Detailed Assessment of a European Space Surveillance System
Final Report

ESOC Contract n° 18574/04/D/HK (SC)

Main contractor: ONERA (France)
Sub-contractors: AIUB (Switzerland), ALCATEL (France), ATEME (France), DGA (France), European Antennas (United Kingdom), FGAN (Germany), INDRA (Spain), Rohde & Schwarz (Germany)
ESA Study Manager: Dr Heiner Klinkrad
Space Surveillance Study
Final Report

ESA study contract summary page

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<thead>
<tr>
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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. Presently, Europe has no operational capability for Space Surveillance, and is strongly dependent on external information from the USA and Russia.

A first design study for a European Space Surveillance System began in 2002 led by ONERA. This study proposed a preliminary system covering the LEO and GEO orbit regions, including the required survey strategies allowing for the autonomous maintenance of an orbit parameter catalogue (including cold start capability). For the surveillance of LEO objects with sizes larger than 10 cm, a UHF bistatic radar with a large field of view (20° in elevation and 180° in azimuth) and a long range (1500 km for a 10 cm sphere) was proposed, based on the French experience with the GRAVES system development. For the surveillance of GEO objects larger than 1 m, four sites equipped with survey and tasking telescopes were proposed. It was estimated that such a system would be capable of maintaining 98% of the LEO objects and 95% of the GEO objects contained in the USSTRATCOM catalogue. The present study is a follow-on of the 2002 study. It analyzes the feasibility of a UHF radar and proposes concepts for the surveillance of the MEO region. This space region will soon gain more importance for Europe due to the GALILEO system deployment.

Concerning the LEO sensor, the main findings are the following:
- The optimal frequency for the detection of 10 cm objects is around 600 MHz (UHF). This option is very risky from the point of view of frequency allocation, since it is reserved for TV broadcasting. The 435 MHz frequency (UHF also) appears to be a good alternative in terms of implementation risk, detection performance and cost.
- Due to continuous wave (CW) transmission, the proposed European surveillance radar is bistatic (one site for transmission and one site for reception). With respect to GRAVES, its design has considerably evolved within this study, decreasing both complexity and cost:
  - The transmission site is equipped with four arrays, each one composed of custom designed high-gain patch antennas, and fed by high-power transmitters. Simulations and experimental validations have demonstrated the possibility of high-power transmitter coupling with patch antennas. They resulted in recommendations for the optimal patch spacing for the antenna array integration.
  - The proposed reception site is equipped with four arrays, each one composed of high-gain patch antennas. One processor for digital beam forming is attached to each array. Due to the modular design using four arrays, and due to the expected evolution of digital and processing technologies, the complexity of the radar reception part has considerably decreased.

The LEO surveillance system will be capable of cataloguing 98% of the LEO objects contained in the US catalogue. A development plan is proposed with three phases: [1] demonstration phase (one partial transmission array and one partial reception array), [2] pre-operational phase (one complete TX array and one complete RX array), and finally [3] the operational phase.

Concerning the MEO region, the main findings are the following:
- MEO space surveillance shall follow a combined survey and tasking strategy. Two sites are necessary for MEO survey, each one equipped with a dedicated MEO survey telescope. MEO tasking observations will be carried out in combination with GEO tasking observations by the previously proposed GEO telescopes.
- Depending on the efficiency of the MEO survey sensors, 89% of the US catalogue can be covered after 2 months using standard detector technology, while 95% can be covered after 1 month using innovative, demanding detector technology.

A development plan for the European Space Surveillance System (ESSS) is proposed, including a cost evaluation.

The study was carried out by:
Th. Donath (Study Manager), T. Michal, X. Vanwijck, B. Dugrosprez, M. Menelle / ONERA, France

ESA Study Manager : Dr Heiner Klinkrad, ESOC
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1. **INTRODUCTION**

1.1 **PROJECT BACKGROUND**

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 for the safety of operational spacecraft, e.g. for the avoidance of collisions with debris objects. Space Surveillance also provides the basic information for the characterization of the space debris population, for establishing space debris models, and for performing associated risk assessments. A particular issue is the re-entry of objects with large masses, where a significant portion may survive re-entry heating. Space surveillance provides an independent capability of determining the trajectory of a re-entering object and of supporting the assessment of risk on ground.

While some European radar and optical facilities exist for tracking space objects on an ad hoc basis, Europe has no systematic, operational capability for space surveillance, and is hence strongly dependant on external information from the USA and Russia. France is presently developing the prototype space surveillance system GRAVES (Grand Reseau Adapté à la Veille Spatiale) for LEO, with limited capability concerning the detectable object size.

In 2002, ESOC specified a design and performance analysis study for a European Space Surveillance System. Following an open tender, the study was awarded to a team led by ONERA. The purpose of the study was to establish the requirements, to define the system architecture, to analyse the performance and to assess the costs of a European Space Surveillance System (ESSS). The main challenges for the system design were the minimum size of objects to be detected and tracked (>10 cm in LEO and >1 m in GEO), and the requirement of autonomous operation, building a catalogue with no external information. In 2004, ONERA and its subcontractors proposed a Space Surveillance System based on two sub-systems, one for LEO and one for GEO surveillance. The proposed LEO surveillance sub-system was a single radar operating in UHF and characterized by a large field of view (20° in elevation and 180° in azimuth), with a maximum range of 1500 km for a 10 cm sphere. This bistatic radar would be located in the south of Spain. GEO surveillance was ensured by a mixed strategy combining survey and tasking. The GEO survey was carried out by four dedicated 0.5 m telescopes, located at four different low-latitude sites (Marquesas Islands, Tenerife, Cyprus and Perth). Four additional 0.5 m telescopes located at the same survey sites performed the necessary tasked observations.

In 2004, ESOC specified a follow-on study dedicated to the detailed assessment of the previously proposed European Space Surveillance System with two major goals: re-assessment of the survey radar proposed for the LEO sub-system, and proposal of solutions for MEO surveillance (that is of increasing importance for Europe due to the GALILEO deployment). The GEO surveillance concept from the previous study was regarded as mature enough to be adopted unchanged.

The project team was led by ONERA (France) and comprised AIUB (Switzerland), ALCATEL (France), ATEME (France), DGA (France), European Antennas (United Kingdom), FGAN (Germany), INDRA (Spain) and Rohde & Schwarz (Germany). The study started in December 2004 and ended in December 2005.

1.2 **DOCUMENT AND STUDY OBJECTIVES**

This document is the Final Report of the Detailed Assessment of a European Space Surveillance System Study [AD1]. It presents a self-sustained synthesis of the findings and propositions made
within this study as well as the recommendations for the European Space Surveillance System development plan.
As was presented in the project background, two major topics were treated:
- Assessment of the feasibility of the UHF radar proposed for LEO Space Surveillance Sub-system;
- Proposition of a strategy and associated sensors for MEO Space Surveillance;
Another topic was also treated: Surveillance of HEOs.

1.3 STUDY ORGANIZATION AND WORK PACKAGES

In order to reach the precedent objectives, the study was divided in three main work packages:
- WP 1000 : Space Surveillance System for LEO
- WP 2000 : Space Surveillance System for MEO
- WP 3000 : Space Surveillance System for HEO.
Three other tasks have been added on to complete this study:
- WP 4000 : Coordination with parallel GSTP study
- WP 6000 : Dual use of the Space Surveillance System
- WP 5000 : Synthesis and recommendations.

WP 1000 was led by ONERA and also involved European specialists: ATEME (France), European Antennas (United Kingdom), FGAN (Germany), INDRA (Spain) and Rohde & Schwarz (Germany). It was devoted to the feasibility analysis of the proposed UHF radar for the LEO space survey. All aspects of the radar hardware were analysed in detail like the transmission part (elementary transmitter and antenna, transmitters integration in one array, optimisation of the transmission diagram), the reception part (use of digital receivers, high performance computing, reception antennas networks). Operational aspects were also taken into account in the proposition of Spanish sites both for transmission and reception. At last, performance evaluation of the consolidated LEO system was done and a development plan was proposed including the evaluation of the costs.

WP 2000 was realised by AIUB. It was devoted to the proposition of a MEO space surveillance strategy. First, the analysis of the evolution of MEO orbits was carried out before the user requirements were formulated. A strategy for MEO surveillance and the derived architecture of sensors able to fulfill requirements were proposed. Finally, performance evaluation of the MEO system was done and a development plan was proposed including the evaluation of the costs.

WP 3000 was led by DGA and also involved AIUB. It was devoted to a first analysis of difficulties linked with HEO surveillance. Within this study, no dedicated solution for such type of orbit was studied. It was preferred to analyse the possible contribution of other sub-systems (for LEO, MEO and GEO) for the HEO surveillance. AIUB was associated to this analysis, particularly in order to evaluate the performance of MEO and GEO sensors for HEO.

WP 4000 was realised by ONERA and was a coordination task between the present study and a parallel GSTP study led by the DEIMOS company. This GSTP study was concerned with the design of a simulator for the European Space Surveillance System.

WP 6000 was realised by ALCATEL. At the end of this analysis, the requirements from military users of the Space Surveillance System were listed and their impact on the operational use of the system were analysed.

WP 5000 was realised by ONERA. This WP was devoted to synthesis and recommendations.
1.4 APPLICABLE AND REFERENCE DOCUMENTS

1.4.1 Applicable documents


1.4.2 Reference documents


(Desmet, 2004c) P. Desmet, WP6230: Development plan and cost for GEO space surveillance system, Study note, Issue 1, March 2004.


1.5 ABBREVIATIONS

AIUB  Astronomical Institute University of Bern
CASTOR  Canadian Automated Small Telescope for Orbital Research
CCD  Charge-Coupled Device
COTS  Commercial Off The Shelf
CW  Continuous Wave
DE  DEclination
DGA  Délegation Générale pour l’Armement
DMS  Data Management System
ESSS  European Space Surveillance System
FoV  Field of View
GEO  Geostationary Earth Orbit
GNSS  Global Navigation Satellite System
GRAVES  Grand Réseau Adapté à la VEille Spatiale
GSM  Global System for Mobile communications
GSTP  General Support Technology Program
GTO  Geostationary Transfer Orbit
FFT  Fast Fourier Transform
FPGA  Field Programmable Gate Array
INTA  Instituto Nacional de Technicas Aeroespaciales
ITU  International Telecommunications Union
LEO  Low Earth Orbit
MASTER  Meteoroid and Space Debris Terrestrial Environment Reference
MEO  Medium Earth Orbit
MoD  Ministry of Defence
PROOF  Program for Radar and Optical Observation Forecast
RA  Right Ascension
RCS  Radar Cross Section
REO  Remaining Earth Orbit
RF  Radio Frequency
SSC  Space Surveillance Centre
SSS  Space Surveillance System
SSUI  Space Surveillance User Interface
S3  Space Surveillance Simulator
TLE  Two Lines Element
UC  Use Case
UHF  Ultra High Frequency
VHF  Very High Frequency
VSWR  Voltage Standing Wave Ratio
WP  Work Package
2. LEO SPACE SURVEILLANCE SYSTEM

Following a brief presentation of the proposed LEO surveillance system in the previous study (Donath et al, 2004) (subsection 2.1), this section covers, in a brief (but self-sustained) manner, the results of the work done and coordinated by ONERA on the consolidated design of the radar (subsection 2.2), the performance evaluation of the updated LEO surveillance system (subsection 2.3) and at last, on the proposition of a development plan and the cost evaluation (subsection 2.4). The structure of this section does not fully respect the WP breakdown of the study proposal.

2.1 PREVIOUS DESIGN FOR LEO SSS

2.1.1 Catalogue maintenance principle

The LEO definition used in this analysis corresponds to orbits whose apogee altitude is lower than 2000 km. Such orbital objects represent almost 70% of the USSTRATCOM catalogue.

The proposed strategy for LEO space catalogue maintenance is based on pure survey observations. The GRAVES system experience (Michal et al, 2005) 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 the 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 that gives the minimum daily detection and tracking interval of 10 s for each object.

2.1.2 Survey sensor requirements

The sensor requirements have been derived from the proposed strategy for the catalogue maintenance. Some of them have been obtained by way of simulations using the S3 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.
- 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 the US catalogue), only one sensor appears to be necessary.

2.1.3 Survey sensor preliminary design

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 was necessary compared to four EGLIN type sensors and that COTS technology may be used for transmitters, the GRAVES sensor design has been recommended.

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

### Table 1 – 2010 sensor characteristics

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power supply</th>
<th>Number of arrays and transmitters</th>
<th>Number of receiving antennas</th>
<th>Reception processing power</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF (600 MHz)</td>
<td>9.6 MW</td>
<td>4x30</td>
<td>4000</td>
<td>17 Tflops</td>
</tr>
<tr>
<td>(\Delta t) integration</td>
<td>Transmitter location</td>
<td>Reception location</td>
<td>Range (10 cm sphere)</td>
<td>FoV (elevation x azimuth)</td>
</tr>
<tr>
<td>1.6 s</td>
<td>5.3°E, 37.9°N</td>
<td>5.3°E, 36.1°N</td>
<td>1500 km</td>
<td>20°x180°</td>
</tr>
<tr>
<td>Min elevation</td>
<td>Elevation measurement precision</td>
<td>Azimuth measurement precision</td>
<td>Doppler measurement precision</td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td>0.25°</td>
<td>0.25°</td>
<td>0.5 m/s</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2 – 2015 sensor characteristics

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power supply</th>
<th>Number of arrays and transmitters</th>
<th>Number of receiving antennas</th>
<th>Reception processing power</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF (600 MHz)</td>
<td>9.6 MW</td>
<td>4x30</td>
<td>10800</td>
<td>47 Tflops</td>
</tr>
<tr>
<td>(\Delta t) integration</td>
<td>Transmitter location</td>
<td>Reception location</td>
<td>Range (10 cm sphere)</td>
<td>FoV (elevation x azimuth)</td>
</tr>
<tr>
<td>1.6 s</td>
<td>5.3°E, 37.9°N</td>
<td>5.3°E, 36.1°N</td>
<td>1700 km</td>
<td>20°x180°</td>
</tr>
<tr>
<td>Min elevation</td>
<td>Elevation measurement precision</td>
<td>Azimuth measurement precision</td>
<td>Doppler measurement precision</td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td>0.25°</td>
<td>0.25°</td>
<td>0.5 m/s</td>
<td></td>
</tr>
</tbody>
</table>

### 2.1.4 Prevision of LEO system performance

The performance of the process of orbital parameters catalogue maintenance is very difficult to demonstrate. In fact, it would have been 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 was out of the scope of the 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 summarised in Table 3.

