ON THE STUDY OF THE SPACE ENVIRONMENT: A TEST-BED CONFIGURATION

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ABSTRACT

In the context of the Space Situational Awareness (SSA) programme of ESA, it is foreseen to deploy several large robotic telescopes in remote locations to provide surveillance and tracking services for man-made as well as natural near-Earth objects (NEOs). The present project will implement a test-bed for the validation of an autonomous optical observing system in a realistic scenario, consisting of two telescopes located in Spain and Australia, to collect representative test data for precursor SSA services.

It is foreseen that this test-bed environment will be used to validate future prototype software systems as well as to evaluate remote monitoring and control techniques. The test-bed system will be capable to deliver astrometric and photometric data of the observed objects in near real-time. This contribution describes the current status of the project.

1 INTRODUCTION

The purpose of the SSA programme is to provide an independent capability to acquire prompt and precise information regarding objects orbiting the Earth. Using this data, a wide range of services will be provided – such as warning of potential collisions between these objects or alerting when and where debris re-enters the Earth's atmosphere. These data will be stored in a catalogue, made available to SSA customers across Europe. The infrastructure required to provide these capabilities comprises surveillance and tracking sensors to acquire the raw data, which are then processed to correlate the detections with known objects, or to identify a new object if this has not been seen before.

Ground–based optical sensors are very efficient systems to detect and track faint objects in GEO and MEO orbital regions, due to their inherent sensitivity advantage over radars for this task. However, these sensors are subject to the variations of atmospheric weather, which can result in the inability to track or observe objects as frequently as desired, which in turn may lead to difficulty re-acquiring the objects at a later date. In order to deal with the atmospheric variability and to implement efficient surveillance and tracking strategies, it is foreseen that the final SSA system will consist of several large robotic telescopes in remote locations to provide efficient surveillance and tracking services for artificial satellites, space debris and NEOs.

It is important to indicate that during the last years, a number of robotic telescope network systems have been deployed for astronomical purposes [1]. In fact, this is a new observing technology that complements the installation of large observing facilities. Robotic telescope networks are essential tools for observing gamma-ray bursts, monitoring of blazars, supernova searches, study of active galaxy nuclei, exoplanet searches and asteroid surveys [2]. The technology is now mature enough to be adapted to the requirements of the ESA SSA programme.

2 THE STUDY PROJECT

The objective of this study project is to provide a test-bed for the validation of all aspects of an autonomous optical observing system used in a realistic scenario. It will be referred as the "ESA´s Optical Surveillance System Test-Bed". The complete system shall be considered as tasking sensors autonomously performing follow-up observations of man-made objects as well as

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NEOs and it will be a precursor system for a future operational ESA network.

To this end, it is envisaged to design, procure and deploy a prototype robotic telescope system of moderate dimensions, consisting of two identical observation systems to be deployed in two sites: one in the Northern and one on the Southern hemisphere, with a large longitude separation. This configuration will allow a realistic operational scenario for future operational strategies.

To minimize logistic problems during the study phase, two ESA deep space stations (DSS) are proposed as initial locations for deployment of the system: at Cebreros DSS, in Spain, and at New Norcia DSS, in Western Australia.

The proposed system will have a dual capability, to provide representative test data that will be used to validate precursor services for surveillance and tracking and to acquire astrometric and photometric data of near-Earth objects.

This test-bed system will also be used to evaluate and validate future prototype software in the areas of remote monitoring and control, generation of automated telescope schedules and for the data processing pipeline to detect and extract astrometric and photometric data of detected objects.

It is foreseen that each observation system will be constituted by moderate aperture (>40 cm) and FOV (> 2 deg x 2 deg) optical telescope and a high performance and sensitive scientific CCD camera with moderate pixel size. This optical configuration should be suitable to perform successful observation exposures for space debris (1-2 sec) and NEOs (10-120 sec). It is intended to arrange the optical systems in a mount capable for fast slew, tracking and repositioning. The final arrangement will be optimized for the follow-up and detection of high altitude objects (GEO, MEO and HEO apogee regions) and NEOs. Both sidereal and orbital elements tracking will be possible.

