PROPOSAL FOR A EUROPEAN SPACE SURVEILLANCE SYSTEM

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ABSTRACT

Space Surveillance denotes the task of systematically surveying and tracking all objects above a certain size and maintaining a catalogue with updated orbital and physical characteristics for these objects. Space Surveillance is gaining increased importance as the operational safety of spacecraft is depending on it. At the moment, Europe has no capability for Space Surveillance and is strongly dependant on external information from USA and Russia.

In 2002, ESA specified a design study for a European Space Surveillance System. The study was awarded to a team led by ONERA and this paper gives its main results. Among the required functions for this ground-based system, the study focuses on establishing and maintaining a catalogue of objects with actual orbital parameters. The main drivers for the system design are the minimum objects size (10 cm in LEO and 1 m in GEO) and the autonomy requirement. Considering space objects distribution, two sub-systems are studied independently: LEO Space Surveillance System (SSS) and GEO SSS. The complete system is considered as the combined use of both sub-systems.

1. INTRODUCTION

Since the first launch in 1957, more than 4500 vehicles have been launched into space and there are now some 9000 objects with a size greater than 10 cm orbiting around Earth. These objects are mainly located in Low Earth Orbit (LEO) between 200 km and 2000 km altitude and to a lesser extent in Geostationary Earth Orbit (GEO). Among them, less than 10% are operational satellites and others represent space debris. It is necessary to add 50000 to 150000 small debris (depending on estimations) with sizes between 1 and 10 cm. Collision risk remains low for the moment, but with the increase of the number of debris, it will become crucial to be capable of reliably predicting potential collisions. Considering that a satellite can be protected against collisions of debris smaller than 1 cm, it would be necessary to predict collisions for all objects larger than 1 cm.

In fact, in Europe, the current situation is very far from this objective. Europe relies on the US Space Surveillance Network which gives orbital information for objects larger than 10 cm in LEO and larger than about 1 m in GEO respectively. This information is then used for European tracking sensors such as the TIRA (Tracking and Imaging RAdar) or French MoD (Ministry of Defence) radars or telescopes like the ESASDT (ESA Space Debris Telescope) at Tenerife. Without external data, Europe may not guarantee the operational safety of its own satellites. To do so, Europe needs an autonomous Space Surveillance System.

Space Surveillance denotes the task of systematically surveying and tracking all objects above a certain size and maintaining a catalogue with updated orbital and physical characteristics for these objects. In 2002, ESA specified a design study for a European Space Surveillance System. The study was awarded to a team led by ONERA and this paper gives its main results. Among the required functions for this ground-based system, the study focuses on developing a concept for establishing and maintaining a catalogue of objects with actual orbital parameters. In fact, this function is the essential basis of the future system without which reliable collision prediction would not be possible. The main drivers for this system design are the minimum objects size (10 cm in LEO and 1 m in GEO) and the autonomy requirement.

The proposed solution focuses on the LEO and GEO regions and may be considered as a low cost solution since it concentrates on Space Surveillance and does not

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include additional functions like Early Warning of Ballistic Missiles.

The experience stemming from existing European systems such as the GRAVES radar system for the LEO part and the ESASDT for the GEO part is used as basis for the proposed solution. Finally, it is concluded that this solution is feasible from the technical point of view.

2. SYSTEM REQUIREMENTS

The final goal of a future ESSS (European Space Surveillance System) is to give autonomy to Europe for guarantying the operational safety of its satellites. In order to propose the design characteristics of such a system, system requirements are derived and they address the following topics:
- System functions to be implemented
- System constraints to be taken into account.

Functions to be realized by a SSS (Space Surveillance System) are numerous and have to be prioritised:
- Orbital parameter catalogue maintenance
- Physical parameter estimation (size, mass, radar cross section …)
- Object owner identification
- Determination of collision risks
- Prediction of atmospheric re-entries.