Table 3 - Performance of 2010 and 2015 solutions with respect to the GRAVES's performance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GRAVES solution</th>
<th>2010 solution</th>
<th>2015 solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct detection % of USSTRATCom LEO objects</td>
<td>20 %</td>
<td>97.7 %</td>
<td>98.8 %</td>
</tr>
<tr>
<td>Mean number of detections for 1 month and 1 object</td>
<td>80-90</td>
<td>100-110</td>
<td>110-120</td>
</tr>
<tr>
<td>Mean duration of detection</td>
<td>130 s</td>
<td>250 s</td>
<td>260 s</td>
</tr>
<tr>
<td>Mean duration of detection gap</td>
<td>8 hours</td>
<td>6 hours</td>
<td>6 hours</td>
</tr>
<tr>
<td>Longest duration of detection gap</td>
<td>13 hours</td>
<td>11 hours</td>
<td>11 hours</td>
</tr>
</tbody>
</table>

2.1.5 Recommendations for feasibility study

As previously presented, the LEO SSS is based on a powerful UHF radar which concept is identical to the one of the VHF GRAVES radar type. This concept has been proven to be operational but direct problems arising from its use must be solved in any cases:
- Two sites are necessary since this radar is bistatic. These two sites must be far enough to ensure a correct functioning: A 200 km distance between two sites has been proven to be the optimal trade-off. The transmission site must be located at the North of the reception site and must be carefully analysed taking into account power supply constraints and safety conditions for persons and environment. The reception site must be also chosen very carefully considering the local electromagnetic noise level. This one must be as low as possible in order to fulfill or give some freedom to link budget.
- Concerning space debris surveillance, previous study (Donath et al, 2004) has shown that a 35° North location was optimal. That prescribes to find two sites in Spain as well as to recommend the possible frequency that could be allowed by this country for transmission.

Because of these problems related to the radar concept, space debris surveillance implies many extensions with respect to the original sensor:
- From the transmission point of view, the reference solution proposed is characterized by a 9.6 MW power supply (compared to the 0.4 MW power supply of the GRAVES radar). The 9.6 MW power is obtained with 4 transmission arrays, each of these arrays composed with 30 elementary transmitters of 40 kW each. The hypothesis which is considered for the efficiency of each transmitter is 0.5. This efficiency value is plausible but must be validated. Moreover, the proposition of using the elementary power class of 40 kW is linked to the fact that the coupling of the transmission antenna and of the transmitter will not cause any problem. Other power classes exist for elementary transmitters which efficiency must be verified as well as the coupling with the transmission antenna.
- From the reception point of view, the reference solution proposed is characterized by 4000 antennas for the mid-term (2010) step and 10000 antennas for the 2015 step (compared to 100
antennas for GRAVES). The reception data processing requires 17 Tflops computing power in 2010 and 47 Tflops in 2015 (compared to 60 Gflops required for GRAVES). These values are reachable within the specified terms but the reception data processing must be re-optimized with respect to GRAVES's one due to the changes in frequency (VHF to UHF), in integration time duration (0.8s to 1.6s) and in the number of channels.

- From the global transmission/reception point of view, the equilibrium which has been proposed between transmission and reception may evolve if unfeasibility arises for one component: For example, a transmitter efficiency lower than 0.5 (hypothesis taken into account in the reference solution) will lead to a higher power supply; this last value may become inconsistent with the proposed site constraints; then, another transmission and reception equilibrium will have to be proposed in order to cope with this problem. Radar cost has also to be considered. This one is mainly due to hardware cost. If another proposition was made with respect to transmission and reception, cost aspects would also have to be deeply analysed in order for price not to increase (better decrease).

Then, the problem of proving the feasibility of such radar is rather complex since the unfeasibility of one element may not lead to the global unfeasibility of the concept but to the proposition of another global trade-off. The next paragraph will show the results obtained with respect to this analysis.

2.2 CONSOLIDATED LEO RADAR DESIGN

2.2.1 Methodology

In order to deal with this complexity, we will adopt following principles:

- Consider the reference solution previously presented just as a candidate solution among others;
- Analyse the feasibility for all possibilities at the component level;
- Authorise new trade-offs for transmission and reception equilibrium;
- Take into account cost and schedule aspects.

The following methodology will be applied:

- In order to recommend the trade-off for transmission and reception:
  - Analysis of the aspects that will affect global solution equilibrium like the final frequency choice, sites recommendations (WP 1200) and use of polarimetry (WP 1110).
  - Analysis of the elements that will impact on the transmission part (WP 1120) of link budget: elementary transmitter efficiency (WP 1121), choice of transmitter power class, feasibility of antenna and transmitter coupling (WP 1122), transmitters' integration on one array (WP 1123), transmission diagram optimisation (WP 1124).
  - Analysis of the elements that will impact on the reception part (WP 1130) of link budget: interest of digital receivers (WP 1131), data processing constraints (WP 1132), high performance computing (WP 1133), arrangement of reception antennas networks (WP 1134).
  - Synthesis of all previous aspects (WP 1100).
- For the final and retained trade-off:
  - Analysis of measurement data processing (WP 1300).
  - System performance evaluation (WP 1400).
  - Update of development plan and cost (WP 1500).

In this final report, a synthesis of the lessons learned in the major fields is presented (cf. paragraph 2.2.2) and their impact on the global design of the radar (cf. paragraph 2.2.3).

2.2.2 Lessons learned

2.2.2.1 Polarimetry analysis

Polarimetry in this context consists in adding a second channel to the receiver which becomes able to receive and process the orthogonally polarized reflected wave. The objectives of the analysis done by the FGAN [AD2] are to assess the benefit of polarimetry:
Concerning the polarimetry for detection/range improvement, conclusions are the following:
- Use of circular polarization with respect to linear one gives 3 dB gain in theory
- Using an optimal processing, the practical average gain is 2.3 dB
- Without the optimal processing, the practical average gain is 0.7 dB
- Phase coherency is required for optimal processing
- Detection of additional targets (only visible in orthogonally polarized channel) becomes possible.

Concerning the polarimetry for target characterization, the preliminary conclusion is that the use of circular polarization eases rough type classification but that further detailed study is necessary.

For its interest in terms of link budget, the technical analysis recommends using circular polarimetry. Nevertheless, the cost impact of such choice may be important and this solution will be considered as an option for the consolidated trade-off to give some margin if necessary.

2.2.2.2 Frequency analysis

The preliminary radar design (Donath et al, 2004) proposed the frequency which optimises the link budget with respect to cost, independently of allocation constraints. This frequency was 600 MHz. The analysis made by INDRA [AD10] shows following elements:
- The 600 MHz frequency lies in the middle of the 470 – 790 MHz band reserved exclusively for analog and digital TV broadcasting. International Radio Regulation does not allow within a certain band the use of its frequency spectrum for any other attribution than those clearly detailed in the Radiocommunications Regulation.
- Two ways can be imagined to obtain the 600 MHz allocation: First, using the article 4.4 of ITU, namely the “principle of no interference” outside the Spanish territory, but the responsible governmental service has proven to stand on a little permissive position regarding this alternative. Second, changing the ITU Radiocommunications Regulation which is an extremely slow process with very little chance of succeeding.
- The 600 MHz frequency has not been discarded for the rest of the analysis but it is certainly not a short-term and low-risk solution.
- Two available alternatives exist for frequency allocation if we consider that the radar offers a radiolocation service: the 430-440 MHz and the 890-942 MHz bands.
- The 890-942 MHz band would correspond to a secondary attribution since the primary one is the GSM mobile service. This band has been studied from the radar trade-off point of view and both the risk of interference problems with GSM and the increased requirement in reception processing power lead us to discard this choice.
- The 430 – 440 MHz band would correspond to a primary attribution. This band has been studied from the radar trade-off point of view and the 435 MHz solution is the recommended frequency as short-term and low-risk solution.

The analysis shows that the 600 MHz frequency is a high risk option with respect to frequency allocation and recommends the 435 MHz solution.

2.2.2.3 Elementary transmission component analysis

The first solution to increase the radar transmission power as keeping the GRAVES’s global transmission array design is to use elementary transmitters with much higher power than the GRAVES’ ones. Then, points to be verified are the efficiency of such high power transmitter and the capability of designing a transmission antenna able to support this type of transmitter with a correct gain and beam width in elevation and azimuth.

The analysis of such elementary transmission component (both transmitter and antenna) is presented hereafter, regarding:
- Transmitter efficiency
- Transmitter maximal power output
- Design of the antenna
- Realisation of a prototype antenna
- Evaluation of the antenna gain and beam width in elevation and azimuth.

The antenna capability to handle high power transmitter is also verified in order to propose:
- The number of transmitters necessary to obtain the required radar range
- The correct spacing between two transmission elements for the global array design.

Then, the sub-contractors Rohde & Schwarz for transmitter and European Antennas for transmission antenna have realised experiments to give a valuable answer. That means for the antenna that a prototype was built in order to ensure the obtained results. Since these WP were defined at the beginning of the study, all the analysis have been done at the initial optimum frequency of 600 MHz since the frequency allocation problems (cf. 2.2.2.2) were not known.

2.2.2.3.1 Elementary transmitter analysis

The objective of this work [AD3] is to verify that it is possible to use COTS elements for transmitter (i.e. standard TV transmitter) while obtaining the best efficiency and power output to lower the power supply and the global number of transmitters (to ease the array integration) and globally to reduce the cost of the proposed radar. In fact, the transmitters for the GRAves radar are 2 kW each and it would be interesting to use higher power transmitters (up to 20 kW) for the proposed European radar.

For the amplifier, Rohde & Schwarz FTK used a TV amplifier VH602A2 (cf. Figure 1). Inside of such an amplifier are eight fundamental amplifiers, one driver amplifier and one pre-driver. A dedicated water system cooling has been designed for this study (“water” for all high power transistors and dummy loads inside the RF part and inside the power supply unit and “air” for heat sources that cannot be connected to the heat sink directly). In order to obtain the maximum efficiency and output power, some modifications have been made on each fundamental amplifier and tests realised on the resulting complete amplifier VH602A2.

The results are very encouraging since Rohde & Schwarz shown that:
- It is possible to get an amplifier for the European radar up to 16 kW per rack,
- The available amplifier must be modified in some points:
  - Input VSWR must be improved in order to decrease reflected power,
  - Quiescent currents must be reduced,
  - Output coupler that sums up the eight outputs has to be redesigned since additional air cooling is needed,
  - The circulator integration in the rack concept has to be defined: either one circulator for the eight outputs or one circulator for each output. The circulator redirects the reflected power towards dummy loads.
- The efficiency will be at about 48% depending on the power supply unit.
- The efficiency will decrease by about 2% depending on the circulator performance.
- The RF output power per rack will be 1 x 15...16 kW (or as possible variants 2 x 8 kW, or 4 x 4 W or 8 x 2 kW)
- The noise figure of an amplifier is about 7.4 dB and it is necessary to take care of the oscillator noise.
- For the system, heat exchangers are required in the range of the total RF-power.
The analysis made for the 600 MHz transmitter recommends using maximum 16 kW amplifier per rack. The efficiency will be at about 48% depending on the power supply unit.

2.2.2.3.2 Elementary transmission antenna analysis

The objective of this work [AD4] is to propose a transmission antenna functioning at 600 MHz with a beam width of 45° in both elevation and azimuth and capable of handling 20 kW continuous power. For this work, following steps are done:
- Antenna design and realisation
- Simulated performance evaluation
- Experimental performance evaluation.

The high power handling requirement for the antenna rules out the use of many commercially available dielectric materials for the construction of the antenna. Air is chosen as the principal dielectric within the antenna design, with high purity alumina being used for structural support of the antenna where necessary. Such a material has the twin benefits of a low loss tangent, therefore minimising the heat dissipation within the material, and a very high chemical stability, so that variation of dielectric characteristics with operation is minimal. This leads to a concept being developed of using a series of brass plates over a ground plane, that are attached via a central pillar. A three brass plate design is selected to be able to get beam widths closest to the 45° specified. The alumina ceramic is used as a spacer to ensure that the individual plates are correctly positioned.

The EIA 3 1/8” coaxial cable system is selected, as it is capable of handling the required 20 kW power level at 600 MHz with sufficient margin in case the final VSWR levels do not prove to be as good as hoped for. Although the VSWR for the antenna was never formally specified, it is understood that the need for a good match is paramount as a design goal, and the internal target for the return loss is –25 dB.