Recent developments in the area of networks of robotic optical telescopes, digital detectors and image processing technologies are helping to reduce the cost and increase the performance of the overall system; therefore, it is intended to implement this test-bed using hardware and software elements available as commercial off-the-shelf (COTS) products in the European market.

3 THE OPTICAL SENSORS

In order to select the hardware of the sensors, a detailed survey has been done in the European market to select suitable components for the telescope, camera and mount, described in the following sections.

3.1 Telescope

Two main drivers have been considered for the hardware design: *(i)* the ability of detecting an object as faint as V = 18 with SNR = 3 with and exposure time of just 2 seconds, and (*ii)* in order to fulfill the follow-up observing requirements, a minimum field of view (FOV) of 2.3° × 2.3° should be ensured (with an acceptable image quality). Taking into account these design drivers, the market survey was conducted based on the following requirements:

- The diameter of the primary mirror shall be at least 400mm with a photographic speed not slower than f/2.7.
- The telescope design shall consider that the spectral band of signal lies between 380 nm and 900 nm, while the point spread function shall be better than the best seeing expected (diffraction-limited). Therefore, the telescope design shall ensure that 80% of the encircled energy from a point source is encircled within one pixel.
- The design will avoid vignetting in the focal plane assembly, and will incorporate measures to reduce stray light (e.g., baffles) to allow observations close to the Moon or in twilight conditions.
- For practical reasons, the length of the central tube shall be limited to two meters.
- As part of the robotic capabilities, the design shall consider a motorized telescope cover that can be controlled by the software.
- The hardware components are expected to endure long periods of time without direct supervision, so a robust and stable telescope with minimum maintenance effort was an additional criterion for the telescope market survey.

At this point there are two factors that play a major role when defining the final optical configuration: the Signal-to-Noise-Ratio (SNR) that strongly correlates with the sky quality of the site, and the Focal Plane Assembly (FPA) position with respect to the optical tube. The former was addressed by the computation of the SNR for different apertures and obstructions, using an all-sky brightness map as reference for the Cebreros ESA tracking station sky quality. The results in Fig. 1 show that a commercial off-the-shelf system with an aperture of 400mm did not meet the SNR>3 requirement for objects of mv=18 in 2s detection with obstruction values above 30%. Therefore, the market survey was forced to go beyond the commercial products and the major potential telescope suppliers, APM, Astrooptik, Alluna Optics and Astelco carried out independent optical feasibility studies in order to find the most suitable system.

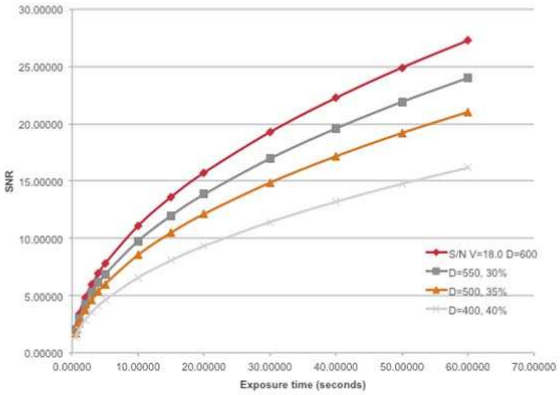

Figure 1. SNR vs exposure time for sidereal tracking

Regarding the camera position, the original favoured design was a Newtonian configuration in order to ease the maintenance effort and minimize the potential risks that come along with a camera placed over the optical assembly. However, the outcome of the optical studies coincided that a Newtonian configuration with the aperture and geometrical speed given, will lead to a significantly lower imaging performance of the system. The reason is that placing the focus outside the optical telescope assembly means to use a main mirror with slightly longer focal ratio to minimize the size of the secondary mirror. Thus the use of a focal reducer corrector unit outside the optical tube is needed and it will yield a high off-balanced system. Moreover, even with the use of a strong aspherical mirror, the optical system will have its limitations compared to the expected optical performance of a prime focus astrograph with similar characteristics. Therefore, the latter configuration was selected for the final optical configuration.

