CONSOLIDATED GROUND SEGMENT REQUIREMENTS FOR A UHF RADAR FOR THE ESSAS.

Principal Author MULLER Florent(1), VERA Juan(2)

(1)*Onera, 29 Avenue de la Division Leclerc 92322 Chatillon (France), Email:florent.muller@onera.fr*
(2)*Indra, Mar Egeo, 4 · Polígono Industrial nº 1, 28830 San Fernando de Henares (Madrid, España), Email:jvera@indra.es*

ABSTRACT

ESA has launched a nine months long study to define the requirements associated to the ground segment of a UHF (300-3000 MHz) radar system. The study has been awarded in open competition to a consortium led by Onera, associated to the Spanish companies Indra and its sub-contractor Deimos.
After a phase of consolidation of the requirements, different monostatic and bistatic concepts of radars will be proposed and evaluated. Two concepts will be selected for further design studies. ESA will then select the best one, for detailed design as well as cost and performance evaluation.
The aim of this paper is to present the results of the first phase of the study concerning the consolidation of the radar system requirements.

The main mission for the system is to be able to build and maintain a catalogue of the objects in low Earth orbit (apogee lower than 2000km) in an autonomous way, for different sizes of objects, depending on the future successive development phases of the project. The final step must give the capability of detecting and tracking 10cm objects, with a possible upgrade to 5 cm objects. A demonstration phase must be defined for 1 m objects. These different steps will be considered during all the phases of the study.
Taking this mission and the different steps of the study as a starting point, the first phase will define a set of requirements for the radar system. It was finished at the end of January 2009.

First part will describe the constraints derived from the targets and their environment.
Orbiting objects have a given distribution in space, and their observability and detectability are based on it. It is also related to the location of the radar system
But they are also dependant on the natural propagation phenomenon, especially ionospheric issues, and the characteristics of the objects.
Second part will focus on the mission itself. To carry out the mission, objects must be detected and tracked regularly to refresh the associated orbital parameters. In order to be able to examine different kind of concepts, trade-offs must be possible. Degrees of freedom must be defined between accuracy and refreshment rate of the measurements, between survey zone and tracking zone (if different).
Third part will deal with the requirements derived from various constraints. Logistical issues depend on the required availability of the system. People and environment security is also a big concern, related to maximal emitted power. There are current known technical limits (regarding current existing radars) that may need to be pushed: peak power, surface emitted power density, etc.

Traceability of derived consolidated requirements is also a key driver of this part of the study. A methodology for traceability of requirements and tests will be defined. It shall be extendable to the next phases of the current study and further studies also. All the requirements will be written in accordance to this methodology.

1. PRESENTATION OF THE STUDY AND MISSION REQUIREMENTS.

The aim of the study is to perform the system design for a ground based LEO space surveillance radar system. A list of requirements will be derived from the technical specifications. Based on this list, at least two architectural designs will be developed, which in the course of the study have to be refined under the aspects of performance, technological availability, costs and schedule. Previous studies have already suggested some possible architectures, based on already working radars. But since the aim of this study is to open the set of possibilities, a particular attention will be paid to the fact the requirements shall stay general enough in order not to restrict the possibilities. Thus, the requirements must remain system oriented, and not radar oriented. It shall provide abacus and general frame for the selection and proposition of combinations of parameters for the radar system designs that would meet the general performances requirements.

The requirements will be centred on the mission of the system that is to build and maintain a catalogue of orbital parameters for LEO objects, as defined in the SOW [1]. It must provide tracks of the LEO objects in order to estimate orbital parameters and catalogue them from cold start.

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

The successive development steps (Demonstration, Final and Upgrade) define the domain covered by the catalogue, in terms of altitude, size of objects (1m for step D, 10 cm for step F, 5 cm for step U), and percentage of the reference populations.

1.1. Glossary

In order to be sure of the meaning of some of the words used in this paper, here are a few definitions:

Field Of Regard (FOR): all the parts of space reachable by a beam of the radar.

Field Of View (FOV): part of the *FOR* illuminated at a given time by the beam.

Plot: a plot is the time tagged set of data corresponding to a measurement by the radar. It also includes the associated covariance matrix. A plot is the output of the radar sensor signal-processing function.

Successive plots: The expression "successive plots" refers to plots corresponding to different detections of an orbiting object during the same crossing of the FOR by this object.

Track: a track is an association of *successive plots* that are supposed to belong to the same space object. The track contains all the information of the *plots* belonging to it. A track is the output of the radar system tracking function.