Orbital parameter catalogue maintenance constitutes the basis of all of them and this study focuses on it. In fact, if this function is realized in an autonomous way, a preliminary SSS exists. Moreover, if this function is not realized, the other functions have no interest. This function may be split into several sub-functions such as:
- Orbital parameter estimation
- Manœuvres identification
- Break-ups identification
- New launches detection.

The following driving constraints have also to be taken into account for the system design:
- Non homogeneous distribution of objects in space
- Size of objects
- System autonomy
- Incremental system implementation
- Feasibility and costs.

The current distribution of objects in space is illustrated by Fig. 1 and Fig. 2 taking as basis the NASA/USSTRATCom catalogue. Following definitions are given in order to classify objects:
- LEO : Apogee altitude < 2000 km (light grey dots)
- MEO (Medium Earth Orbit) : Perigee altitude > 2000 km and apogee altitude < 34000 km and mean motion between 1.5 and 2.5 revolutions/day (grey dots).
- GEO : Perigee altitude > 34000 km and apogee altitude < 38000 km (dark grey dots).
- REO (Remaining Earth Orbit) : Other orbits (dark dots).

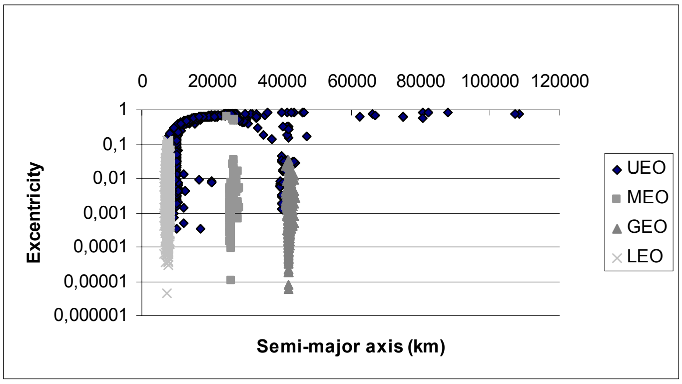

Figure 1 – Space objects distribution according to NASA/USSTRATCom data

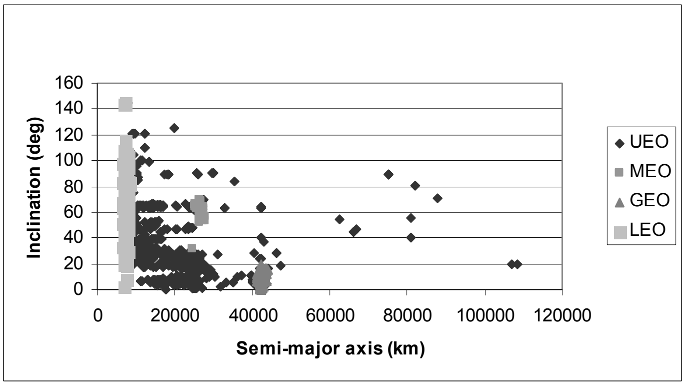

Figure 2 – Space objects distribution according to NASA/USSTRATCom data

Of course, the majority of objects are LEO objects (70%) and operational orbits are essentially low eccentricity ones (lower than 0.1). This study focuses primarily on surveillance of LEO and GEO objects (together this is about 80% of global population). Ongoing work (not presented here) is dealing with MEO objects (2.2%) and part of REO ones.

Concerning the minimum size of objects, ESA requirements are 10 cm in LEO and 1 m for other orbits.

The system must be autonomous, i.e. the system shall not depend on inputs from external catalogues and shall have a “cold-start” capability. The analysis must also take into account development constraints such as incremental system implementation (first step in 2010 and next step in 2015) as well as feasibility (for the required steps) and cost.

3. LEO SPACE SURVEILLANCE SYSTEM

Taking as a reference the NASA/USSTRATCom catalogue, Fig. 3 presents the LEO object distribution according to perigee altitude. Grey bars represent active satellites and dark bars, debris.

