It provides enough visibility to download the payload data on a regular basis (only 4 blind orbits per day) and to update the satellites tasking with enough time to respond to active tracking requests (the requirement is to be able to respond to these requests in less than 48 hr, no tough requirement has been imposed to data timeliness).

- Flight Operation Segment (FOS), containing the spacecraft monitoring and control, flight dynamics, mission planning, data acquisition and external data acquisition functions.

- Payload Data Ground Segment (PDGS), containing the data processing, calibration and validation, archive and cataloguing, dissemination, and performance monitoring functions.

2.7. Performances

The performances of the system have been evaluated using software developed by GMV for previous ESA SSA activities. The SBSS architecture is built in the simulator which is fed with a reference object population generated with MASTER 2009 and extrapolated for the epoch 2040. The population contains objects as small as 1cm.

Several simulations have been run for different epochs to take into account the effect of the illumination conditions long the year. The effect of the events of Moon and/or Jupiter entering or being close to the FOV has not been included. In the case of Jupiter, no impact is expected at operational level since the exclusion angle is only 3deg (it will never blind two of the four declination stripes defined at the same time). In the case of the Moon, if nothing is done, up to 8% of operational time could be lost, but in this case the declination stripes could be moved at the same pave of the Moon to avoid the blinding of two consecutive stripes at the same time.

The results of the simulations are summarised in the following table. The results are based on 14 days of simulation, neglecting the data of the first 4 days for cataloguing purposes.

Table 3: SBSS operational system performances

Detectability	Low MEO	High MEO	GEO	HEO
Spring Equinox	40.7%	60.4%	99.3%	73.5%
Summer Solstice	51.1%	76.6%	99.5%	69.9%
Winter Solstice	53.4%	78.7%	99.1%	71.6%

Pre-Cataloguing	Low MEO	High MEO	GEO	HEO
Spring Equinox	0.0%	9.8%	98.1%	6.8%
Summer Solstice	0.4%	12.8%	97.9%	7.7%
Winter Solstice	1.2%	15.1%	97.9%	7.7%

Cataloguing	Low MEO	High MEO	GEO	HEO
Spring Equinox	0.0%	6.2%	94.7%	3.7%
Summer Solstice	0.0%	7.7%	90.0%	4.5%
Winter Solstice	0.1%	6.4%	94.1%	4.3%

As can be seen, the performances are maximised for the detection and cataloguing of GEO objects, as initially requested. Indeed, a full catalogue can be built in less than 2 weeks. For the other orbital regimes the performances are pretty low in terms of cataloguing, but quite good in terms of detection. In order to improve the situation, specific observation strategy could be envisaged for the fourth satellite.

3 SBSS DEMONSTRATION MISSION

The second part of the study has been devoted to the definition of a SBSS demo mission. It would be flown in advance of the full scale operational mission in order to reduce the technological and programmatical risks associated to an operational mission of these characteristics. The main objective of the demo mission is to demonstrate the system performances, mainly in terms of detectability and cataloguing. Therefore the main characteristics of the payload shall be replicated as well as the payload supporting services, like platform agility.

Initial trade-offs identified possible de-scopes at both payload and platform level, but after a cost analysis it was demonstrated that the loss of representativeness did not compensate the cost reductions for the demo mission. Therefore the demo mission will consist of a single spacecraft almost identical to the one of the operational mission.

The spacecraft will be injected in the same orbit as the spacecraft of the operational mission. This will ensure that the observation geometry is maintained and will open the possibility of using this first spacecraft as a component of the operational system.

The same observation strategy as the one followed by each operational spacecraft will be exercised and new strategies will be implemented to be able to demonstrate the detectability performances during different epochs along one year. In this way the exact illumination conditions will be replicated.

In order to demonstrate the cataloguing performances, specific observation strategies have to be designed. With a single spacecraft it is not possible to define a leak proof strategy for the GEO region (a minimum of two spacecraft are required for detection of all GEO objects and three for cataloguing purposes).

Therefore the focus has been set in observing a subset of the GEO population in such a way that three different observations can be obtained per day (requirement to achieve cataloguing performances). The first strategy consists in scanning declination stripes at +38.5 deg, +15deg and -15 deg in a synchronised way with respect to the movement of a GEO object along a day. With this strategy it is not possible to avoid that the Earth enters the FoV of the instrument at some points, and therefore the achieved cataloguing performances are not very high, although it is the most representative strategy.

A second strategy has been designed in which three declination stripes are observed at +45deg and +/-19deg. Each stripe will be swept four times in half the satellite´s period, and it will change to a different stripe in the Earth´s poles. In this strategy, the detectability becomes slightly worst due to the illumination conditions, but it provides a more systematic observation for cataloguing purposes.

The performances obtained by such strategy are summarised in *Figure 9* where the results for the full SBSS operational mission have been included as well for comparison purposes. In terms of detection, the performances of the system are comparable to those of the operational system, a slight difference of 10% is observed in all regimes. When having a look at the temporal evolution of the detections, it can be seen that if the duration observation campaign is enlarged, the final performances in terms of detectability of the Demo mission will be almost equal to the ones of the operational mission in the GEO region, with a small difference due to the illumination conditions.

In terms of cataloguing performances, obviously the demo mission does not manage to catalogue more than 15% of the objects in the GEO regime and nothing in the other regimes.

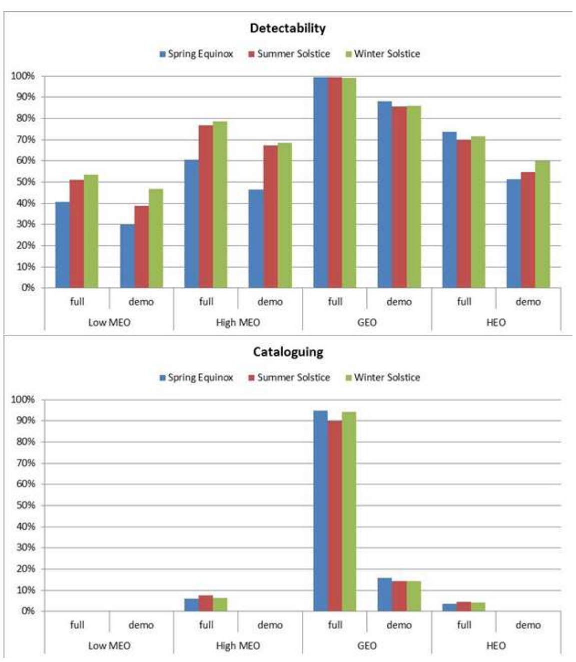

Figure 9: SBSS demo mission performances

4 CONCLUSIONS

A full scale operational SBSS system has been defined based on a constellation of 4 small spacecraft (based on an existing platform like PROBA) carrying a medium size optical telescope. The performances of the system fulfil the user requirements both in terms of detectability performances, cataloguing performances and responsiveness.
In a second phase of the study, a demonstration mission has been defined that would mitigate the risks of the full operational system by demonstrating the most critical aspects of the full SBSS operational mission. This mission is fully representative (except in the number of spacecraft) of the operational one and in line with typical ESA IOD requirements

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