The required beam width of 45 degrees in each perpendicular cut is narrower than would be obtained from a normal single patch. Therefore, it is intended to increase the directivity of the patch by using a series of parasitic resonators placed over the individual patch. A number of structures are modelled to optimise the beam widths and the VSWR. In order to keep the dielectric strength of the
antenna high for power handling purposes, the distance between each element is also kept large as a design requirement. The structures are then optimised for return loss and beam widths at the resonant frequency. The resulting antenna is shown in Figure 2.

Figure 2: High power transmission antenna

Performance is first assessed using simulation and then confirmed by measurements in a test range. Figures 3, 4 and 5 show the obtained results with respect to beam widths and return loss.

Figure 3: Simulated and experimental elevation patterns (Frequency 600 MHz)
Then, simulation is extended to a pair of patches placed side by side. In this mode, the effect of an adjacent antenna upon the radiation patterns of a single antenna can be analysed. The coupling between the input ports of each adjacent antenna is also computed. These simulations are performed for antenna spacings of 0.5\(\lambda\) and 0.7\(\lambda\). The 0.7\(\lambda\) spacing is finally recommended.

2.2.2.3 High power testing

As the agreement with both the simulated data and the original project requirements is good, the antenna has been sent to Rohde & Schwarz in Berlin for high power testing [AD4]. As the transmitter in Berlin is not capable of a continuous output of 20 kW, but is able to deliver 20 kW in a pulsed mode, the test is therefore devised whereby the antenna subjected to increasing levels of CW power, and a final pulse test is then conducted to the full pulsed capability of the transmitter. Each step in power is applied for a period longer than the thermal time constant of the antenna and the antenna is inspected prior to increasing the power to the next step (cf. Figure 6).
The monitoring during the high power tests show no antenna fault at the possible levels of power. The antenna therefore demonstrates successful operation at 6.3 kW average, and 19.9 kW peak. The temperature increase of 7°C above ambient temperature for 6.3 kW input power, leads to a calculated value of 22.2°C above average for 20 kW, due to the linear relationship between heat flow and temperature gradient. As the antenna structures can withstand 100°C above ambient temperature, this shows that the antenna can withstand the 20 kW power level with a substantial margin. The peak power test also shows that in addition to the thermal issues having been successfully addressed, all issues with dielectric breakdown have also been fully addressed. This antenna can therefore be used directly with any of the transmitter variants up to 20 kW that are under consideration (i.e. 2, 5 and 10 kW). Although the dielectric breakdown limit for the antenna has not been proven, it is clearly above 19.9 kW, and analysis of the field strengths in the simulation would again indicate that there is a substantial margin at the 20 kW level.

The design and analysis made for the transmission antenna show that it is possible to get a patch antenna capable of handling continuous high power transmission (up to 20 kW), with a beam width of 33 ° in elevation and 55 ° in azimuth and a gain of 11.2 dB.
2.2.2.4 Transmission array integration

To allow for the previous solution's failure, i.e., using high power transmitters and then globally aiming to keep the global design of the GRAVES's transmission array (cf. paragraph 2.2.2.3), the second solution is to use low power transmitters but to increase their number. If three lines of transmitters are kept for the array, as for the GRAVES's one, the number of columns must be increased as much as decreasing the power of each elementary transmitter. This will decrease the azimuthal beam width of the main lobe. In order to keep a constant beam width, the idea is to add a phase on the signal of every transmitter.

This solution has been analysed in parallel to the technological solution presented before [AD5]. In order to have a complete view of the capability of such solution, it has been derived for all types of transmitters from 2 kW (GRAVES equivalent ones) up to 20 kW (upper limit of previous solution). The tested configurations are:

- 3 lines and 100 columns of 2 kW transmitters
- 3 lines and 40 columns of 5 kW transmitters
- 3 lines and 20 columns of 10 kW transmitters
- 3 lines and 10 columns of 20 kW transmitters.

The developed numerical method gives good results in all tested configurations. For all cases, the side lobes are smaller than in the GRAVES's configuration and the main lobes are square with 120 (40 x 3) or 300 (100 x 3) transmitters per panel.

The method is robust. An error with a standard deviation of 10% on amplitude and 2° on phase involves a 1.5 dB variation on the radiation pattern in the main lobe.

2.2.2.5 High performance computing

The objective of this work [AD6] is to evaluate the feasibility of high performance computing as required for the proposed radar design. Let us recall that the GRAVES radar design requires for digital beam forming 60 GFlops and the European radar may require up to 17 Tflops for the 1500 km range version (cf. paragraph 2.1.3). The requirement for such a computing performance is due to the global radar trade-off and the interest in decreasing as much as possible the transmitted power.

The ATEME company analysed this problem and the conclusion is that there is no hard point in the realisation of a computer of the 10 Tflops class for the 2010 horizon, knowing that several supercomputers of 100 TFlops already exist.

The architecture proposed by ATEME would be a mixed hardware solution using COTS processors for the digital beam forming process and customised FPGA for the FFT process. FPGA are programmable specialized hardware for optimisation of cost and performance. The data transfer between receivers (probably digital receivers as was shown to be interesting in [AD7]) and real time computer would use optical fibres technology. This solution has the advantage to limit the power supply and the thermal dissipation problems and to reduce the cost.

2.2.2.6 Sites analysis

The proposed radar is a bistatic one and the recommended location for this sensor is the South of Europe. Taking into account the fact that Spain was highly interested in receiving such type of sensor, INDRA [AD10] analysed the feasibility of proposing two Spanish sites, one for transmission (TX) and one for reception (RX).

2.2.2.6.1 Radar TX site

TX site is of course the more difficult site to choose since many constraints must be taken into account: safety, cost and performance. Extremadura appears to be the most valuable Spanish region for the ESSS project with following characteristics:

- Lowest population density in Spain
- Cheaper ground prices
- Wide area of protected air space
- Dense network of high voltage power lines
- Close to main power plants.

Taking into account air space and environmental protected areas as buffer areas of 5 km with restricted population (less than 200 people), 5 areas are proposed in Extremadura and 12 candidate sites for TX. Each one has been surveyed in-situ and results are graphed under the dimensions of safety and cost (see Figure 7).

![Comparison of candidate TX sites with respect to safety and cost](image)

Figure 7: Comparison of candidate TX sites with respect to safety and cost

Pico Villuercas seems to be a singular point. This is a site belonging to the Ministry of Defence that used to be a transmission centre (see Figure 8). It benefits from a privileged placement on top of a mountain and existing infrastructures. This site presents good communications by road. The ground shape is elongated (TX arrays will have to be arranged in a particular way) and there is no room for further scalability.

The final recommendation for the TX site is to use Pico Villuercas as first option and Logrosan as backup alternative.
2.2.2.6.2 Radar RX site

Major constraints for RX site are linked to radar bistatism and noise factor. The RX site must be located in a Southern location from the TX site, at a distance of around 200 km. Due to the TX site location in Extremadura, the RX site will invariably be in Andalucia. Safety is not an issue, neither is performance since simulations have been done with a lot of TX and RX couples of sites and the sensitivity of detection rates is very low.

After in-situ investigations, the area of Eastern Sevilla seems to provide innumerable candidates for the RX site. Among them, one site offers particular interest due to the low risk involved. It is the base of Arenosillo, in Huelva (see Figure 9). This base belongs to INTA and is mainly dedicated to scientific and technological research. Noise factor has been measured in the 430 – 440 MHz band and is below the noise floor of the spectrum analyser.

The final recommendation for the RX site is to use Arenosillo for easiness of deployment and low risk reasons.

The Figure 10 illustrates the locations of recommended TX and RX sites on Spain map.
2.2.3 Impact on the global radar trade-off

Lessons learned from WPs relative to technological issues lead to the main following conclusions:

- Except for frequency allocation, previous assumptions made for the preliminary radar design are consolidated.
- The patch antenna design made for transmission part appears to be very interesting in terms of gain.
- The 600 MHz frequency is a high-risk option from allocation point of view, but the corresponding radar trade-off will be studied.
- The 435 MHz solution is a lower risk solution and will be studied in terms of radar global design.

2.2.3.1 Radar global trade-off requirements

The European radar trade-off requirement is presented taking as a reference the GRAVES’s concept (Dugroprez, 2003). Let us recall the link budget equation for a bistatic radar:

\[
\frac{S}{N} = \frac{P_t G_t G_r \lambda^2 \sigma(\lambda) T_{int}}{(4\pi)^3 R_1^2 R_2^2 LFKT_0}
\]

Where

- S/N : Signal to noise ratio
- \(P_t\) : Transmitted power
- \(G_t\) : Transmission antenna gain
- \(G_r\) : Reception antenna gain
- \(\lambda\) : Transmitted wavelength
- \(\sigma\) : Object RCS depending on wavelength
- \(T_{int}\) : Integration time
- \(R_1\) : Range between transmitter and detected object
Taking the GRAVES’s link budget as a reference, it is required to get for the European radar the following equilibrium:

\[
\frac{P_t G_r G_s \lambda^2 \sigma(\lambda) T_{\text{int}}}{S/N R_i^2 R_s^2 L F} \quad \text{GRAVES}
\]

\[
\frac{P_t G_r G_s \lambda^2 \sigma(\lambda) T_{\text{int}}}{S/N R_i^2 R_s^2 L F} \quad \text{European radar}
\]

Let us distinguish the parameters imposed by the radar mission and those required to be designed. Radar mission impose: wavelength (frequency), RCS (depending on frequency) and range. Comparing both missions, the European radar one and the GRAVES radar one, it is possible to evaluate the global link budget requirement for the European radar with respect to GRAVES. Two frequency versions must be studied for the European radar, the previous one (at 600 MHz) and a new version at 435 MHz. The following table gives the gains or losses on link budget for each frequency version due only to mission fulfilment.

### Table 4: European radar requirements with respect to GRAVES requirements

<table>
<thead>
<tr>
<th>Radar parameters</th>
<th>Gain/loss 600 MHz</th>
<th>Gain/loss 435 MHz</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>-12.45 dB</td>
<td>- 9.66 dB</td>
<td>The use of a higher frequency induces losses with respect to the VHF GRAVES’s frequency.</td>
</tr>
<tr>
<td>Object RCS</td>
<td>-21.05 dB</td>
<td>-26.19 dB</td>
<td>The European radar must detect 10 cm size object (assumed spherical).</td>
</tr>
<tr>
<td>Range</td>
<td>+2.17 dB</td>
<td>+2.17 dB</td>
<td>The European radar has a reduced range with respect to the GRAVES’s one.</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-31.33 dB</strong></td>
<td><strong>-33.68 dB</strong></td>
<td>Evaluation of the European radar losses with respect to GRAVES link budget due to the mission fulfilment.</td>
</tr>
</tbody>
</table>

In any frequency case, the mission of debris surveillance is very demanding on link budget improvement. More than 30 dB must be added to the GRAVES link budget to fulfill this mission. In the previous design (cf. paragraph 2.1.3), this was obtained by increasing the transmitted power, increasing the number of receiving antennas, and consequently increasing the processing power. The following table indicates the choice made for the other parameters to equilibrate the link budget.
Table 5: Previous parameter design for the European radar

<table>
<thead>
<tr>
<th>Radar parameters</th>
<th>Gain/loss 600 MHz previous version</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of transmission antennas</td>
<td>+1.24 dB</td>
<td>The previous 600 MHz solution has 30 antennas with respect to GRAVES.</td>
</tr>
<tr>
<td>Elementary transmitter power</td>
<td>+13 dB</td>
<td>The previous 600 MHz solution uses 40 kW transmitter compared to the 2 kW GRAVES ones.</td>
</tr>
<tr>
<td>Transmission antenna gain</td>
<td>0 dB</td>
<td>Assumed to be identical to the GRAVES one.</td>
</tr>
<tr>
<td>Circular polarization</td>
<td>+3 dB</td>
<td>Theoretical gain given by circular polarization is assumed.</td>
</tr>
<tr>
<td>Duration of measurement</td>
<td>+3 dB</td>
<td>The duration of measurement is 1.6s compared to 0.8s for GRAVES.</td>
</tr>
<tr>
<td>Reception antenna gain</td>
<td>0 dB</td>
<td>Assumed to be identical to the GRAVES one.</td>
</tr>
<tr>
<td>Reception network gain</td>
<td>+6.02 dB</td>
<td>The previous 600 MHz solution has ten sub-networks of 400 antennas with respect to the GRAVES solution of 100 antennas.</td>
</tr>
<tr>
<td>Reception sub-network gain</td>
<td>+5 dB</td>
<td>The previous 600 MHz solution has ten sub-networks.</td>
</tr>
<tr>
<td>Detection threshold</td>
<td>0 dB</td>
<td>Assumed to be identical to the GRAVES one.</td>
</tr>
<tr>
<td>Loss factor</td>
<td>0 dB</td>
<td>Assumed equivalent to the GRAVES loss factor.</td>
</tr>
<tr>
<td>Noise factor</td>
<td>0 dB</td>
<td>Estimated equivalent to the GRAVES noise factor.</td>
</tr>
<tr>
<td>Total</td>
<td>+31.26 dB</td>
<td>The previous 600 MHz solution has an equilibrate link budget with respect to the GRAVES solution.</td>
</tr>
</tbody>
</table>

Next paragraphs will present the way the previous parameters have been changed to take into account the results of the present study.