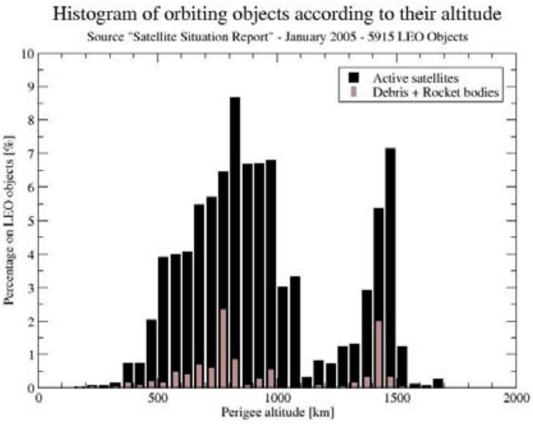

Figure 3 – LEO objects distribution according to NASA/USSTRATCom data

3.1 LEO Space catalogue maintenance

The proposed strategy for LEO space catalogue maintenance is based on pure survey observations. The GRAVES (Grand Réseau Adapté à la VEille Spatiale) system experience [1] shows that if each object is observed every day, for at least 10 s, the orbit estimation accuracy will be sufficient for object re-identification at next crossing. Then, space catalogue maintenance may be done as following:

- Space survey made by sensor(s) gives several measurements for several objects ;
- A tracking procedure identifies the measurements belonging to the same object ;
- The catalogue correlation procedure either recognises that the object is already catalogued and updates its orbital parameters, or adds new objects (resulting from launches or explosions), or deletes objects (resulting from re-entry or original exploding object).

This procedure allows the “cold start” to establish the catalogue and therefore, the system is autonomous.

The pure survey strategy is made possible due to LEO orbital characteristics that allow defining a region in space which is crossed every day by all objects. The last difficulty is to define the necessary sensor FOV (Field Of View) that gives the minimum daily detection and tracking interval of 10 s for each object.

3.2 Sensor requirements

The sensor requirements are derived from the proposed strategy for the catalogue maintenance. Some of them have been obtained by way of simulations using the S3 (Space Surveillance Simulator) software and the NASA/USSTRATCom catalogue:

- From catalogue completeness point of view, it is shown that LEO surveillance must be done by ground radar sensors. Optical sensors are not suitable for objects in very low orbits (the object must be illuminated by the Sun, while the telescope must be in the dark).
- From object minimum size point of view, the radar frequency to be used is UHF (Ultra High Frequency).
- From maximal LEO altitude consideration and radar feasibility considerations, the maximum radar slant range is 2000 km.
- From maximal observation gap duration (1 day) and minimum tracking interval (10 s), the radar FOV must be 20° in elevation and 180° in azimuth (oriented towards the South).
- From actual objects distribution, the best minimum elevation is 20° and the best location for the radar is 35° north.
- From current object distribution (given by US catalogue), only one sensor appears to be necessary.

3.3 Sensor proposal

Two concepts of phased-array radars have been studied for LEO Space Surveillance:

- The US Eglin type (Mark Major - 1994) which uses a narrow beam for both transmission and reception.
- The GRAVES type which uses a large transmission beam and narrow reception beam. GRAVES is a bistatic radar, transmitting in a continuous mode and using digital beam forming at reception level. See Michal et al. (2005) for further details.

Taking into account the fact that, for the same total power, only one GRAVES sensor type is necessary compared to four EGLIN type sensors and that COTS (Commercial Off The Shelf) technology may be used for transmitters, the GRAVES sensor design is recommended.

An incremental system implementation is proposed for this sensor. Main characteristics are given in following tables. Tab. 1 corresponds to the proposed sensor for the 2010 term as Tab. 2 is given for the 2015 sensor.