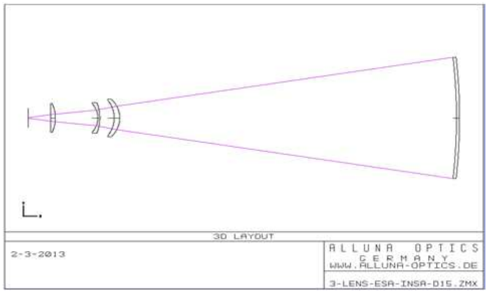

Figure 2. 600mm f/2.7 Prime Focus layout system by Alluna Optics

Finally, due to the configuration of a prime focus astrograph, a custom-made filter holder has been also considered as part of the telescope design in order to reduce the central obstruction of the system.

3.2 Mount

Several possibilities are available in the market and could be considered, either alt-azimuth or equatorial. The former design has the advantage of a simpler and more compact design, however the need of a de-rotator for long exposures, and the existence of a blind spot in the zenith area are strong drawbacks for this project.

Equatorial mounts are usually larger, thus requiring a larger dome but do not require de-rotators and can generally access any point in the sky with some constraints in elevation. The most widely used equatorial designs are the German and the fork mounts. The latter configuration was abandoned for this survey primarily due to its disadvantage in stability, weight, and telescope versatility compared to the German configuration. Therefore, the mount market survey conducted focused on German equatorial mounts.

Recently, a new technology mount has appeared in the European market, the so-called “direct drive mounts”. In configuration, the right ascension and declinations axes are actually the motor shafts, and electromagnetic clutches are used to hold the mount in a certain spot with minimal friction and next to zero backlash. The performance of this system is above other drive methods, with tracking precision that could reach < 1arcsec in 120min, pointing accuracy of the order of 5arcsec RMS and moving speed up to 20º/s. There are three potential suppliers of direct drive mounts: ASA in Austria, and Astelco and APM in Germany.

Figure 3. ASA DDM-160 mount with equatorial pier

Finally, a heavy loading capacity design (~300kg) was favoured in the mount market survey in order to ensure stability and vibration-free mechanics.

3.3 Camera

The camera market survey was led by the preliminary results on the optical design. In order to ensure the whole FOV coverage at the primary focal plane, the linear size of the CCD should be around 61mm. The only standard sensor with that size is a CCD with 4096x4096 pixels, with a pixel size of 15microns.

Therefore, the main driver of the camera market survey was to find a commercial camera that could house a sensor with the above characteristics. The camera market survey was based on the following requirements:

- Typical exposure times shall be 1-2 seconds for space debris observations, 10 to 120 s for NEO observations. Exposure times between 1ms and 1h shall be supported.
- Cooling of the detector should reduce dark current to about 0.1e- /pixel/second, and the temperature control shall be better than 1 K at all times
- The readout-noise should be less than 5e- rms, no visible cross talk between the readout channels should be ensured, and the detector readout during re-positioning shall be possible
- Binning of pixels and read-out of windows shall be possible.
- The detector will have a high dynamic range and the nonlinearity should be less than 0.5% It should also be sensitive between 380-900nm wavelengths, and its peak quantum efficiency shall be more than 90%, better than 75% at 550nm,
- “Smear mode” functionality shall be implemented, that allows the controlled detector read-out while still exposing, resulting in faint vertical trails attached to bright objects.

Only few non-European companies provide commercial cameras with the above specifications. The camera market survey focuses on three different camera models: the Fairchild Peregrine486 and the Spectral Instruments 800 and 1100 Series.

Figure 4. Spectral Instruments 1100 Series camera

4 THE SOFTWARE

As mentioned in section 2, the project has to use as many COTS software components as possible to reduce costs and to improve the system performance making use of the state-of-the-art in robotics telescopes.

The foreseen software components to be used in the system are:

- Monitoring and Control software system.
- Automated scheduling.
- Processing software systems.