2.2.3.2 New radar reception design

After analysis of the study made by European Antennas, it appears that the use of patch antennas is very interesting because of their high and predictable gain. Then, the idea comes to use such antennas both for transmission and for reception. Such solution would provide additional gain on transmission and reception through two ways:
- The gain of directivity would be applied either on transmission and reception.
- The use of such patch in reception implies to change the horizontal configuration of the GRAVES’s reception array. Historically, the GRAVES radar uses such a single antenna array in reception in order to provide an omni-directional capacity in azimuth, and to limit the number of antennas and consequently, the processing cost. For the European radar case, the need for a
A great increase in transmitted power combined with the reduction of the processing cost allow to propose a radar architecture based on a powerful reception part (with respect to the GRAVES's one). Therefore, the reception part of the European radar is proposed to be made of four arrays, each one tilted towards the space area that is illuminated by each transmission array. Each reception array would be composed of a higher number of patch antennas with respect to the GRAVES's design. The Figure 11 illustrates the new radar design especially from the reception side point of view. On this figure, only one transmission array and one reception array are illustrated.

2.2.3.3 Radar global trade-off

Taking into account this new radar design, the following table shows the global trade-off that is proposed for both frequency solutions.
Table 6: Parameter design for the European radar (600 MHz and 435 MHz solutions)

<table>
<thead>
<tr>
<th>Radar parameters</th>
<th>Gain 600 MHz</th>
<th>Gain 435 MHz</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of transmission antennas</td>
<td>0 dB</td>
<td>0.64 dB</td>
<td>The 600 MHz solution has the same number of transmission antennas as GRAVES. The 435 MHz solution has 2 more antennas.</td>
</tr>
<tr>
<td>Elementary transmitter power</td>
<td>+7.78 dB</td>
<td>+8.75 dB</td>
<td>The 600 MHz solution uses 12 kW transmitter, the 435 MHz solution uses 15 kW transmitter as GRAVES uses 2 kW ones.</td>
</tr>
<tr>
<td>Transmission antenna gain</td>
<td>+2.45 dB</td>
<td>+2.45 dB</td>
<td>This gain results from the patch antenna design (cf. paragraph 2.2.2.3.2). Same gain is assumed at 435 MHz.</td>
</tr>
<tr>
<td>Circular polarization</td>
<td>0 dB</td>
<td>0 dB</td>
<td>The link budget is equilibrated without taking into account the practical benefit of circular polarization in order to keep some margin and reduce cost.</td>
</tr>
<tr>
<td>Duration of measurement</td>
<td>+0.97 dB</td>
<td>+0.97 dB</td>
<td>For both solutions, the duration of measurement is 1s compared to 0.8s for GRAVES.</td>
</tr>
<tr>
<td>Reception antenna gain</td>
<td>+9.70 dB</td>
<td>+9.70 dB</td>
<td>The reception antenna gain is assumed identical to the transmission antenna gain (cf. paragraph 2.2.2.3.2).</td>
</tr>
<tr>
<td>Reception network gain</td>
<td>+10 dB</td>
<td>+8.75 dB</td>
<td>The 600 MHz solution has one network of 1000 antennas with respect to the GRAVES solution: 100 antennas. The 435 MHz solution has two sub-networks of 750 antennas.</td>
</tr>
<tr>
<td>Reception sub-network gain</td>
<td>0 dB</td>
<td>+1.51 dB</td>
<td>The 435 MHz solution has two sub-networks.</td>
</tr>
<tr>
<td>Detection threshold</td>
<td>+1 dB</td>
<td>+1 dB</td>
<td>The threshold for both European solutions is reduced from 1 dB with respect to GRAVES.</td>
</tr>
<tr>
<td>Loss factor</td>
<td>0 dB</td>
<td>0 dB</td>
<td>Assumed equivalent to the GRAVES one.</td>
</tr>
<tr>
<td>Noise factor</td>
<td>0 dB</td>
<td>0 dB</td>
<td>Estimated equivalent to the GRAVES one.</td>
</tr>
<tr>
<td>Total</td>
<td>+31.9 dB</td>
<td>+33.77 dB</td>
<td>Both solutions have an equilibrated link budget with respect to GRAVES.</td>
</tr>
</tbody>
</table>

Concerning the required processing power for reception, the following table gives the breakdown between main operations: digital beam forming, FFT and others (Hilbert transform, incoherent summation, threshold operation ...) for both frequency solutions. In this calculation, data processing (i.e. measurement processing for orbital parameters catalogue maintenance) is not included.

Table 7: Breakdown of the operations for reception processing

<table>
<thead>
<tr>
<th>Operations</th>
<th>600 MHz solution</th>
<th>435 MHz solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital beam forming / array</td>
<td>1.17 TFlops</td>
<td>0.88 TFlops</td>
</tr>
<tr>
<td>FFT</td>
<td>1.63 TFlops</td>
<td>1.11 TFlops</td>
</tr>
<tr>
<td>Others</td>
<td>0.83 TFlops</td>
<td>0.61 TFlops</td>
</tr>
<tr>
<td>Total</td>
<td>3.63 TFlops</td>
<td>2.60 TFlops</td>
</tr>
</tbody>
</table>
Both frequency solutions are presented in the following tables in the same manner as the results of the previous study in paragraph 2.1.3.

### Table 8 – 600 MHz radar characteristics

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power supply (assuming 0.48 for transmitter efficiency)</th>
<th>Number of arrays and transmitters</th>
<th>Number of arrays and receiving antennas</th>
<th>Reception processing power</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF (600 MHz)</td>
<td>2.6 MW</td>
<td>4 x 26</td>
<td>4 x 1000</td>
<td>3.6 Tflops</td>
</tr>
<tr>
<td>Δt integration</td>
<td>Transmitter location</td>
<td>Reception location</td>
<td>Range</td>
<td>FoV (elevation x azimuth)</td>
</tr>
<tr>
<td>1 s</td>
<td>Pico Villuercas</td>
<td>Arenosillo</td>
<td>1500 km (10 cm sphere)</td>
<td>20°×180°</td>
</tr>
<tr>
<td>Min elevation</td>
<td>Elevation measurement precision</td>
<td>Azimuth measurement precision</td>
<td>Doppler measurement precision</td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td>0.25°</td>
<td>0.25°</td>
<td>0.5 m/s</td>
<td></td>
</tr>
</tbody>
</table>

### Table 9 – 435 MHz radar characteristics

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Power supply (assuming 0.48 for transmitter efficiency)</th>
<th>Number of arrays and transmitters</th>
<th>Number of receiving antennas</th>
<th>Reception processing power</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF (435 MHz)</td>
<td>3.5 MW</td>
<td>4 x 28</td>
<td>4 x 1500</td>
<td>2.6 Tflops</td>
</tr>
<tr>
<td>Δt integration</td>
<td>Transmitter location</td>
<td>Reception location</td>
<td>Range</td>
<td>FoV (elevation x azimuth)</td>
</tr>
<tr>
<td>1 s</td>
<td>Pico Villuercas</td>
<td>Arenosillo</td>
<td>1500 km (10 cm sphere)</td>
<td>20°×180°</td>
</tr>
<tr>
<td>Min elevation</td>
<td>Elevation measurement precision</td>
<td>Azimuth measurement precision</td>
<td>Doppler measurement precision</td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td>0.25°</td>
<td>0.25°</td>
<td>0.5 m/s</td>
<td></td>
</tr>
</tbody>
</table>

Conclusions relative to these global radar trade-offs are the following:

- Both frequency solutions seem acceptable with respect to power supply. The 600 MHz solution remains the “easiest” one but the 435 MHz solution corresponds to a balanced solution between power supply and reception processing costs.
- Due to the new radar reception design and the high gains for antennas, radar complexity has decreased a lot.
- Some assumptions are made: antenna gain for both frequencies are the same, transmission and reception antenna gains are the same.
- Some margins exist: use of circular polarimetry, for example.
2.3 LEO SSS PERFORMANCE EVALUATION

2.3.1 Methodology

2.3.1.1 Evaluation methods

The analysis done within this study [AD12] is the same as the one presented in paragraph 2.1.4 for previous study. It consists in evaluating the performance of the orbital parameters catalogue maintenance by means of three kinds of criteria:

- Number of correctly detected objects (an object is correctly detected if it is detected every day more than 10 seconds).
- Duration of detection, duration of detection gap with respect to the GRAVES equivalent parameters.
- Accuracy of orbital parameters estimation.

2.3.1.2 Hypothesis

Concerning object populations, detection performance is evaluated using two “catalogues”, the present one from USSTRATCOM (July 2005) and a predicted one (at the 2010-2012 horizon) by the MASTER software. In the following analysis, LEO objects are defined as objects whose apogee altitude is lower than 2000 km. With this definition, the considered “catalogues” are distributed as follows:

- The USSTRATCOM catalogue contains 5933 objects (i.e. 69.4 % of the global catalogue)
- The MASTER population contains 8552 objects (i.e. 52.3 % of the global catalogue).

For the object RCS, the value given by the US catalogue is considered for the 430 MHz radar solution. For the 600 MHz radar solution, the US RCS value is corrected [AD11] in order to take into account the evolution of RCS with respect to frequency. For the MASTER catalogue, the RCS is evaluated assuming each object to be a sphere.

For the accuracy of orbital parameters estimation, five representative objects are chosen and their characteristics are given in the Table 10.

Table 10: Objects characteristics for the evaluation of the orbital parameters accuracy

<table>
<thead>
<tr>
<th>Name</th>
<th>COSPAR ID</th>
<th>Owner</th>
<th>RCS (dBm^2)</th>
<th>Perigee height (km)</th>
<th>Apogee height (km)</th>
<th>Inclination (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISS</td>
<td>25544</td>
<td>ISS</td>
<td>374.5</td>
<td>351</td>
<td>356</td>
<td>51.6</td>
</tr>
<tr>
<td>SPOT 5</td>
<td>27421</td>
<td>France</td>
<td>8.5</td>
<td>824</td>
<td>825</td>
<td>98.7</td>
</tr>
<tr>
<td>Hubble (HST)</td>
<td>20580</td>
<td>USA</td>
<td>55.9</td>
<td>564</td>
<td>577</td>
<td>28.5</td>
</tr>
<tr>
<td>MAQSAT-3</td>
<td>25503</td>
<td>ESA</td>
<td>35</td>
<td>1012</td>
<td>35494</td>
<td>7.6</td>
</tr>
<tr>
<td>1999-057MR (Debris)</td>
<td>27677</td>
<td>China</td>
<td>0.001</td>
<td>693</td>
<td>807</td>
<td>98.1</td>
</tr>
</tbody>
</table>

Concerning the LEO survey sensor, following hypothesis are taken:

- Two terms are considered: 2010 with a 1500km-range radar and 2015 with a 1700km-range radar.
- Two radar frequencies: 600 MHz and 430 MHz.\(^1\)
- TX and RX sites in Spain (Pico Villuercas for TX and Arenosillo base for RX).

Concerning the simulations done for performance evaluation, they are realised with the S3 software over one month duration.

---

\(^1\) All calculations have been realised for a radar frequency of 430 MHz and not 435 MHz as recommended in the radar trade-off. In fact, the candidate frequency of 435 MHz has been known after performance evaluation analysis but we are confident that a 5 MHz drift would not modify the obtained results.
2.3.2 Detection performance

All radar solutions are evaluated first with respect to detection performances: An object is correctly detected if it is detected every day for 10 s at least. The Table 11 gives the percentage of LEO objects which are correctly detected, depending on which catalogue is used, the frequency of the radar and its range.

Table 11: Performances of LEO objects detection

<table>
<thead>
<tr>
<th>Radar range</th>
<th>Radar frequency</th>
<th>USSTRATCOM catalogue (%)</th>
<th>MASTER population (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 km</td>
<td>600 MHz</td>
<td>99.34</td>
<td>98.8</td>
</tr>
<tr>
<td>1500 km</td>
<td>430 MHz</td>
<td>98.57</td>
<td>96.08</td>
</tr>
<tr>
<td>1700 km</td>
<td>600 MHz</td>
<td>99.44</td>
<td>99.57</td>
</tr>
<tr>
<td>1700 km</td>
<td>430 MHz</td>
<td>99.07</td>
<td>97.81</td>
</tr>
</tbody>
</table>

It is confirmed that the 600 MHz solution is the optimal one from a detection performance point of view, but this frequency remains a high risk option from the allocation point of view. The 430 MHz solution leads to very convenient results and seems acceptable. The far-term solution (1700km range) does not seem as interesting from a detection point of view but this phenomenon is explained by the fact that the US catalogue is relatively empty in the upper-LEO region (due to US sensors sensitivity). The difference of results with the MASTER population is due to the fact that this population contains a higher proportion of small size objects in the upper LEO-region than the US catalogue and these objects cannot always be detected by the radar.

A sensitivity analysis of the detection performance has been realised with respect to the link budget. The objective is to analyse the detection performance robustness in case of a decreased radar link budget. The Figure 12 gives the performance sensitivity in case of the USSTRATCOM catalogue.

Figure 12: Sensitivity of the detection performance to radar link budget
The 600 MHz solution seems to be more robust than the 430 MHz solution since the decrease in detection rate is lower for the same decrease in delivered power. Nevertheless, for the 430 MHz, the detection performance remains acceptable even with a decrease of 1 to 1.5 dB.

### 2.3.3 Catalogue maintenance performance

The following parameters are analysed in order to demonstrate the capability of the proposed European radar to give the convenient information for orbital parameters catalogue maintenance. They are compared to the corresponding GRAVES values:

- Mean number of detections
- Mean duration of a passage in visibility
- Mean and maximal durations of a detection gap.

The Figure 13 gives the mean number of detections over one month with respect to the percentage of correctly detected objects.

![Repartition of the number of detections per month](image)

**Figure 13: Mean number of detections per month**

This figure gives the comparison of the mean number of detections per month for all proposed solutions with respect to the GRAVES radar. For example, 50% of the correctly detected population is detected 82 times a month for the GRAVES radar and 102 times a month for the 430 MHz solution (1500 km range). This increased number of detections for the European radar is very interesting in terms of cataloguing performance since the number of measurements that is available directly affects the orbit estimation accuracy.