Survey (function): function of a sensor system aiming to scan the *survey zone*, searching for targets and contributing to the collection of plots detected during the scan. Survey ensures first detection(s).

Tracking (function): function of a sensor system aiming to collect and associate *plots* supposed to belong to the same object into *tracks*. The association is based on the knowledge of the motion of the targets, their degrees of freedom and their manoeuvrability. Tracking function also ensures management of the *tracks* (creation of new tracks, deletion of old ones…)

Even a survey radar system has a tracking function, but it is a "low accuracy" tracking. It can be understood as an orbit validation function. The tracking function can be passive (TWS) or active (Active Tracking).

Cueing (function): function of a sensor system aiming to acquire an object whose presence in its FOR is indicated by another mean (other sensor or external data)

Confirmation (function): function of a sensor system aiming to check the validity of a detection reported by the *survey function*. The *FOV* is pointed immediately after the detection on the detection zone in order to assess the target presence and get more accurate measurements. Eventually, it can also reveal a false alarm.

Survey Zone: it is the part of the *Field of Regard* scanned by the *survey function*.

Tracking Zone: it is the part of the *Field of Regard* exploited by the *tracking function*. In the case of a TWS survey only radar, the *tracking zone* is the same as the *survey zone*.

Survey revisit time: it is the time between two consecutive identical positions of the *FOV* while scanning the *survey zone*.

Active Tracking (AT): some sensors can perform an active tracking. Pointing management is looped with *tracking function* in order to be able to predict future position of the target and thus to set the *FOV* on it and to track it. This allows getting more plots and associated measurements for a given object to refine the estimation faster. But it keeps the asset busy and prevents it to ensure other functions (like survey). A dedicated algorithm ensures the resource management between *survey* and *tracking functions*

Track While Scan (TWS): Tracking function is ensured by post-processing. Plots are gathered by the survey function, during the scan of the survey zone, in a passive way. In this case, plots may be less numerous, but time and energy of the sensor is dedicated to survey. This can either increase the survey performances or decrease the need in energy.

Cataloguing: function aiming to associate tracks corresponding to the same object detected at different crossings of the FOR. The plots of these tracks can correspond to measures from different kind of assets. These associated tracks can then be used in an orbitographic filter in order to get the associated orbital parameters. This function is not performed by the radar system, but by the data center.

1.2. Hypothesis and general ideas

The main degrees of freedom for the radar system are the following ones:

- Location (latitude of the radar)
- Frequency
- survey zone characteristics:
  - Lower elevation limit of the survey zone(s)
  - Width of the survey zone(s) in elevation
  - Azimuth direction of the centre of the survey zone
  - Azimuth opening of the survey zone(s)
- Range on a given RCS reference.

We can assume the survey zone is south-oriented, as it has been proved in previous studies that it is the best orientation [2].

Thus, for the rest of this paper, it will be assumed that azimuth direction of the centre of the survey zone is set equal to 180°

The radar system should face many constraints: a mission to fulfil, environmental constraints (targets and propagation conditions), legislation and regulations, links with other assets…

The methodology proposed here is to list and detail the different constraints, and then to translate them into "radar system requirements" from different points of view more useful for a radar system specialist.

For instance, defining Field Of Regard (FOR) characteristics can be seen from final performance point of view, through the associated cataloguing performance.
But it can also be seen from the radar time-load point of view, corresponding to a maximum number of detectable satellites at a given time.
From the radar measurements point of view, a given FOR will correspond to a certain range of values for the measurements.
A given set of parameters shall become easily transposable into a set of radar system constraints. The radar system specialist shall then have all the elements to define if there is a feasible concept corresponding to it.

2. DEFINITION OF THE REQUIREMENTS.

In order to correctly define the requirements for the radar system, first part of this document will deal with its environment and targets.
Concerning environment, important points are propagation and noise conditions.
Concerning targets, the LEO objects population to be catalogued is also characterized by some parameters:

- size, allowing computing RCS taking the candidate transmitting frequencies into account.
- orbital parameters distribution.
- a reference catalogue, that is a particular representation of the true population.

Then, starting from the mission, different functions can be defined in order to fulfil it. These functions will define a set of derived requirements. They are presented in a second part.

The radar system will also have to face pragmatic concerns, like security, availability, energy transportation and data exchange, leading to another set of requirements, constituting the third part of the document.