Tab. 1. 2010 sensor characteristics

Frequency	Power supply	Number of arrays and transmitters	Number of receiving antennas	Processing power
UHF (600 MHz)	9.6 MW	4x600	3 600	17 Tflops
Δt integration	**Transmitter location**	**Reception location**	**Range**	**FOV**
1.6 s	5.3°E, 37.9°N	5.3°E, 36.1°N	1500 km (-23 dBm²)	20°x180°
Elevation measurement precision	**Azimuth measurement precision**	**Doppler measurement precision**	**Min elevation**	
0.25°	0.25°	0.5 m/s	20°	

Tab. 2 – 2015 sensor characteristics

Frequency	Power supply	Number of arrays and transmitters	Number of receiving antennas	Processing power
UHF (600 MHz)	9.6 MW	4x600	10 000	47 Tflops
Δt integration	**Transmitter location**	**Reception location**	**Range**	**FOV**
1.6 s	5.3°E, 37.9°N	5.3°E, 36.1°N	1700 km (-23 dBm²)	20°x180°
Elevation measurement precision	**Azimuth measurement precision**	**Doppler measurement precision**	**Min elevation**	
0.25°	0.25°	0.5 m/s	20°	

3.4 System architecture

The primary function of the LEO SSS is the maintenance of the orbital parameter catalogue.

The future LEO SSS architecture will comprise three major elements:
- The SSUI (Space Surveillance Users Interface)
- The DMS (Data Management System)
- The UHF radar.

Fig. 4 describes the proposed architecture.

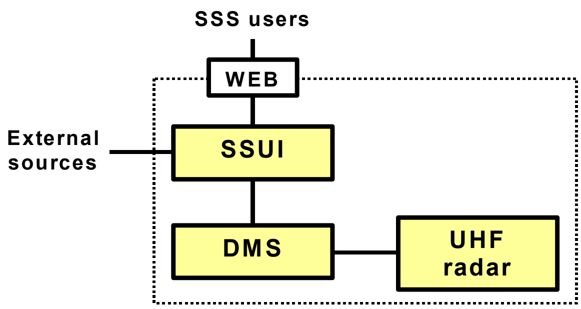

Figure 4 – LEO SSS architecture.

The following sub-systems are identified for each major element:
- For the SSUI :
  - Publishing catalogue sub-system to manage issues of the updated catalogue
  - Data management sub-system to exchange data between DMS and external sources of information or collateral and contributing sensors
  - Management sub-system to administrate the system.
- For the DMS:
  - Measurements acquisition sub-system (reception of UHF radar data)
  - Catalogue maintenance sub-system to manage the internal catalogue and published updates
  - Database composed of orbital parameters (mean and full covariance matrix)
  - Data management sub-system to exchange data with SSUI.
- For the radar:
  - Transmitter site
  - Reception site.

Concerning network architecture, the amount of data exchanges does not lead to any difficulty.

3.5 System performances

The performance of the process of orbital parameter catalogue maintenance is very difficult to demonstrate. In fact, it would be necessary to simulate all possible measurements of the 2010 and 2015 radars, process the data and carry out the complete catalogue maintenance operations. The effort would be quite the same as producing the real catalogue and so far, it is out of the scope of this study. Therefore, performances of the 2010 and 2015 solutions have been analysed in comparison to the GRAVES system (Bouchard et al. – 2001). The GRAVES design (i.e. measurement frequency, duration and precision) has demonstrated that if every object is observed at least once a day for a minimum period of 10 s, then the catalogue maintenance process is operationally feasible.

Thus, the performances of the 2010 and 2015 solutions have been studied in terms of:
- Number of correct detections (detection interval greater than 10 s)
- Duration of detection
- Duration of detection gap.

with respect to the GRAVES equivalent parameters. The results are summarized in Tab. 4.

Tab. 4. Performance of 2010 and 2015 solutions with respect to GRAVES's performance.

Parameter	GRAVES solution	2010 solution	2015 solution
Correct detection % of USSTRATCom LEO objects (Minimal duration of detection =10 s)	20 %	97.7 %	98.8 %
Mean number of detections for 1 month and 1 object	80-90	100-110	110-120
Mean duration of detection	130 s	250 s	260 s
Mean duration of detection gap	8 hours	6 hours	6 hours
Longest duration of detection gap	13 hours	11 hours	11 hours

Finally, performances have been also studied in terms of precision of orbital parameter estimation for 4 representative objects: SPOT-5, Hubble telescope, ISS, a debris object.