The Figure 14 gives the mean duration of a passage in visibility over one month with respect to the percentage of correctly detected objects. For 50% of the correctly detected population by the
GRAVES system, a passage in visibility lasts 104 seconds on average. For 50% of the population detected by the European solution at 430 MHz (1500 km range), a passage in visibility lasts 245 seconds on average. Another analysis consists in observing that a passage in visibility lasts on average more than 3 minutes for only 3.4% of the population detected by the GRAVES system. For the European solution at 430 MHz (1500 km range), it is the case for 76% of the population. As we have seen before, the longer the passage in visibility, the more accurate the orbit estimation process.

![Repartition of the mean duration of a passage in visibility](image)

**Figure 14: Mean duration of a passage in visibility**

The Figure 15 gives the mean duration of a detection gap for one month with respect to the percentage of correctly detected objects.
For 50% of the correctly detected population by the GRAVES system, a detection gap lasts 8.4 hours on average. For the same percentage of the population detected by the European solution at 430 MHz (1500 km range), a detection gap lasts 6.6 hours on average. Another analysis consists in observing that a detection gap lasts more than 24 hours on average for 14.3% of the population detected by the GRAVES system and for only 7.3% of the population detected by the European solution at 430 MHz (1500 km range).

The Figure 16 gives the mean duration of the maximal detection gap with respect to the percentage of correctly detected objects (percentages are given here for all the detected population and not only the LEO detected population).
The longest duration gap lasts on average more than 24 hours for 20% of the population detected by the GRAVES system. For the European near-term solution at 430 MHz (1500 km range), this is the case for only 11.5% of the population detected.

2.3.4 Orbit estimation performance

The orbit estimation process takes into account measurement accuracies. For the European radar, the following Table gives the expected values.

<table>
<thead>
<tr>
<th></th>
<th>GRAVES</th>
<th>European solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>**</td>
<td>0.25°</td>
</tr>
<tr>
<td>Azimuth</td>
<td>**</td>
<td>0.25°</td>
</tr>
<tr>
<td>Doppler</td>
<td>Limited by the ionospheric effect</td>
<td>0.5 ms(^{-1})</td>
</tr>
<tr>
<td>Radial acceleration</td>
<td>Not used</td>
<td>5 ms(^{-2})</td>
</tr>
</tbody>
</table>

The main difficulty of the GRAVES system is the influence of the ionosphere due to the low frequency. This one limits the use of Doppler measurements and prevents the use of radial acceleration. For the European radar, since the transmitted frequency is much higher, the influence of ionosphere is much lower and both the Doppler measurement and the radial acceleration will be available for the orbit estimation process.

Complete results are given in [AD12] and as we presented it in the paragraph 2.3.1.2, they concern five objects. In this final report, we only recall the results obtained for the 430 MHz solution (1500 km range). The Figure 17 gives the evolution of the standard deviations for objects position estimation along 10 passages in visibility.
The main improvement of the accuracy occurs during the three first passages in visibility. The analysis shows that the estimation of the MAQSAT orbit (MAQSAT is a HEO object) is not as accurate as the LEO ones. This is because a HEO object is not observed as often as the LEO ones.

In conclusion, the performance of the consolidated European radar design is confirmed by the estimation made on two populations, the actual one and a predicted one at the 2010 – 2012 horizons.

2.4 LEO SSS DEVELOPMENT PLAN AND COST

2.4.1 Development plan

Two features are taken into account for the proposition of the system development plan [AD13]:
- Technical aspects
- Cost aspects.

Technical aspects : Within this study, some difficult points have been solved from the radar elements point of view : for example, a high power transmitter has been studied, transmission antenna may be designed with an interesting gain, patch reception antenna may also be designed .... The integration of the radar is obviously another difficult point especially from the transmitter side point of view. The radar trade-off (cf. paragraph 2.2.3.3) shows that one transmission array would be composed of 28 transmitters for the 435 MHz solution. Each transmitter would be a 15 kW type. It is clear that the coupling effects on one central transmitter must be studied and experimented. This requires 9 transmitters at least (3 columns and 3 rows) in order to reproduce the worse operational configuration for one transmitter. Such an experience was not possible at this step of the study but remains essential.

Cost aspects : We have mentioned in the previous paragraph that the feasibility of the integration phase of the sensor has to be done. Therefore, it is interesting to propose an incremental
development that spreads financial expenses over time (in particular, taking into account this feasibility phase of sensor integration) and that minimizes these financial expenses (by integrating this feasibility phase in the operational system development). Such constraints may be solved taking into account the modular aspects of the radar proposal.

Three phases are proposed for the development of the LEO sensor of the ESSS and are detailed in the following paragraphs.

2.4.1.1 First phase: Demonstration radar

First phase is a demonstration phase based on a low-cost radar made with a partial transmission array and a partial reception array. This radar will demonstrate the 10 cm size detection capability and will give the opportunity to analyse high power transmitters coupling. In terms of detection capabilities, this radar will have a range of 550 km over a 10 cm sphere and will be able to survey 45° in azimuth. This sensor will only be able to perform object detections since its FoV will not be large enough for ensuring the orbital parameters catalogue maintenance. However, it will allow us analyze the performances of the system concerning the accuracy of the measurements. This phase must use the GRAVES development experience and will allow the training of an industrial team in charge of the following phases of development. At the end of this demonstration phase, the corresponding sensor will be integrated in the development of the operational system.

The technical features of the proposed radar are the following:
- The frequency is 435 MHz since it seems the low-risk choice for a demonstration to be realised as soon as possible.
- The radar is composed of two arrays, one for transmission and one for reception.
- The transmission array is composed of 9 transmitters, 15 kW each. This corresponds to a power supply of 0.281 MW. The FoV in elevation is 20° from 30° up to 50°, which corresponds to an array tilted slightly differently from the operational one. The FoV in azimuth is 45° from 135° up to 180° (South) which corresponds to the operational configuration of the array. The site is Pico Villuercas (Extremadura – Spain).
- The reception array is composed of 220 antennas. The required processing power is 244 Gflops. The site is Arenosillo (Andalucia – Spain).

The detection performances of such radar are evaluated with the S3 software with a one-month experiment and the USSTRATCOM catalogue (cf. 2.3.1.2):
- Among the 5933 LEO objects of the catalogue, 197 objects are correctly detected (i.e. every 24 hours for 10s at least).
- Among the 5933 LEO objects of the catalogue, 3836 objects are detected but not correctly detected.

In parallel to the demonstration radar development, it will be important to identify the special points that will differentiate the European system data processing from the GRAVES system one. If such specific aspects exist, specific algorithms will have to be developed and tested.

2.4.1.2 Second phase: Pre-operational radar

Second phase gives a pre-operational version of the radar. The arrays of the demonstration radar are completed in order to obtain one operational array. The operational range of 1500 km over a 10 cm sphere will be obtained and the survey in azimuth will be 45°. Due to its reduced FoV in azimuth, this sensor will not be able to ensure the orbital parameters catalogue maintenance (mainly because of the low frequency of revisit of the detected objects). Nevertheless, this phase will have a major impact in the development process since an industrial team will lead it.

The technical features of the pre-operational radar are the following:
- The frequency is kept to 435 MHz.
- The radar is composed of two arrays, one for transmission and one for reception.
The demonstration transmission array is completed up to 28 transmitters, 15 kW each. This corresponds to a power supply of 0.87 MW. The FoV in elevation is now 20° from 20° up to 40°, which corresponds to the operational configuration. The FoV in azimuth is 45° from 135° up to 180° (South) which corresponds to the operational configuration of the array (unchanged with respect to the demonstration one). The site is Pico Villuercas (Extremadura – Spain).

The demonstration reception array is completed up to 1500 antennas. The required processing power is now 650 Gflops (This implies the replacement of the reception computer for digital beam forming). The site is Arenosillo (Andalucia – Spain).

Detection performances of such radar are evaluated by simulation covering one-month experiment and the USSTRATCOM catalogue. Results are the following:

- Among the 5933 LEO objects of the catalogue, 953 objects are correctly detected (i.e. every 24 hours for 10s at least).
- Among the 5933 LEO objects of the catalogue, 4943 objects are detected but not correctly detected.

Second phase for data processing will consist in realising the operational data processing system and test it on the available campaigns of detection made with the demonstration radar.

2.4.1.3 Third phase: Operational system

Third phase gives the operational version of the radar: Three more transmission arrays and three more reception arrays are added to obtain the operational system. The operational range of 1500 km over a 10 cm sphere will be obtained and the survey in azimuth will be 180°. This sensor will be able to ensure the orbital parameters catalogue maintenance.

The technical features of the operational radar correspond to the ones presented in paragraph 2.2.3.3:

- The radar is composed of eight arrays, four for transmission and four for reception.
- Each transmission array has the same design as the transmission array realised for the pre-operational step.
- Each reception array has the same design as the reception array realised for the pre-operational step. To each reception array is associated a 650 Gflops computer. That means that the previous reception computer (for the pre-operational step) is kept and three new computers are added to process data from each new reception array.

The predicted performances are those given in paragraph 2.3.

Concerning data processing, the third phase will connect the operational data processing system with the Data Management System (interface with the users). Of course, this requires that the DMS development be initiated earlier (for example, during the demonstration step).

Taking as a hypothesis a beginning in January 2006, the following schedule is proposed:

<table>
<thead>
<tr>
<th>Year</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>6</td>
<td>12</td>
<td>18</td>
<td>24</td>
<td>30</td>
<td>36</td>
</tr>
<tr>
<td>First step</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second step</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Third step</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With respect to other phases, the first phase has a relatively long duration since it is a technical feasibility phase, a demonstration phase and allows the “training” of the industrial team in charge of the operational phases (second and third ones).
2.4.2 Cost evaluation

The cost evaluation is made for the three preceding phases distinguishing the transmission part (hardware only), the reception part (hardware only) and the manpower part. The operational system is based on the 435 MHz radar solution (1500 km range).

For the transmission part, the following elements are taken into account:
- Transmitter development (for the case of the demonstration step)
- Number of elementary transmitters
- Number of patch antennas
- Number of transmission arrays
- Number of connectors
- Number of shelters and required air-conditioning.

For the reception part, the following elements are taken into account:
- Number of patch antennas
- Number of digital receivers
- Number of reception arrays
- Number of computers
- Number of connectors
- Number of shelters and required air-conditioning.

For the manpower part, the evaluation made by the industrial team in (Donath et al, 2004) has been kept and applied to the pre-operational and the operational steps. For the demonstration step, an additional manpower evaluation has been made and is presented here.

The following table 13 presents the cost evaluation breakdown for the three successive steps:

<table>
<thead>
<tr>
<th></th>
<th>Demonstration step (M€)</th>
<th>Pre-operational step (M€)</th>
<th>Operational step (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission part</td>
<td>4.5</td>
<td>7.0</td>
<td>33.3</td>
</tr>
<tr>
<td>Reception part</td>
<td>4.0</td>
<td>9.3</td>
<td>30.4</td>
</tr>
<tr>
<td>Man power</td>
<td>2.8</td>
<td>5.7</td>
<td>17.1</td>
</tr>
<tr>
<td>Cost for each step</td>
<td>11.3</td>
<td>22.0</td>
<td>80.8</td>
</tr>
</tbody>
</table>

Then, the global cost of the system based on the 435 MHz radar solution (1500 km range) is evaluated to 115 M€. This cost is lower than the one given in the previous study thanks to the design of some high performance elements and a global optimisation of the system.

Concerning the 600 MHz design (1500 km range), the following table 14 presents the cost evaluation breakdown for the three successive steps:

<table>
<thead>
<tr>
<th></th>
<th>Demonstration step (M€)</th>
<th>Pre-operational step (M€)</th>
<th>Operational step (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission part</td>
<td>4.0</td>
<td>5.2</td>
<td>26.4</td>
</tr>
<tr>
<td>Reception part</td>
<td>4.4</td>
<td>6.2</td>
<td>22.3</td>
</tr>
<tr>
<td>Man power</td>
<td>2.8</td>
<td>5.7</td>
<td>17.1</td>
</tr>
<tr>
<td>Cost for each step</td>
<td>11.2</td>
<td>17.1</td>
<td>65.8</td>
</tr>
</tbody>
</table>

Then, the global cost of the system based on the 600 MHz radar design is evaluated to 94.1 M€. (i.e. 17.5% less than the 435 MHz design). But this option due to frequency allocation point of view remains a high risk one.
Concerning the sensitivity of the cost to the level of performance, we have redesigned the 435 MHz radar with a new hypothesis of minus 1.5 dB on the global link budget. The performance is lowered from 1% with respect to the nominal 435 MHz design (see Figure 12) and the cost may be evaluated to 98 M€ (16.7% less than the nominal design).
3. MEO SPACE SURVEILLANCE SYSTEM

Following the context description (subsection 3.1), this section covers in a brief (but self-sustained) manner the results of the AIUB work on MEO population assessment and evolution (subsection 3.2), MEO observation strategies (subsection 3.3), sensor selection for survey and tasking (subsection 3.4), formulation of MEO space surveillance system requirements (subsection 3.5), MEO space surveillance system performance evaluation (subsection 3.6), and the generation of the MEO space surveillance system development plan (subsection 3.7). The structure of this section does not, however, fully reflect the work-package breakdown in the study proposal.