2.1. Environment and targets related requirements

Some major constraints are the environment and the targets of the radar.
The location of the radar elements can have an impact on performances, through the reachable objects, for instance. The elements of the radar shall be stationary located in European countries, Spain being preferred.
Location shall take into account the electromagnetic (EM) environment: residential and business zone can have high levels of EM noise, interfering with the radar. Thus, they shall be avoided.

2.1.1. Propagation

One of the main environmental constraints are propagation issues. They can have impact on accuracy, link budget and design.
Troposphere and lower layers have an impact through refraction effects, limiting accuracy.
But the main region of the atmosphere with the major impact on the space surveillance radar is the ionosphere.
Ionosphere is the ionized upper layer of the atmosphere, going from 50 km in altitude up to 2000 km. An absorbing D-layer appears with the Sun light from 50 to 90km in altitude (corresponding to mesosphere). E and F layers, above 90km have a refraction effect. Ionosphere has major effects on radar signals passing through it, decreasing with frequency. The amplitude of the effects is dependant on the current solar activity that is the main contributor to the ionization of the air at this altitude.
The Total Electron Content (TEC, the column density of electrons, i.e. number of electrons in a vertical column of 1 square meter surface, varying between 1E16 and 1E18 electrons/m²) of the ionosphere varies mainly due to day-to-night variations, but also depends on the geomagnetic latitude, time of year, and sunspot cycle.

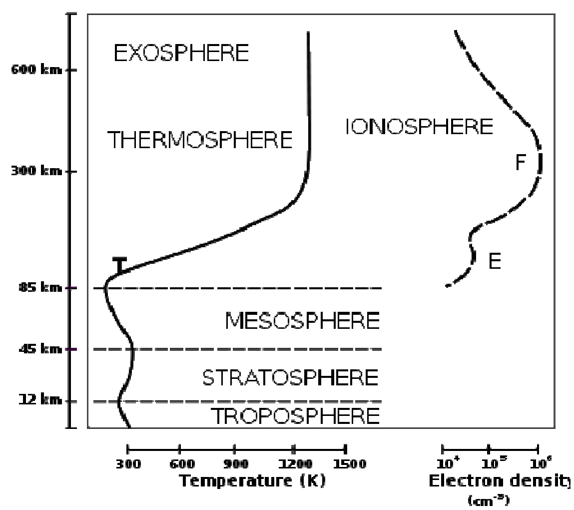

Figure 1 – Different regions of the atmosphere

It leads to different effects on radar signals:

- Fading (amplitude scintillation)
- Fluctuation on the phase (phase scintillation)
- Faraday effect (rotation of the polarization plan)
- Refraction
- Delay on the propagation time
- Phase shift
- Frequency dispersion

Ionosphere activity is surveyed through an international sensors network based on 350 GPS/NAVSTAR reception centres. It is also modelled and predicted. The NWRA (“ Northwest Research Associates, Inc. ”) gives forecasts for the ionosphere activity.
The different effects are known and modelled, corrections exist.

The radar system shall take into account the propagation effects and apply possible corrections in the case it is possible. Remaining effects (errors, biases) shall be estimated.

2.1.2. Considered objects populations

Different sources of information will be considered about orbiting objects.

- The first one is the NORAD catalogue, and the associated SSR (Satellite Situation Report). For this study, we will use the NORAD catalogue of 10th of February 2009 and the SSR from the 9h of February 2009.
- The second one is the Master-2005 population for objects with size greater than 5cm in diameter.

The distributions of the populations of objects have to be examined considering the degrees of freedom for the radar system. Indeed, as the first step to maintain a catalogue is to be able to detect the objects, the survey zone of the radar has to be correctly defined.

The choice for the survey zone characteristics wrt the targets populations may impact various aspects of the radar system and may be linked with location, range… or other aspects.
The choice for frequency is linked to the size of objects to be detected (through their RCS) and the possible allocations. Two domains will be studied more precisely, around 435 MHz and 1250 MHz. 3200 MHz is another possible frequency band.

Considering the target model, we will consider a Swerling 3 hypothesis. Indeed, satellites are complex objects with a relatively slow relative attitude movement. Debris can be considered as convex small elements, with a relatively slow relative attitude movement.

We have different sources of information, with different characteristics. Thus, they induce different constraint on the system.

2.1.2.1. Distribution of the RCS of objects

The Table 2 gives the computed RCS for the considered frequencies and for perfect spheres whose diameters would be the reference size considered at each step:

Table 2 – RCS wrt. frequency and size of objects

RCS (dBm²)		Diameter (m)		
		>0.05 (U)	>0.1 (F)	>1 (D)
Frequency (MHz)	435	-43.3	-25.3	-0.2
	1250	-25.5	-24.0	-0.7

Figure 3, *Figure 4* and *Figure 5* show the distribution of the LEO objects (apogee < 2000km) for the NORAD catalogue and for Master 2005 catalogue at 435 MHz and 1250 MHz.