The software survey has been conducted to make a reasonable comparison between all the options, having in mind the software requirements. At this point we have to remark that out of all the software studied, none of them fulfill completely the system requirements. Therefore it is absolutely clear the need to customize and tailor the final software system.

In a first stage, a stand-alone assessment was done on each software module to know if it fulfills the generic requirements for each particular group (control, scheduling and processing). This analysis has provided a good understanding about the functionalities and main constraints of the software elements. For that purpose, we contacted the owners of the different software components. A check list with all the software requirements was prepared and filled for each candidate software component to be assessed. Then, in a second stage the software component is studied in relation with other complementary components to understand possible options for integration.

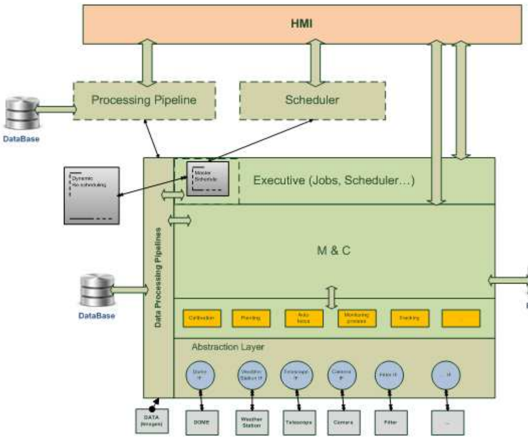

Figure 5. Software: high level architecture

The proposed high-level architecture of the software system is shown in Fig. 5. The selected software products for each software subsystem are described below.

4.1 Monitoring and Control

With the recent development of robotic telescope networks, several monitoring and control (M&C) systems were analysed as part of the survey. The software components considered are:

- FEC-T,
- CSI/INDI (Clear Sky Institute Inc.),
- RTS-2.

The FEC (Front-End Controller) [5] is a multi-platform operational software framework that performs control functions for the antenna and front-end equipment in satellite tracking or data reception stations, according to a set of data that defines a specific target

The FEC system is already being adapted, in a parallel project (SSA DC-IV), to implement a generic controller for any kind of sensor in SSA's ground-based sensor network, telescopes included. This system is referred to as the SEC (Sensor Equipment Controller) and we briefly introduce this concept below:

- The SEC shall be responsible for the M&C and the autonomous execution of high level commands or schedules received from an SSA sensor planning system.
- The SEC shall gather monitoring data and be capable of providing this data to other SSA systems.
- The SEC shall harmonize the operation of various sensor types (eg. radar, telescope, SW sensor) from the perspective of a centralised system.
- The SEC is intended to be a generic system that can be tailored for any SSA sensor.
- SEC FAT is planned for end of 2013

Intermediate product in the evolution from FEC to SEC we propose to use: Straight forward adaptation of the FEC for telescope systems, simplifying requirements of multi-sensor generic support: FEC-T.

The FEC is the current front-end system baseline for the ESA ESTRACK stations, being operative for more than 10 years.

The CSI/INDI control system is based on the INDI protocol architecture, whose creator E.C. Downey has deployed, among other observatories, the TFRM (Telescope Fabra-Roa Montsec) observatory [3].

The core of INDI is the idea that all information is captured in Properties. Properties are small typed XML packets that contain anything from telescope azimuth to current wind direction to a camera image. INDI drivers communicate among themselves to perform coordinated operations or can communicate with INDI servers.

INDI protocol is client agnostic, since clients learn the properties of a particular device at runtime using introspection. This decouples the device driver implementation from clients. The device driver may be updated completely independent of the client.

The CSI/INDI implementation system at TFRM has two main programs that provide a graphical user interface to the observatory control system. One is ObsCon (an abbreviation for Observatory Control). The other is ObsCam (an abbreviation for Observatory Camera). Both are Java client programs that connect to the INDI servers. Multiple simultaneous instances of both of these tools may be run at the same time, and all have equal peer control over the system, so take care to arrange an arbitration scheme in a separate manner to determine who has responsibility for operating the equipment and who is just monitoring.