3.1 CONTEXT

The previous study “Space Surveillance” (Donath et al., 2004) showed that, for space surveillance of objects in MEO, a system based on the fusion of the proposed LEO and GEO sensors cannot be considered as efficient. As a matter of fact, the space surveillance of the MEO region will gain great importance for Europe very soon due to GALILEO deployment and the presence of numerous constellations such as GPS and GLONASS in MEO. Therefore, concerning MEO surveillance, an efficient and feasible solution for orbital parameters catalogue maintenance must be proposed in the scope of a future European Space Surveillance System. The feasibility of the sensors in the proposed solution will correspond to same terms (2010 – 2015) as to the LEO and GEO subsystems. It was further shown already that MEO space surveillance is most efficiently carried out using optical technologies.

We used as baseline the space surveillance use-cases for MEO derived from the definition of space surveillance use cases in (Donath et al., 2004):

- UC-1 : Knowledge of space situation
- UC-2 : Detection of new launches
- UC-3 : Determination of collision risk
- UC-4 : Detection of in-orbit explosions
- UC-5 : Detection of manoeuvring objects
- UC-6 : Predictions of atmospheric re-entry.

Compared to the GEO region, the MEO region is more difficult to characterise:

- The space that needs to be scanned for the search of uncatalogued objects is larger.
- FOV-crossing direction and velocity can differ significantly between MEO objects. Therefore blind-tracking during the exposure, as used for GEO observations, is expected not to be efficient.
- In terms of space surveillance, the MEO region is poorly understood (or at least methods and strategies are poorly documented).
- There is no standard MEO definition. Here, we consider the MEO objects having altitudes between LEO and GEO and nearly circular orbits. We focus on objects with revolution times of about 12 h, like GNSS satellites. We use here a “work” definition of the MEO [AD14] :
  - Mean motion : \[1.5 \leq n \leq 2.5\] [rev/day]
  - Eccentricity : \[0 \leq e \leq 0.16\]
  - Altitude : \[2,000 \leq r \leq 34,000\] [km]

  - With the above difficulties in mind, the main tasks for the development of a MEO space surveillance concept during this study were formulated as follows :
    - Gain a state-of-the-art understanding of the MEO population and the evolution of this population. This involves the analysis of the stability of potential MEO orbits.
    - Formulate a leak-proof survey strategy, estimate the feasibility of this survey strategy and formulate the trade-offs in the case of an incomplete survey.
    - Discuss the necessity of splitting the MEO space surveillance into sub-tasks survey and tasking, as proposed for the GEO space surveillance.
    - Formulate an optimal image acquisition strategy. The driving requirements will be the minimal detectable object diameter and the orbit determination accuracy.
o Develop a concept for MEO space surveillance. This involves discussing the use of already existing and proposed facilities besides assessing new facilities dedicated for MEO space surveillance.

At the Kick-Off, it was agreed that the space surveillance of the MEO region shall focus on 1 m (or larger) objects.

The proposed methodology for the development of a MEO space surveillance concept assumes that it is reasonable to break the work down following the above list of main problem areas (see Figure 18).

A literature review (WP 2100) summarised the current possibilities of MEO space surveillance and identified applicable approaches and strategies. The definition of requirements and strategy (WP 2200) started with a discussion of the expected MEO population evolution. The MEO space surveillance (user) requirements were deduced from the discussion results. This process involved the identification of the design-driving data processing and cataloguing issues. For the optimal strategy, the requirements for a MEO space surveillance system were formulated (WP 2200). Those requirements allowed the selection of sensors for MEO space surveillance (WP 2300). After that, the simulation of the MEO surveillance strategy with the proposed sensors provided two performance characteristics: the coverage of a reference population as well as the minimal detectable object diameter estimation. The orbit determination accuracy according the proposed strategy was assessed, too (WP 2500).

Finally, a summary of the MEO space surveillance system was given. This included the presentation of the system architecture (sensor, observation sites and processing architecture) and the elaboration of a preliminary development plan and first rough cost estimates (WP 2600).

Figure 18: Breakdown of work related to MEO space surveillance. The dashed lines denote the four study notes that were prepared by AIUB.

3.2 MEO POPULATION ASSESSMENT AND POPULATION EVOLUTION

In [AD14] we defined four “reference population classes” out of the available space objects catalogue data for MEO objects: the GPS, the GLONASS, the (synthetic) Galileo, and the class ‘Other’.

A compilation of the population assessment results for the individual classes is given in Table 15.
Table 15: Population assessment results for all reference classes

<table>
<thead>
<tr>
<th></th>
<th>Topocentric Range [km]</th>
<th>Phase Angle (during night) [deg]</th>
<th>Angular velocity (horizon) [&quot;/s]</th>
<th>Angular velocity (in declination) [&quot;/s]</th>
<th>Typical dwell time [s] (Sidereal tracking, 1 deg FOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GPS</strong></td>
<td>20'000 – 27'000</td>
<td>&lt;120 deg</td>
<td>26 – 40</td>
<td>18 – 38</td>
<td>300 – 1000</td>
</tr>
<tr>
<td>GLONASS</td>
<td>19'000 – 27'000</td>
<td>&lt;120 deg</td>
<td>30 – 41</td>
<td>20 – 40</td>
<td>300 – 1100</td>
</tr>
<tr>
<td><strong>Galileo</strong></td>
<td>23'500 – 29'500</td>
<td>&lt;120 deg</td>
<td>15 – 25</td>
<td>23 – 30</td>
<td>350 – 1000</td>
</tr>
<tr>
<td>Other</td>
<td>19'000 – 24'500 (5'000 – 40'000)</td>
<td>&lt;120 deg</td>
<td>30 – 41 (10-300)</td>
<td>20 – 40</td>
<td>300 – 1100 (&lt;100)</td>
</tr>
</tbody>
</table>

We conclude that the worst phase angle is approximately 120 deg during the night. Phase angles of 0 deg are possible. The angular velocities are between 23 and 40 "/s in the horizon system. In the declination, the maximum angular velocity is found at low and modest declination between 15 and 40 "/s. Galileo objects move slowest in declination. The typical dwell times for a 1 deg FoV fixed in the inertial space are expected at 5 minutes for low declination (6 min for Galileo) and at about 15 minutes at the high declinations (>50-60 deg). Topocentric ranges are typically smaller than 25,000 km (or 29,000 km for Galileo).

With the use of simple calculations (the apparent brightness is dominated by the square of the observation distance (~R^2), the square of the objects diameter (~d^2) and the phase angle) typical magnitudes for MEO objects were estimated. Using conservative assumptions for albedo and shape, 1m objects in MEO appear between 15.5 mag (best illumination) and 17 mag (worst illumination at 90 deg phase angle).

In order to study the evolution of the reference population orbits, we used the ephemeris propagation capabilities of the program SATORB, contained in the CelMech software (Beutler, 2005). The software was slightly adapted to match the requirements of a long-term propagation. The propagation covers ~55 years from 2004-2059. The results from the population evolution assessment are contained in Table 16.

Table 16: Population evolution results for all reference classes

<table>
<thead>
<tr>
<th></th>
<th>Eccentricity (30 years)</th>
<th>Motion of node</th>
<th>Inclination variation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GPS</strong></td>
<td>Up to 0.08 (in 50 years up to 0.16)</td>
<td>-14deg/yr (Block-II)  -11deg/yr (Block-I)</td>
<td>60 - 66deg, ~35 years period (Block I)  50 - 58 deg, ~30 years period (Block II)</td>
</tr>
<tr>
<td>GLONASS</td>
<td>up to 0.015</td>
<td>-12 deg/yr</td>
<td>63 - 67 deg, ~35 years period</td>
</tr>
<tr>
<td>Galileo</td>
<td>0.01 (for higher A/m)</td>
<td>-12 deg/yr</td>
<td>53 - 60 deg, ~45 years period</td>
</tr>
<tr>
<td>Other</td>
<td>up to 0.02 (circular) varying between 0.4..0.65 (eccentric)</td>
<td>-9.5 deg/yr (circular)  18 - 20 deg/yr (eccentric)</td>
<td>63 - 67 deg, ~35 years period (circular)  67 - 72 deg (eccentric)</td>
</tr>
</tbody>
</table>

From the results compilation, we see that the motion of node is maximal with 14 deg/yr for GPS-like objects. The analysis of the evolution of the MEO objects showed that MEO objects will cover the entire range of ascending nodes. Therefore, the complete range of right ascension of ascending nodes needs to be considered in the strategy definition.
The long-term growth of the eccentricity is maximal for the GPS-class with up to 0.08 within 30 years or 0.16 within 50 years. All MEO objects show inclination variations with a period of 25 - 35 years (or 45 years for Galileo), if no manoeuvres are assumed. We may consider the semi-major axis as stable for all classes.

3.3 MEO OBSERVATION STRATEGIES

The definition and analysis of MEO space surveillance observation strategies in a future European Space Surveillance System was the main objective of [AD15].

In a first step, we identified and discussed conflicts and trade-offs between the MEO space surveillance system and the proposed GEO space surveillance system (Donath et al., 2004). The discussion took system requirements, observation strategy and sensors architecture into account. The analysis of the trade-offs showed that optical observations acquired for GEO space surveillance may only partly be suitable for detecting MEO objects larger than 1 m in diameter. Those objects appear bright enough to be within the limits of the GEO survey sensor performance, but may not in every case, show valid FoV crossing characteristics (it is assumed that the GEO survey strategy is carried out, of course). Those objects are simply too fast to be observed successfully with the GEO strategy so that likely less than the minimum of 3 consecutive observations are available. This minimum number of observations is needed for the determination of a full-parameter initial orbit. The alternative determination of a circular orbit (4 parameters or at least two observations) requires immediate follow-up, as the initial orbit is of a poor accuracy in this case (the eccentricity is not determined). However, even if the observation frequency was increased in order to cope with the faster MEO objects crossing the FOV, the GEO survey strategy would not be able to provide full coverage survey of MEO orbits.

Various approaches for the space surveillance strategy in MEO have been assessed and analysed. We concluded that it is most advisable to follow the combined survey and tasking strategy, if it is not required to build-up the catalogue in a very short time nor necessary to guarantee a very short time for the detection of fragmentation events. A combined survey and tasking was already the proposed solution for the GEO part of the European Space Surveillance System. The proposal included dedicated telescopes for survey and tasking, both acting independently. The tasking coordination should be carried out by the proposed Space Surveillance Centre (SSC).

In general, a combined survey and tasking strategy follows a twofold approach: dedicated survey telescopes are used to fill the catalogue with newly detected or re-detected lost objects. The tasking telescopes are needed to cover the whole longitude range in order to allow uninterrupted accessibility of the MEO region for tasked observations. Those tasked observations are used to improve the orbits of the newly detected objects through follow-up observations, and for catalogue maintenance. Also, the tasking system performs observations that are requested by the SSC in order to fulfill the collision avoidance, fragmentation detection and launch assessment requirements. The analysis of the MEO population in the RA/DE space shows each MEO object crossing the equator once in about 6 hours (the mean motion is around 2 rev/day). Thus, the continuous and uninterrupted observation of a so-called “fixed declination stripe” allows a complete survey of the MEO population. Such a declination stripe denotes a region in the sky defined by the entire right ascension range (considered as stripe “width”) and the sensor FoV (considered as stripe “height”).

In order to access even objects in low-inclined orbits, a stripe covering the declination of DE=0 deg is proposed for the survey strategy. Using a single survey sensor, the complete MEO population would not be accessible at once, but would be after a few months. For better performance, two survey telescopes, spaced by 90 deg in longitude are needed. In this case, the total available observation time per night is extended and even the slower Galileo objects can be accessed at least once per night (assuming the 14 h revolution time).

The main limitation of this approach is the extended time until the scan of the targeted declination stripe is finished. Thus, the sensor architecture has to guarantee that a leak-proof scan is possible and that the necessary number of observations for each object crossing the FoV is acquired to allow initial orbit determination. In turn, the covered arc length is driving the sensor requirements and/or the number of observations per objects. At least 3, better 4, observations per objects and declination
stripe crossing event need to be acquired in order to determine an initial orbit from the survey. This initial orbit is used to conduct the follow-up observations that result in an orbit that can be considered as "secured" and added to the catalogue of orbital elements.

However, it is very likely not necessary to survey the whole MEO population in a short time. Due to the drift of orbital planes, the accessibility of the whole MEO population under valid illumination conditions is guaranteed from a single site within a few (about 3) months. The drift is caused by the revolution of the Earth around the sun (about 1deg/day) and the significantly smaller motion of the right ascension of the ascending node of the MEO objects (about 2''/day).

For the tasking observations, we may assume the possibility of ephemeris tracking. This gives a relative velocity of the objects of nearly 0 - the FoV dwell time is "infinite".

It was found that the proposed 0.5 m Schmidt-Cassegrain telescopes for GEO tasking observations are able to serve as tasking sensor for MEO observations, too. There is enough spare sensor time available, as there is a lower number of MEO objects compared to GEO objects expected. Further, the MEO tasking puts a very small load on the tasking system, due to the lower expected frequency of catalogue maintenance observations than GEOs. The radiometric performance of the 0.5 m telescope is sufficient for observing 17 mag objects. The proposed tasking schedule is t0+1h, t0+2h and t0+12h, with t0 being the observation epoch of the discovery. All three follow-up observations must be guaranteed in order to keep the object. A fourth follow-up after 24h is expected to be part of the survey procedure. At least an arc of 30 days can be covered with the orbit determined from the three first follow-ups. Maintenance observations are thus required once within about 30 days, but would always be acquired during the survey "implicitly". It is possible to perform the first two follow-ups earlier at t0+45 min and t0+90 min, which allows over 95% of the objects to be recovered 12 h after the first observation.