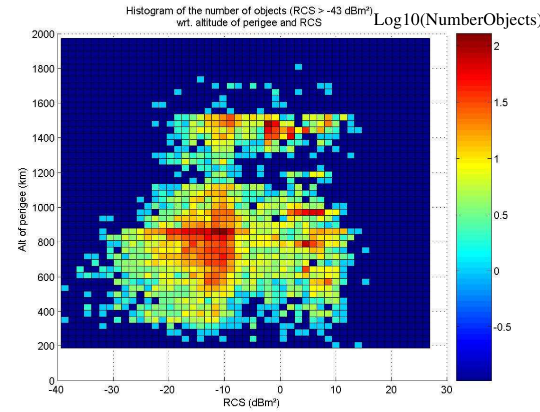

Figure 3 – Number of objects wrt. altitude of perigee and RCS (NORAD catalogue, US measured RCS information)

Concerning NORAD catalog (*Figure 3*), we can notice there are very few objects with RCS below -20 dBm² (except around 850 km, corresponding to the debris of the 2007 Chinese ASAT test, that may have been especially tracked for geopolitical reasons). This corresponds to a catalogue based on actual measurements by existing radar assets.
Very few objects have a perigee altitude above 1500 km, corresponding to the cataloguing limit for the US assets. All the objects with a high altitude of apogee have a “big” eccentricity, coming back down to a reachable distance of the radars. The higher objects with smaller eccentricity may not be detected often enough.

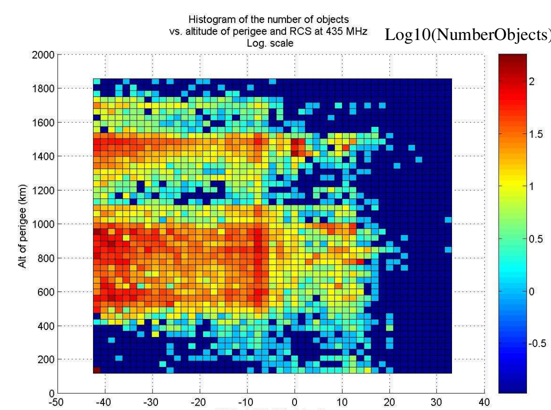

Figure 4 – Number of objects wrt. altitude of perigee and RCS (Master-2005 catalogue at 435 MHz)

MASTER-2005 population is a modelled population. That is why there are many objects at any altitude, whatever their size is. This may enhance the difficulty to reach a high level of the percentage of the population, since high altitude objects will be difficult to reach.

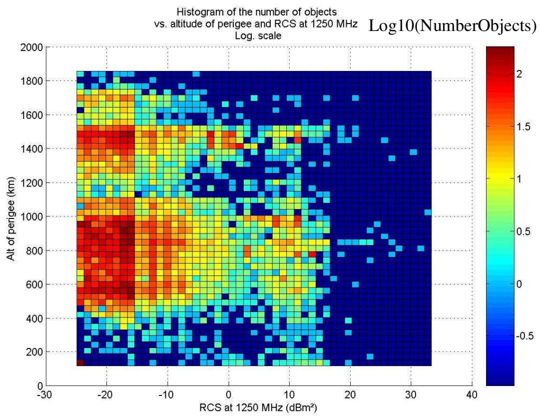

Figure 5 – Number of objects wrt. altitude of perigee and RCS (Master-2005 catalogue at 1250 MHz)

2.1.2.2. Distribution of the inclination of the orbits

If we consider the inclination of the orbits of the objects versus the size of the objects, we get *Figure 6*, based on Master2005 catalogue.

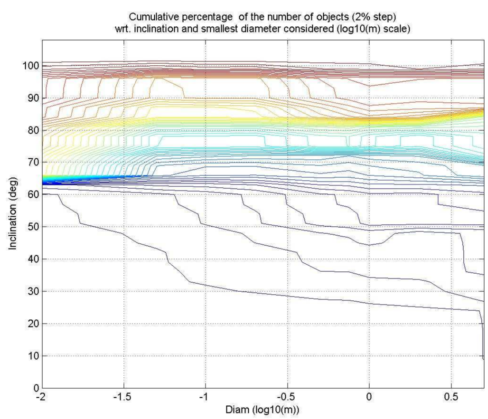

Figure 6 – Cumulative Distribution of inclination of orbits for different populations of LEO objects (Master-2005 catalogue) (size in log-scale, each line corresponds to a 2% increase of the cumulated population)

Excepted if we only consider large size objects (more than 1 meter, step D), most of the objects have an orbit with an inclination over 50 degrees.