ObsCon provides command and monitoring capability for all observatory systems except the camera which is performed by ObsCam. In order to function, it must connect to the observatory INDI server.

Some examples of observatories where INDI has been successfully implanted, among others, are: Fabra-ROA (Montsec, Lleida, Spain); Magdalena Ridge Observatory (Socorro country, New Mexico); Hoher List Observatory (Daun, Germany); Moletai Observatory (Vilnius, Lithuania)

The development of the Remote Telescope System (RTS2) started in 2002 [4]. It is an open source package with the aim to create a modular environment for observatory control, that could cope easily with a change of camera, mount, or weather sensor, that would enable script-driven operation, and permit automatic (and fast) reaction to emerging targets of opportunity, most notably the Gamma Ray Burst (GRB) localizations.

RTS2 central server is the core of the software. It communicates through RTS2 protocol with the telescope, device drivers (like cameras, dome, weather station,..), executor and selector that through predefined strategies select next object to be observed. All communication is done through TCP/IP, only from camera to camera driver USB is used. Control and data transfer between components does not delay the observation in any way. The architecture of RTS2 is shown in Fig. 6.

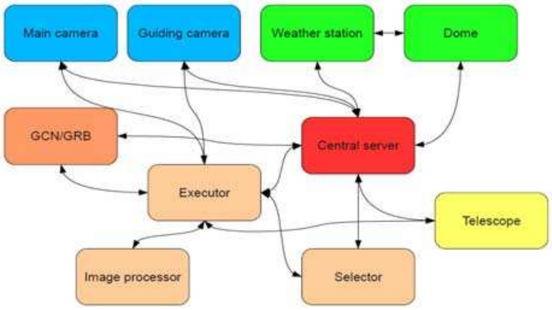

Figure 6. Architecture of RTS2

RTS2 benefits from the object oriented features of the languages it mainly uses - C++ for the system core and Python for the scripting.

RTS2 has been selected to participate on various state-of-the-art projects, including control of the LSST CCD calibration and testing laboratory, ESO/Danish 1.5m, RATIR 1.5m, and SAO/FLWO/Harvard 1.2m.

4.2 Scheduling

The scheduling system is the key component for observatory operations. On the one hand, it has to be in close contact with the control software and it has to command the observation strategies to be performed. On the other hand, the scheduler determines the processing method.

The COTS scheduling packages that have been studied are:

- Space Debris Software of the University of Bern (only scheduling SW modules)
- ISDEFE NEO Scheduling tool
- RTS2 internal scheduler
- OGS Visualization Tool: Survey and Follow-ups
- CSI/INDI Scheduler

The main goal of the scheduler system is to create the appropriate planning for follow-ups of man-made objects and NEOs, and the creation and execution of incremental and scalable survey strategies, as autonomous and automatize as possible.

Because of the heterogeneity between man-made and NEOs observations, we couldn’t find one single scheduling software able to cope with all the scheduling requirements.

For example: OGS visualization tools and ISDEFE schedulers are able to prepare planning for NEOs follow-ups and survey mode. While Space Debris Software of the University of Bern, is able to handle man-made follow-ups and survey scheduling.

The TFRM scheduling system is a simple interface to define the INDI commands you want to execute, define the target and any additional constraints for the observation.

The RTS2 internal scheduler was originally created to quickly react to optical transients of γ-ray bursts. The system allows observers to quickly build and combine different observational scenarios, while still retaining ToO (Target of Opportunity) and weather interruption capabilities.

Scheduling queue entities are targets which should be observed. When the next target should be observed, it is removed from the top of the queue.

The designation "queue scheduling" is somewhat misleading and might be renamed to "scheduling from an ordered set of targets." RTS2 queues become even more complex than the ordered set. Then, the meta-queues can be configured to order and select targets in a different fashion to the standard first-in-first-out (FIFO) algorithm.

Therefore, the RTS2 internal scheduler is complementary to any possible external scheduler. .

4.3 Processing

As indicated in the previous section, the processing software and the scheduling system are two components very close related. The observing strategies will define in a later stage the processing methodology. Or the other way around, the processing capabilities should define the strategies modes.