After the first tracking interval, the orbit determination accuracy is of poor quality. After 10 days, the estimation quality is excellent. It is slightly better for the 1700 km range radar than for the 1500 km range radar due to the longer tracking duration. Taking into account all these comparison results, it is confirmed that the proposed solutions for the 2010 and 2015 terms will have higher performances than the GRAVES system and therefore, the orbital catalogue maintenance process will be feasible. For more details, see Donath et al. (2004).

4. GEO SPACE SURVEILLANCE SYSTEM

Within this study, the GEO region comprises the altitude range from the geostationary altitude plus or minus 2000 km, and the inclination smaller than 17 deg. Taking the NASA/USSTRATCom catalogue as a reference, Fig. 5 presents the object distribution according to perigee altitude. The grey bars represent the active satellites and the dark bars debris.

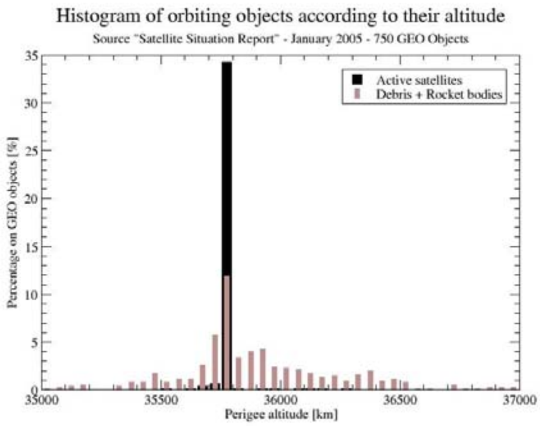

Figure 5 – GEO objects distribution according to NASA/USSTRATCom data.

4.1 Space catalogue maintenance

The proposed GEO space catalogue maintenance strategy relies on the fact that each object must be observed at least once every 15 days to keep the orbits secure for further re-observations. Consequently, the GEO space surveillance strategy contains two elements: search for uncatalogued objects (survey observations), and tasked observations for orbit improvement, catalogue maintenance, manoeuvre identification, and other system sub-functions (tasked observations).

The survey strategy makes use of the fact that all GEO objects cross a 34 deg wide declination stripe of fixed right ascension and centred at 0 deg declination once per day. If the survey sensors are able to scan this stripe within 15 days, the survey is considered complete, and the catalogue can be built up from scratch. Flohrer et al. (2005) describe the strategy in more detail. The authors also discuss the performance of the strategy.

The survey strategy alone does not provide highly accurate orbits for newly detected objects. Additional follow-up observations are required to improve the orbit accuracy. Otherwise, the correlation of the observations with objects of the catalogue would be ambiguous and would fail in many cases. The orbit improvement strategy follows a proposal by Musci et al. (2004). The follow-up strategy for orbit improvement implies a tasking procedure taking into account visibility constraints, sensor availability, and the time span since the last successful observation of the object.

4.2 Sensor requirements

The sensor requirements are derived from the proposed space catalogue maintenance strategy:

- From the catalogue completeness point of view, it is shown that GEO surveillance must be done by passive optical sensors using CCD detectors.

- Taking into account the presented survey strategy, a minimum of 3 low latitude sites distributed equally in longitude are necessary to allow for the required continuous observation of the mentioned declination stripe.
- The survey strategy and the fact that the stripe must be scanned within 15 days require a telescope FOV as large as possible. The achievable astrometric accuracy and the telescope design on the other hand limit the FOV. The survey strategy does only require small telescope slew rates.
- For the follow-up observations (tasking strategy), one dedicated telescope per site is necessary, as the survey must be uninterrupted. Its FOV should be as large as possible. For the tasking, high telescope slew rates are required.

4.3 Sensor proposal

Two sensors for the GEO Space Surveillance have been studied:
- A one-meter class telescope;
- A half-meter class telescope.