Considering *Figure 7*, we can see that for the upgrade step from step F to step U, the orbit of most of the new objects to consider (size between 5 and 10 cm) have an inclination above 60 degrees.

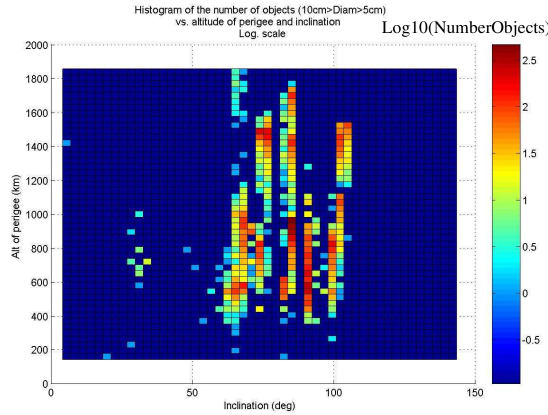

Figure 7 – Number of LEO objects wrt. inclination of the orbit and altitude of perigee, size between 5 and 10 cm (Master-2005 catalogue)

2.1.2.3. Choice of frequency wrt. population

The main driver for the frequency at this step of the study is performance. It may also depend on technological issues (readiness, affordability…), but these are criteria related to the design of the radar elements. They will be taken into account later, in the suggested designs for the concepts.

Performance and frequency are linked by the RCS of the objects, and thus by their size. Concerning Master-2005 population, size information is available, enabling comparisons. This is not the case for the NORAD population. The only additional information are the Satellite Situation Report (SSR) giving the measured RCS, without any frequency reference.

So this study is based on the Master-2005 population data.

The radar equation in dB can be written as in Eq. 1, if we only want to take RCS and distance into account:

$$SNR_{dB} = K_{dB} + \sigma_{dB} - 40 \cdot \log_{10}(D) \tag{1}$$

where σ_{dB} is the RCS and D the distance (calculated on the basis of the perigee altitude). Squared frequency also matters in the K constant, but the aim here is to compare only the effect of RCS and distance for different frequencies. So, we assume the direct effect of frequency in the link budget is balanced by more emitting power at higher frequencies in order to keep the K value constant (+9.1 dB for emission at 1250 MHz compared with 435 MHz). That is equivalent to say that the reference range on a -20dBm² target is the same at both frequencies.

The relation induced by this link budget equation between RCS and distance is linear in log scale, the detectable objects correspond to those verifying

$40 \cdot \log_{10}(D) \leq \sigma_{dB} + K'$ with K' a constant corresponding to a threshold.

Comparing different radars at different frequencies, all other parameters being equal (especially the reference range on a -20dBm² target) is now easy. From the RCS/distance figures (cf. *Figure 3*, *Figure 4* and *Figure 5*), we can add up the number of objects detectable for a given value of the threshold K' and for different RCS as described above.
An example is visible on *Figure 8*, showing the part of the population that is declared as non reachable.

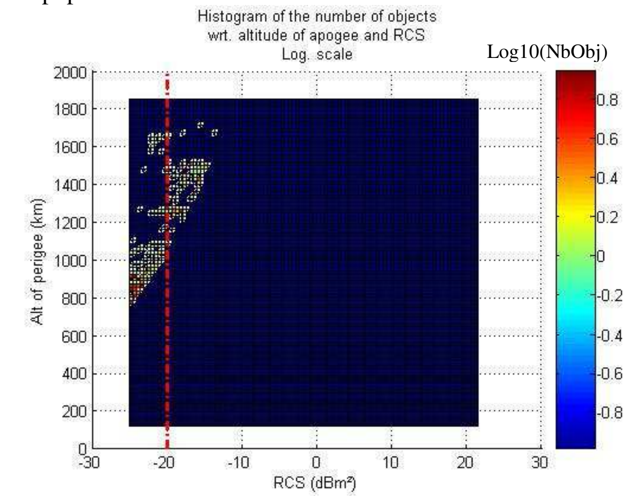

Figure 8 – Proportion of non reachable population for a radar located in Spain with a 30° mean elevation survey zone. Threshold here is 90% of the population.