The main goals for the processing system are: it has to be as autonomous as possible, and it has to deliver astrometric and photometric data in near real-time.

The COTS Processing software packages that have been studied are:

- Space Debris Software of the University of Bern (only processing SW modules)
- TOTAS (only processing SW modules)
- APEX II
- IRAF

In this case of processing packages we can also distinguish between software that deals with man-made observations and software able to process NEOs observations.

Space Debris Software of the University of Bern is able to process man-made observations having the following main features: sky survey, astrometry, astrometric calibration and orbit determination. The online processing tool follows instructions in the command file generated by the planning tool.

APEXII is an automatic image reduction package developed by the Pulkovo Astronomical Observatory, Russian Academy of Sciences. It is used within the ISON network. It is highly modular and it is able to process solar system bodies and space debris observations.

TOTAS processing software package has been developed by Matthias Busch and is used to process NEOs survey images taken at the OGS observatory. It is based on the commercial astrometric data reduction package PinPoint which scans a set of 3 images of the same sky area. Possible NEO candidates are presented on a web page waiting for confirmation by users.

Finally, IRAF is a general Image Reduction and Analysis Facility providing a wide range of image processing tools for the user. IRAF is a product of the National Optical Astronomy Observatories (NOAO) and was developed for the astronomical community although researchers in other scientific fields have found IRAF to be useful for general image processing.

5 THE OBSERVATORY

After selection of the hardware and software elements of the complete test-bed observatory, the components will be procured and integrated for test and validation. The final deployment of the complete network includes the elements described in this section.

5.1 Dome

The enclosures for telescopes can be classified in two large categories: rotating and retractable ones. Rotating enclosures have partial opening and consequently they need to move. They are very suitable for astronomical observatories where not intensive slewing is required. But they do not fulfill the requirements due to high rate slew, beyond 5 deg/s, needed by the test-bed scopes. Besides they would need to be synchronised with the telescope, increasing complexity of the control system, the overheads and the possibility of failures.

On the other hand, retractable domes are widely used for this kind of telescopes. The most suitable ones for this project are the “clamshell”, “flip top” and fully retractable domes. These designs are able to move the roof and the walls, leaving an unobstructed view over 10 degrees in elevation for all the azimuths. However roll-off roofs are limited by design, unless they are oversized to keep the telescope far enough from the walls. Other SSA telescopes like Starfire/AEOS are housed under collapsible enclosure, however they are custom made and not COTS.

Clamshell solutions allow full and rapid access to all the sky opening completely the dome like an eyelid. It becomes a very optimal house cover because at the same time it is a very compact configuration and it is very robust to weather conditions.

These total opening solutions are not the classical dome used for most observatories; however, its use is widespread in professional observatories. Some of them have enclosures using solid segments that are moved sideward or downwards (e.g., Vacuum Tower Telescope, AEOS, Liverpool Telescope). The other option is using cloth segments, which are folded together (e.g., DOT, Gregor).

Main concern about open observatories is image blurring due to telescope wind-shake. Wind load is highly dependent on the telescope design. However typical values are below the scale plate values under consideration.

5.2 Safe Operations

Although the observation systems will be located within existing ESA’s facilities having operational support, the operation of the systems will be remote and automated. It will require a series of complementary hardware and software subsystems to ensure the safe operation and protection of each observation system preventing incidences from any operation error or any environmental event. These subsystems shall be redundant and autonomous to assure that they can complete their protection functionality independently of the power supply availability or network connectivity.

The safe operation control system will monitor remotely the health of the observing system and the internal and external environment. It will incorporate both autonomous and interactive actuators to force the protection of the system (i.e. emergency dome or roof close out). Passive and active elements will be considered for a correct evaluation of the secure operation and environment:

- Passive Safe Operation Subsystems
  - Webcams
  - Meteo Station
  - Time Servers
- Active Safe Operation Subsystems
  - Autonomous emergency system
  - Lightning Protection
  - Uninterrupted Power Supply

The safe operation design will assure the operation of the system through the following interfaces:

- Interactive and remote via a login program,
- Non interactive and robotic, with automatic pre-programmed tasks.