3.4 SENSOR SELECTION SURVEY AND TASKING

The process of sensor selection and the architecture outline is detailed in [AD15]. The premise of the process was that the survey strategy required a wide-field, large aperture sensor equipped with a high-efficiency CCD detector that allows fast readout.

The dedicated MEO survey sensors must be capable of detecting 17 mag objects, corresponding to 1 m diameter spherical objects observed at 90 deg phase angle. A 0.8 m aperture wide field (Schmidt design) telescope with f/D=1 is proposed as baseline. The telescope shall be equipped with a 4k*4k CCD, which allows a pixel scale of 4.1 ''/pixel and a 4.7 deg FOV. In order to cover 120 deg in longitude, and to acquire series of 4 exposures per survey field, the CCD must be read out with 5 MHz through 4 channels.

For a SNR detection threshold of 4, the expected performance of such an optical system allows the detection of a 17 mag objects (see Figure 19). This corresponds to a 90 deg phase angle observation of a 1 m diameter object orbiting in MEO. Most 16 mag objects can even be detected, if the background is as bright as 16 mag/arcsec2. While for a good site such as Tenerife with a sky background better than 19 mag/arcsec2, the detection of 17.5 mag objects is possible.
The proposed tasking sensor for GEO and MEO observations is a 0.5 m f/2 Schmidt-Cassegrain system with field flattener. This telescope provides a 3 deg FoV and a pixel scale of 5.6 “/pixel for a 2k*2k CCD. A backside illuminated CCD detector is proposed that provides highest quantum efficiency. The performance analysis of this sensor showed that the detection of 17 mag objects is possible even under non-optimal observation conditions (Flohrer et al., 2005). The design goal “observation of 1 m diameter objects in MEO” is fulfilled.

3.5 MEO SSS REQUIREMENTS

The MEO system requirements were formulated, covering the proposed strategies and the derived proposal for the system architecture. In general, it was assumed that the “complete system requirements” from the previous study (Walker, 2002) are still valid, but are in some cases superseded by the new MEO requirements of this document. The entire list of all requirements and a traceability matrix between use cases and the system requirements is given in [AD16].

3.6 MEO SSS PERFORMANCE EVALUATION

In [AD16] the minimal detectable object diameter in MEO while executing the proposed MEO survey strategy using the proposed MEO survey sensor was estimated to be always below 1 m. For the estimation, we followed a similar approach as in the ESA study “Space Surveillance” (Flohrer et al., 2004) using the ESA PROOF tool together with the ESA MASTER-2001 population of space debris objects. Objects as small as 0.3 m in diameter are expected to be detectable under average phase angle and background brightness conditions.

The coverage of a reference catalogue was estimated using a given reference population of MEO objects, assuming the proposed MEO survey strategy of continuously scanning a “fixed-declination stripe”. Depending on the length of the covered arc in right ascension (or longitude), the coverage can be considered as nearly complete already after 30 days, if the survey results from two sites, spaced by 90 deg in longitude are combined. The accessible population during a single night is up to 50% from a single sensor, and up to more than 80% if the observations from one night from two survey sites are combined. The combination of two sites spaced by about 90 deg in longitude is
needed, as a single site may not access more than 66% of the reference population, even if 60 days of observation are covered.

The performance evaluations showed that typically 3-4 (and sometimes 5) observations per declination stripe crossing that are spaced by the field re-acquisition time are acquired per MEO object.

There is no significant overlap of the covered observed population between the two sites if the covered arc length is shorter than 100 deg. It should be aimed to survey a stripe as long as possible\textsuperscript{2}.

3.7 MEO SSS DEVELOPMENT PLAN AND COST

In [AD17], we developed the MEO space surveillance system architecture. It was concluded that the proposed GEO system architecture should form the baseline for the MEO system architecture. The MEO space surveillance system benefits from the re-use of the GEO space surveillance sub-systems as the SSUI, the DMS, and the selected survey sensor sites Tenerife and Marquesas Islands. Only minor upgrades in those sub-systems are needed to ensure MEO space surveillance capabilities within a European Space Surveillance System.

For the proposed MEO space surveillance strategy “combined survey and tasking” two additional survey sensors are needed for space surveillance, while the GEO tasking network can be used for the MEO tasking observations. The survey sensor need to be developed from scratch, some risk in the sensor design must be addressed beforehand. Applicable sensor requirements have been presented in [AD15].

The sensor sites and the communication network can be shared between GEO and MEO space surveillance systems. Means to reduce the amount of transmitted data are needed. The definite amount of transmitted data is still unclear, depending on raw-data request frequency and on-site pre-processing level. The MEO space surveillance data rate is expected to be of the same order of magnitude as during the GEO survey but significantly less during tasking (due to the lower number of objects in MEO).

The work breakdown for the development and implementation of the MEO system is given in [AD17]. We showed that the MEO and GEO work breakdown and system architecture are compatible and even widely identical, the previous development plan (Donath et al., 2004) stays valid.

Beside the necessary risk reduction phase for survey sensor design, no additional major Phase-A activities are needed for the MEO space surveillance system. In fact, the system feasibility and performance are shown within the current study and the preliminary MEO system requirements are already formulated.

In consequence, no update is needed according to the schedule presented in (Desmet, 2004c) and (Donath et al., 2004). We emphasize that this schedule is applicable to the development of the MEO space surveillance system in Figure 20. The only changes made were the replacement of “GEO ESS management” by “MEO ESS management”. The project has to start at the end of 2005 for a delivery at the end of 2009. The engineering of the MEO survey telescope is expected to take the same time as the GEO telescopes. The MEO survey telescope development will last about 18 months, as it was estimated for the half-metre class telescopes forming the GEO space surveillance network. This estimation is preliminary, as delays in the manufacturing due to limited capacity may occur if the same manufacturer as for the GEO telescopes is selected.

\textsuperscript{2} If the number of observations per crossing objects drops to less than 3 observations, in consequence, the survey of a part of the arc could be passed to a tasking telescope during spare time. This improvement would not lead to a leak-proof coverage of the additional arc, but is expected to increase the survey procedure anyhow, as even batches from a few minutes are sufficient for the initial orbit determination of previously unknown objects. However, a leak-proof survey of an arc as long as possible (>>100 deg in longitude) stays baseline.
We performed the preliminary cost estimation using the approach of (Desmet, 2004c) following the assumptions (Donath, 2004):

- 1 person*month = 16k€,
- We consider the GEO space surveillance system being developed as proposed in the study “Space Surveillance” and the MEO space surveillance being added as an additional module to that system,
- The costs do not include buildings, facilities, domes, etc., and the related validation means,
- We consider two additional MEO survey telescopes installed at Tenerife and Marquesas (no redundancy).

The results of the cost estimation are compiled in Table 17.
Table 17: MEO ESSS cost estimation

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management</td>
<td>42 person*months</td>
<td>50% of GEO effort needed in addition</td>
</tr>
<tr>
<td>System engineering: phases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>36 person*months</td>
<td>Same as GEO</td>
</tr>
<tr>
<td>B/C/D</td>
<td>72 person*months</td>
<td>Same as GEO</td>
</tr>
<tr>
<td>Telescope engineering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8 m wide field, fast design</td>
<td>72 person*months</td>
<td>Same as GEO</td>
</tr>
<tr>
<td>telescope equipped with</td>
<td></td>
<td></td>
</tr>
<tr>
<td>back-illuminated CCD detector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>allowing fast read-out</td>
<td>2.5 M€</td>
<td>New development, synergies with development of 0.5 m class telescopes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>possible (mounting, automation, design concept,…)</td>
</tr>
<tr>
<td>Site adaptation</td>
<td>None</td>
<td>All effort accounted for GEO space surveillance system</td>
</tr>
<tr>
<td>Telescope site software</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data management</td>
<td>1 person*months</td>
<td>Synergies with the GEO data management software development out from</td>
</tr>
<tr>
<td></td>
<td></td>
<td>existing solutions like the AIUB ODPS, (generic software)</td>
</tr>
<tr>
<td>Data analysis</td>
<td>3 person*months</td>
<td>Synergies with the GEO data analysis software development</td>
</tr>
<tr>
<td>SSUI software</td>
<td>1 person*months</td>
<td>Additional effort to GEO SSUI development (generic software), incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>management</td>
</tr>
<tr>
<td>DMS software</td>
<td>3 person*months</td>
<td>Additional effort to GEO DMS development (generic software), incl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>management</td>
</tr>
<tr>
<td>DMS database</td>
<td>None</td>
<td>GEO DMS database fulfils needs for storage of MEO space surveillance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fully</td>
</tr>
<tr>
<td>SSUI, DMS, Web server hardware</td>
<td>None</td>
<td>No additional web server etc. needed.</td>
</tr>
<tr>
<td>Site operation</td>
<td>50 k€/year</td>
<td>Operation is carried out coordinated with GEO survey operation,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>automated operation of survey sensors assumed</td>
</tr>
<tr>
<td>Logistic and support</td>
<td>Not estimated</td>
<td>As GEO</td>
</tr>
</tbody>
</table>

The overall costs for the MEO space surveillance system were estimated to be 8M€ (188 person*months+2 telescopes), assuming the development in parallel with the GEO space surveillance network and the procurement and development of two new survey sensors. As a highly automated system is to be developed, the running costs are estimated to be very low at about 50 k€/year/site.

The global costs can be split to 5M€ (63%) for hardware, 2.43M€ (30%) for phase B/C/D engineering and software development, and 0.57M€ (7%) for additional phase A work. The global cost split is comparable to the proposed GEO space surveillance system long-term solution.
4. **HEO ANALYSIS**

Considering that the study objective is to propose a complete space surveillance system and that up to now only circular orbits, i.e. LEO, MEO and GEO were studied, it was decided to complete the present study mainly focused on LEO, GEO and MEO parts, by a preliminary analysis of the very special case of the HEO orbits.

The first problem to solve was to define what the HEO orbit is (as many different definitions exist) and what this orbit is made of. For that purpose, it was decided to subtract from the entire catalogue, LEO, GEO and MEO objects, in order to build what has been called the Remaining Earth Orbits (REO). These REO orbits represent 18.4% of the entire population and are widely distributed in terms of semi-major axis, eccentricity and inclination as show Figures 21 and 22. Due to this large distribution, it seems very improbable that a common surveillance system may treat all these orbits efficiently.

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**Figure 21:** Space objects orbital distribution (Eccentricity versus semi major axis)

**Figure 22:** Space objects orbital distribution (Inclination versus semi major axis)
Another problem to treat was the complete lack of information. In fact, both the literature review made within this study and questions to our IADC colleagues reveal that no system or strategy dedicated to HEO surveillance exists. Only one reference was identified: it concerns an optical system called the Canadian CASTOR (a concept demonstrator and not a dedicated system) which is used to only track (and not survey) some MOLNIYA objects.

A more detailed study of the contents of the REO orbit based on eccentricity criteria was then undertaken. The whole REO orbit was divided in eight classes of eccentricities and each class obtained was studied according to two parameters:

- Number of objects involved in each class
- Identification of the content of each class in terms of mission or orbit.

Two representative classes were identified:

- The super-LEO orbit made of objects with low eccentricities (less than 0.1)
- HEO objects defined as objects with eccentricity greater than 0.5.

Then, a characterization of the HEO orbit was attempted using two ways; a practical approach analysing a set of TLE elements (from 1993 up to now) and a theoretical one using a literature review. This analysis reveals two special cases of objects called MOLNIYA and COSMOS objects, using both highly eccentric orbit (eccentricity near 0.7) for respectively communications and early warning missions and having a very complex movement with many perturbations acting on them (both gravitational and non gravitational).

Considering that this study was a very preliminary study, the purpose of which was only to identify problems (and not to solve the whole HEO surveillance problem), it was decided:

- To consider only super-LEO and HEO objects,
- To study the interest for such orbits surveillance of proposed sensors for circular orbits (UHF radar for both super-LEO and HEO orbits and MEO and GEO sensors for HEO orbits).

DGA/DE has performed the UHF radar applicability analysis and AIUB has performed the GEO and MEO sensors applicability analysis. Next paragraphs present the interest of UHF radar for such orbits cataloguing (cf. paragraph 4.1), then the interest of MEO survey (cf. paragraph 4.2) and finally the interest of GEO survey (cf. paragraph 4.3).

### 4.1 UHF RADAR SURVEY APPLICABILITY

The hypotheses considered in this analysis are the following:

- The characteristics of the UHF radar are given in paragraph 2.2.3.3. The chosen frequency is 600 MHz.
- The USSTRACOM catalogue (July 2005) gives the object population.
- Simulation is made over one month (January 2005).
- An object is correctly detected if it is detected every day and 10s at least.
- Within this object population, 314 objects are considered as super-LEOs (eccentricity lower than 0.1) and 1019 objects are considered as HEOs (eccentricity higher than 0.5).

The S3 software is used for simulation and Figure 23 illustrates the quality of detection for super-LEOs.
Over 314 objects in super-LEOs, more than 64% are correctly detected by the UHF radar and will be catalogued. The cataloguing performance can be enhanced to 71% if the cataloguing criterion is raised to 26 hours, and more if subtracting objects with low mean motion and low RCS.

For HEOs, results are not so good (14% considering all RCS). Of course, this is due to small RCS objects and phasing problems. Let us also notice that the cataloguing criteria were developed for LEO treatment. Perhaps, some new criteria will have to be announced for high eccentric orbits in order to get enough accuracy for orbit re-identification at each FoV crossing. Figure 24 illustrates the quality of detection for HEOs.
An additional and very preliminary study focused on the very special case of MOLNIYA and COSMOS objects, reveals slightly better results (24% and 46% respectively for RCS greater than one square meter).