The one-meter class telescope is a narrow FOV sensor, which may be designed for 1.2 deg by 1.2 deg FOV. The focal length is 5700 mm and the CCD dimension is 110 mm*110 mm. The best candidate optical layout is clearly a Ritchey-Chretien telescope with a focal reducer composed of 4 lenses.

The half-meter class telescope is a wide FOV sensor, which may be designed for 3 deg by 3 deg FOV. The focal length is 1000 mm and the CCD dimension 52 mm*52 mm. The best candidate optical layout is a Schmidt-Cassegrain telescope with a focal corrector.

An incremental system implementation is proposed for this system:
- 2010 solution: 3 sites along the equator distributed over longitude are chosen: Canary Islands, Perth and Marquesas Islands. Each of these sites shall be equipped with one half-meter class telescope for survey and one half-meter class telescope for tasked observations. The half-meter class telescope is recommended since the larger FOV allows the stripe survey in 8 days rather than in 15 days. This may cure some of the restrictions from bad weather conditions.
- 2015 solution: 1 site in Cyprus is added to the 2010 solution in order to close the coverage gap between Canary Islands and Perth. This site is also equipped with one half-meter class telescope for survey and one half-meter class telescope for tasked observations.

4.4 System architecture

As for the LEO SSS, the primary function of the GEO SSS is the maintenance of the orbital parameter catalogue.

The future GEO SSS architecture will have three major elements:
- The SSUI
- The DMS
- The telescopes.

Fig. 6 describes the proposed architecture.

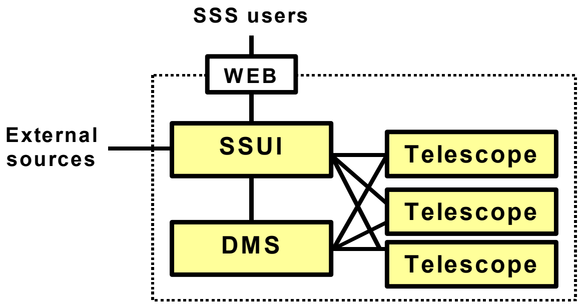

Figure 6 – GEO SSS architecture.

The following sub-systems are identified for each major element:
- For the SSUI :
  - Publishing catalogue sub-system to manage issues of updated catalogue
  - Data management sub-system to exchange data between DMS and external sources of information or collateral and contributing sensors, to exchange plans with telescope sites
  - Observation planning sub-system
  - Management sub-system to administrate the system
- For the DMS :
  - Measurements acquisition sub-system (reception and analysis of telescope data)
  - Catalogue maintenance sub-system to manage the internal catalogue and published updates
  - Database composed of orbital parameters (mean and full covariance matrix)
  - Data management sub-system to exchange data with SSUI
  - Internal catalogue of uncorrelated observations from uncatalogued objects or insecure orbits.
- For telescope sites :
  - Survey telescope
  - Tasked telescope
  - Measurements analysis sub-system (determination of the object position and raw magnitude by processing the acquired frames)

- Data management sub-system to exchange measurement data towards DMS and observation plans from SSUI.

Concerning network architecture, the amount of data exchanges does not lead to any difficulty.

4.5 System performances

The half-meter class telescopes were shown to fulfil the 1 m object detection requirement, if low phase angles can be guaranteed. This is the case with the proposed strategies.
The analysis of the proposed survey strategy shows that the 2010 solution will be able to cover 85% of the existing catalogue and that 95% may be reached with the 2015 solution. The remaining coverage gap results from the bad coverage of the GEO ring between Marquesas Islands and Tenerife. Using the half-meter telescope allows to complete the whole survey strategy within 8 days instead of 15 days. There will be some overlapping of frames, which allows acquiring enough observations for objects near the border of a frame and (due to the higher repetition rate) minimizes the effects of bad weather conditions. Also, the shorter survey time allows to cover fast drifting objects better.

The catalogue maintenance procedure is based upon two catalogues:

- The main catalogue, which contains "secured" orbits and is available for users.
- The temporary catalogue, which contains uncatalogued objects and "non secured" orbits. These objects are deleted as soon as they appear in the main one.