The following safe operation functionality will be implemented to manage adequately the protection of the system.

- Safe Mode triggering events: Safe mode is entered automatically upon the detection of a predefined operating condition or event that may indicate loss of control or damage to the system. Usually the trigger event is a system failure or detection of operating conditions considered dangerously out of the normal range. Automatic or Manual
- Safe Mode Activation: The process of entering safe mode involves a number of immediate physical actions taken to prevent damage or complete loss.
- Safe Mode Permanence: While in this mode the preservation of the system is the highest priority.
- Safe Mode Recovery: Recovery from safe mode involves re-establishing the safe conditions.
- Safe Mode Suppression: The safe mode operation may be suppressed during required periods, such as during deployment and maintenance.

With this strategy, the safe operation control systems shall be able to protect the observing system of any weather event that could potentially damage the observing system: very high wind speeds (>200km/h) and any kind of severe precipitation, lightning, etc. The operational mode will be possible at temperature, pressure, relative humidity and wind speed in the ranges commonly used as secure in standard observatories. Due to the size of the observing system, when possible these limits will be extended: temperature between -15 and 40 degrees, low pressure, relative humidity between 0 and 90% and wind speeds up to 20 m/s. Operation at higher wind speed is not usual in astronomical observatories and put the complete system in a serious risk: it is very difficult to maintain the observing system without any kind of vibration and the operation of the cover (dome or sliding roof) can be critically endangered. Loss of power supply and network connection after defined time thresholds will be also drivers to trigger the safe mode activation.

5.3 Location of the observatory

The architecture of the ESA's Optical Surveillance System Test-Bed involves two optical observing systems in two different geographical locations controlled remotely from a Control Centre located at ESA premises, ESOC as a first option.

To minimize logistic problems during the deployment and operation of the Test-Bed, two ESA deep space stations (DSS) are proposed as initial locations for deployment of the system: at Cebreros DSS, in Spain, and at New Norcia DSS, in Western Australia:

- Cebreros Station (Lat: +40° 27' 09"; Lon: -04° 22' 03"; Alt: 795m) is the prime site selected. It is the location where the first observing system will be deployed and the second one tested.
- New Norcia Station (Lat: -31° 2' 54"; Lon:+116° 11' 29"; Alt: 252m is the location selected for the second observing system and where it will be deployed after testing. An alternate ground station being considered is Dongara (-29°2'44"; Lon:+115°21'5", Alt: 270m) also in Western Australia.

Although the simultaneous observation of the same area of the sky will not be possible with this configuration, weather permitting, it will allow the coverage of most of the Northern and Southern Sky at the same time, the follow-up of any Earth orbiting object in any orbital position and continuous NEO's visibility.

Weather conditions in both places are quite optimal for optical observations. However, although good enough for the test-bed purposes, the conditions for astronomical conditions are not the best. Light pollution is low in the two locations but it is foreseen that the low altitude of the considered places will imply moderate seeing.

Complementary, these infrastructures guarantee the availability of power supply, IT network and security services.

The first option considered for the Control Centre of the Test-Bed is a centralized control system located at ESOC (European Space Operation Centre) in Darmstad, Germany. Both test bed observing systems will be operated from there and these will be linked through it with the ESA SSA programme infrastructure and the observation, data processing and archiving infrastructures of other SSA and NEO programmes.

6 CONCLUSION

The test-bed project started in November 2012 funded by the ESA GSTP programme, with reference G532-004GR, titled: "*Demonstration Test-Bed for the Remote Control of an Automated Follow-Up Telescope*". Next milestone is the preliminary design review, scheduled in May 2013.

At this moment relevant European experts in telescope design have been contacted to provide suitable designs of the optical system components. The software market survey has been completed and a feasible implementation strategy is being defined to provide the required services for the test-bed system so as to fulfill the observing needs for man-made and natural objects orbiting the Earth.

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