4.2 MEO SURVEY APPLICABILITY

Applicability of the MEO existing and proposed solutions to the HEO orbit has been studied by AIUB and is reported as part of the WP2500 study note [AD16].

It was found that the MEO survey allows only a poor coverage of about 10-20% of the HEO population from one-night observations. The coverage steadily increases during one year with about 6% per month. Thus, a built-up and maintenance of a catalogue of HEO objects would be possible in principle. It has been shown that the needed tasking observations for HEO objects are feasible using the proposed tasking network. However, 30% of the covered objects are crossing the surveyed declination range too fast to allow initial orbit determination from survey observations, as these objects would not be observed often enough. Unfortunately this involves nearly all MOLNYIA objects in high inclined orbits.

The conclusions deduced from this study indicate that the MEO space surveillance strategy is:
- Not applicable for survey observations of the HEO orbit
- Applicable for tasking observations of the HEO orbit.

4.3 GEO SURVEY APPLICABILITY

Applicability of the GEO existing and proposed solutions to the HEO orbit has been studied by AIUB and is reported in the WP2300 study note [AD15].

The conclusions deduced from this study indicate that the GEO strategy (combined survey and tasking) is:
- Not applicable for survey observations of the HEO orbit (Poor coverage of about 10% of the HEO population from one cycle)
- Applicable for tasking observations of the HEO orbit.
5. DUAL USE OF SPACE SURVEILLANCE SYSTEM

The Work Package « Dual Aspects of the future European Space Surveillance System (ESSS) » consisted in a preliminary collection of the user needs originating from military/state users through interviews of potential users and identification of the impacts on the currently proposed architecture. In that frame, informal meetings were organised with French and British military/state user representatives and contacts were initiated with Spanish military authorities, still pending due to clearance problems.

Broadly speaking, the civilian user products primarily identified so far in the ESSS cover the range of military/state user needs, but some specific additional user needs are already identified:
- More detailed definition of requirements with regards to timeliness and accuracy;
- Capability to autonomously maintain a complete catalogue, condition for having confidence in the delivered data products;
- Access to ESSS raw measurements data, enabling their combination with those from state/military owned sensors in specific cases;
- User's-private data base and catalogue, at least partially (e.g. for the complementary "object's mission attributes") even though common tools and standards could be uniformly agreed;
- Cataloguing objects with more attributes than currently envisaged for civilian users in order to characterise their missions and capabilities ("threat"). Note that this information is not only provided by the ESSS but also relies on complementary human intelligence;
- Security of the system (sensors and information infra-structure), as well as confidentiality, integrity, availability, traceability of data and information at various levels of processing and dissemination, are also a specific requirement that needs to be further defined and may impact the system architecture;
- The data policy - not only the pricing but the data release - also needs to be specifically defined as well as the share policy of the system capability and resources, especially for the sensors or system resources that are taskable (for which it is necessary to allocate priorities);
- Concerning the use of already existing national sensors or systems, although this has to be further investigated, some countries may accept to share a controlled amount of their capability with the European system.

The conclusions of this work package, at that stage, are the following:
- There is a clear mutual interest for achieving a dual use system, with a major common design at sensors and information system level.
- However, the presence of defence users requires to consider some specific needs and subsequent architecture provisions; they are felt to bring no major design improvements provided they are taken into account from the very beginning. Conversely, this may result in implementing some elements (e.g. national data bases) in each country, even though based on a unique development.
- Such aspects like concept of operations, data policy, security, etc. are of high importance for defence users.
- All these results are preliminary and require further investigations with MoDs. From informal contacts, we understand that they are open and even willing to continue such investigations.
6. SYNTHESIS AND RECOMMENDATIONS

6.1 SYNTHESIS

This study complements an earlier analysis (Donath & al, 2004) concerning the assessment of a European Space Surveillance System (ESSS). Three types of orbital regions dominate the surveillance system proposal: LEO, MEO and GEO. Most objects in these regions are in nearly circular orbits. They represent 82% of the global population of objects contained in the USSTRATCOM catalogue, and they include more than 90% of the operational orbits.

The objective of the ESSS is to build (from scratch) a catalogue of orbital parameters, and to maintain it autonomously. Here, objects larger than 10 cm in LEO and larger than 1 m in other parts of space are considered. Dedicated space survey strategies and sensors are proposed for each orbital region:

- **LEO**: Due to orbital characteristics and Earth rotation, one can demonstrate that a large FoV radar sensor (20° in elevation and 180° in azimuth, with a 1500 km range) located at the south of Europe allows the observation of nearly all orbits catalogued by the US. The corresponding observations are long and repetitive enough to ensure the identification of a new object or the re-identification of an existing catalogue object at the next FoV crossing. This strategy for LEO surveillance, based on survey only, is very attractive since it allows a catalogue cold start (with no a-priori knowledge) and the maintenance of such a catalogue with only one sensor. A ground-based radar is a good candidate for such a sensor since it is able to detect objects in all-weather day-and-night conditions. The GRAVES radar has demonstrated the feasibility of such a system.

- **GEO and MEO**: The proposed survey strategies use a combination of survey observations (searching for new objects) and tasking observations (for initial orbit determination and orbit improvement) in order to enable a catalogue cold start. Orbits determined from the survey observations are not accurate enough to allow the correlation of future observations. Thus, it is required for the build-up of the catalogue to follow-up newly detected objects for a sufficient time span to improve the accuracy of their orbit. Regular re-acquisitions of the catalogued objects are required to ensure the maintenance of the catalogue. It was demonstrated that ground-based optical telescopes equipped with CCDs can carry out the proposed survey strategy.

- **Super-LEO and HEO**: The applicability of LEO, GEO and MEO sensors was also analysed for other orbital regions. The LEO radar is able to detect super-LEO orbits and also GTOs when their perigee is within the FoV. Likewise, highly eccentric orbits appear in the GEO and MEO survey data, but it is not possible to maintain their orbital parameter catalogue due to too short FoV dwell times. If a special interest in such orbits exists, the combination of radar and optical measurements for the orbit determination and catalogue maintenance should be studied.

**LEO sensors**: From a feasibility analysis within this study, the following findings emerged.

- The optimal frequency for 10 cm objects detection is around 600 MHz (UHF). This option is not feasible from of a frequency allocation point of view (reserved for TV broadcasting). A frequency of 435 MHz (also UHF, just outside the TV band) is a good alternative in terms of development risk, detection performance and cost.

- Due to continuous wave (CW) transmission, the ESSS radar is bistatic (one site for transmission and one site for reception). The ESSS radar design has considerably evolved within this study, leading to reduced complexity and cost as compared with a previous proposal.

- The proposed transmission site is equipped with four arrays, each one fed by high-power transmitters and equipped with custom-designed high-gain patch antennas. Simulations and experimental validations have demonstrated the possibility of coupling of the high-power transmitter with the patch antenna. This phenomenon resulted in recommendations for the optimum spacing of patches for the array integration. Coupling between adjacent transmitters still needs to be investigated (but is assumed to be not critical).
The reception site is now equipped with four arrays, each one composed of high-gain patch antennas. One processor for digital beam forming is attached to each array. Due to the modular design using four arrays, and due to the evolution of digital and processing technologies, the complexity of the radar reception part has considerably decreased. The LEO surveillance system will be capable of cataloguing 98% of the LEO objects contained in the US catalogue.

**GEO sensors:** The GEO sensor concept was re-analysed based on results of the previous study (Donath et al, 2004). Eight sensors located at four low-latitude sites (Marquesas Islands, Tenerife, Cyprus and Perth) will cover 95% of the GEO objects contained in the US catalogue. At each site, two telescopes are necessary: one telescope for survey (50 cm aperture, 3°x3° FoV), and one identical telescope for tasked observations.

**MEO sensors:** Survey strategies and dedicated MEO sensors were analysed in this study. The proposed GEO telescopes cannot be used for the MEO survey, due to a necessary improvement in radiometric performance as a result of the non-optimal phase angles. A new class of 80 cm telescopes is proposed for MEO survey. Two low-latitude sites are necessary (for example, Marquesas Islands and Tenerife), each one equipped with a dedicated MEO survey telescope of this new class. MEO tasked observations will be coordinated with GEO tasked observations, using the previously proposed telescopes of the GEO surveillance sub-system. Depending on the efficiency of the MEO survey sensor, 89% of the MEO objects contained in the US catalogue may be covered after 2 months when applying standard detector technology, and 95% can be catalogued after 1 month when using a demanding detector technology.

The Figure 25 illustrates the sensor locations of the global ESSS network.

![Figure 25: Sensor locations for the proposed ESSS system](image-url)
For the UHF radar, two sites are necessary in the south of Spain: one for transmission and one for reception (displaced to the south at a distance of 200 km). Viable transmitter (TX) and receiver sites (RX) are Pico Villuercas (TX, Extremadura) and the Arenosillo military base (RX, Andalucia).

On the Marquesas Islands and on Tenerife, three telescopes are needed: one for MEO survey, one for GEO survey, and one for MEO and GEO tasked observations. In Cyprus and Perth, two telescopes are needed: one for GEO survey, and one for MEO and GEO tasked observations.

The development plan and the cost estimate for the combined LEO, MEO and GEO surveillance system are given in Table 18. The plan is based on the assumption that the development is starting in 2006, with no time gaps between steps. Table 19 illustrates the different phases related to each sub-system development (orange: demonstration phase, light blue: pre-operational system, dark blue: operational system).

Table 18: Development steps of the ESSS, associated performances, and estimated costs (these costs do not include buildings, facilities, and means of validation).

<table>
<thead>
<tr>
<th>ESS sub-system</th>
<th>Development phase</th>
<th>Phase end date</th>
<th>Performance / US catalogue</th>
<th>Cost (M€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO (435 MHz)</td>
<td>Demonstration</td>
<td>Mid 2008</td>
<td>Detection only</td>
<td>11.3</td>
</tr>
<tr>
<td>LEO (435 MHz)</td>
<td>Pre-operational</td>
<td>End 2009</td>
<td>Detection only</td>
<td>22</td>
</tr>
<tr>
<td>LEO (435 MHz)</td>
<td>Operational</td>
<td>End 2011</td>
<td>98 %</td>
<td>81</td>
</tr>
<tr>
<td>GEO (3 sites)</td>
<td>Pre-operational</td>
<td>End 2009</td>
<td>87 %</td>
<td>13</td>
</tr>
<tr>
<td>GEO (4 sites)</td>
<td>Operational</td>
<td>End 2011</td>
<td>95 %</td>
<td>3.2</td>
</tr>
<tr>
<td>MEO (2 sites)</td>
<td>Operational</td>
<td>End 2009</td>
<td>89 / 95 %</td>
<td>8</td>
</tr>
<tr>
<td>ESS system</td>
<td>Operational</td>
<td>End 2011</td>
<td></td>
<td>138.5</td>
</tr>
</tbody>
</table>

Table 19: Development calendar for the ESSS (beginning in 2006 assumed)
6.2 RECOMMENDATIONS

Proposed ESSS design and development steps:

- For the LEO sub-system it is recommended to perform detailed simulations of the UHF radar system performance for all development phases (also serving as input to a safety analysis).

- For the LEO sub-system it is recommended to develop a low-cost demonstration radar to verify the overall system concept. This test set-up will later become a part of the operational radar.

- For the GEO and MEO sub-systems it is recommended to install a 0.5 m telescope, equipped with a CCD camera, in order to test and validate the proposed survey strategies for GEO and MEO. This telescope will later become a part of the operational system for GEO/MEO tasking and for GEO survey.

- For the GEO and MEO sub-systems it is recommended to investigate the usefulness of a passive RF sensor to facilitate the identification of active objects and to possibly improve the survey strategies for these objects.

- For other orbital regions it is recommended to investigate a combined use of measurements made by the UHF radar and by the GEO and MEO telescopes. If this approach fails, orbital regions of particular interest and dedicated survey strategies for these regions shall be identified.

Proposed ESSS data processing strategy:

- For the LEO sub-system, it is recommended to develop a data processing strategy based on the proven concept of the operational GRAVES system.

- For the GEO and MEO sub-systems it is recommended to develop a prototype data processing concept using observations provided by the existing optical sensors in Europe.

- For other orbital regions it is recommended to explore a processing strategy with combined measurements from the UHF radar and from the GEO and MEO telescopes. If this cataloguing approach fails, dedicated processing schemes shall be developed for orbital regions of particular interest.

- In order to set up an operational data processing system as soon as possible, it is recommended to develop a Data Management System in the following sequence: [1] using data from existing sensors (e.g. GRAVES, ESA SDT, PIMS, ZIMLAT), [2] using data from demonstration sensors (LEO, GEO and MEO), and [3] using data from the operational ESSS sensor network.

Following space-surveillance-relevant developments in ESA Member States during the past 15 years (e.g. GRAVES, ESA SDT, PIMS, ZIMLAT), the required technical expertise, the necessary system components, and the required infrastructure for the deployment of a European Space Surveillance System (ESSS) are available. The overall development and deployment cost of the ESSS is estimated to be of the same order as the cost of a single Ariane 5 launch.

Due to a time-phased completion of several space surveillance development projects in ESA Member States, Europe is presently in the unique position of having at its disposal a large number of engineers and scientists with state-of-the-art expertise in all relevant fields (e.g. radars, telescopes, surveillance techniques, and processing schemes). This opportunity is limited in time. Hence, any decision with respect to a European Space Surveillance System needs to be taken soon.