Two major steps are necessary for catalogue maintenance based on a mixed survey and tasking strategy:

- Observation planning for survey (determine declination and right ascension of ascending node to be surveyed) and tasked observations (determine objects to be tracked for the best suitable sensor)
- Catalogue maintenance taking as inputs both surveyed and task observed objects.

5. OTHER ORBITS

Within this study, the complete Space Surveillance System is considered as the combination of both, the LEO SSS and the GEO SSS.
GTOs (Geostationary Transfer Orbit) are the coupling orbits between LEO and GEO. The LEO radar may detect GTO objects at perigee but, due to gravitational perturbations, this detection is not repetitive enough in order to ensure continuous catalogue maintenance. GEO telescopes detect these objects around apogee. However, in the survey mode GTO objects cross the survey area in a very short time interval. This in turn does not allow the determination of an orbit without a priori information. This issue needs to be addressed in a future study.
In general, objects in MEOs are not detected by radar (due to link budget, of course). Telescopes can detect them but no observation strategy was defined, neither suitable sensors were selected. Ongoing studies address those points.
For "perigee locked" Molnyias, the apogee seems to be the best location for them to be observed. But due to their high inclination, the GEO survey strategy would not allow to observe them. Specific telescopes in specific locations are then necessary. For "unlocked" Molnyas, the normal GEO survey may partially contribute.

6. CONCLUSIONS

The LEO SSS is using a pure survey strategy. The recommended sensor is a UHF ground-based radar with a coverage of 20° in elevation and 180° in azimuth oriented towards South. The radar is a GRAVES-type system with 4 transmission arrays on one site and reception antennas in another site and digital beam forming. The 2010 solution is a 1500 km range radar located in southern Europe that will be upgraded (2015) to reach 1700 km range. In 2010 (2015), LEO coverage is 98% (99%) with respect to the US catalogue.

The GEO SSS is based upon a mixed strategy: survey and tasked observations. The recommended sensor for this strategy is a half-meter telescope with a FOV of 3° by 3°. The 2010 solution is given by three sites distributed globally. Each site consists of two telescopes, one for survey and one for tasked observations. For the 2015 solution, a fourth site is added to improve coverage. In 2010 (2015), GEO coverage is 87% (95%) with respect to the US catalogue.

The complete SSS combines the LEO and GEO sub-systems (cf. Fig. 7 and Fig. 8). With this system also objects in GTOs can be detected on a routine basis. For Space Surveillance in other orbits, e.g. MEO and HEO, ongoing studies will propose solutions.

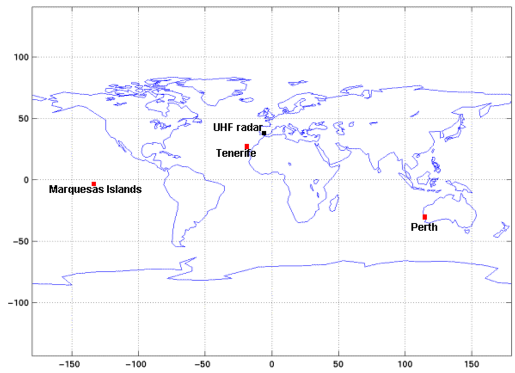

Figure 7 – Sensor locations for 2010 ESSS proposal.

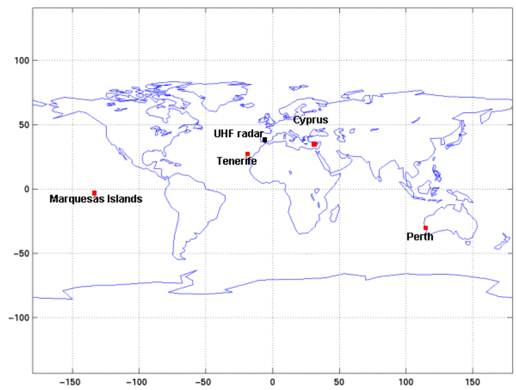

Figure 8 – Sensor locations for 2015 ESSS proposal.

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