We can then get the following results, for 10cm objects (*Figure 9*) and 5 cm objects (*Figure 10*), for different values of K' in abscissa:

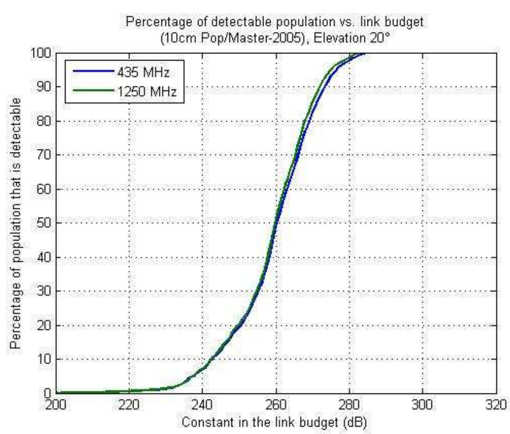

Figure 9 – Percentage of detectable objects vs link budget constant - Mastrer-2005 population – 10 cm objects.

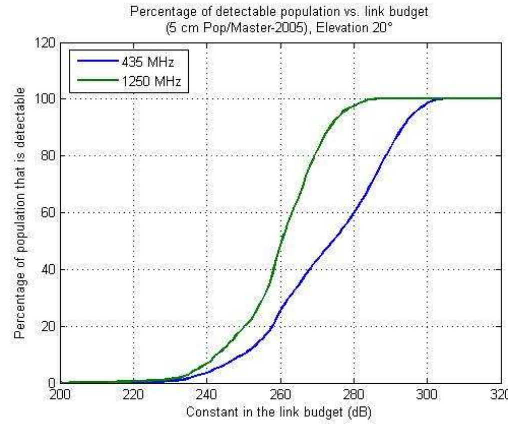

Figure 10 – Percentage of detectable objects vs link budget constant - Mastrer-2005 population – 5 cm objects.

We can see the results are consistent with the data in Table 2:

- Concerning 10cm objects, since RCS at both frequencies are rather equivalent, the difference is low, reaching 2 dBs at the very end of the curve.
- Concerning 5 cm objects, the difference appears sooner, reaching 18dBs to get the whole population. This corresponds to the difference between the RCS of a 5cm sphere at 435MHz and 1250 MHz.

In terms of performance, higher frequencies are better to get smaller objects. Technological issues may balance this result in the next phase, as well as design constraints, leading to a trade off.

2.1.3. Survey zone characteristics

The choice for the survey zone characteristics can be based on the information given by the distribution of the objects.

2.1.3.1. Reachable population in inclination

The distribution in inclination (*Figure 6* and *Figure 7*) has an impact on the choice for the survey zone characteristics in terms of elevation and on the location of the radar: low inclination orbits may not be reachable if the radar is located at high latitude or if the survey zone lower limit is too high in elevation.

Figure 11 shows the influence of the minimum value of a 20° wide elevation survey zone. Located 45° North, 30° inclination orbits may be detected by a radar with a [10°-30°] survey zone, but not by a [40°-60°].

Similar figures can be established considering different values for the range or for the elevation aperture, giving other interesting drivers.

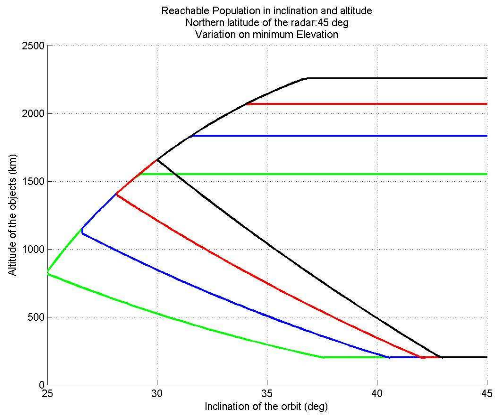

Figure 11 – Influence of the lower elevation value of the survey zone on the reachable population (radar located at 45° in latitude2500 km range, 20° elevation aperture) Variation of the minimum elevation:
[10° - 30°], [20° - 40°], [30° - 50°], [40° - 60°]

2.1.3.2. Detectable population in altitude

In order to be detected, objects have to be in the survey zone during a minimum time, in order for the survey beam to illuminate them and to detect them.

This is especially true for low altitude objects.
On the basis of the orbital mechanics and the distribution of the orbits in term of eccentricity and altitude of perigee, the requirement to reach the minimal duration of visibility can be estimated. Orbital mechanics gives the speed at a given altitude; geometry allows estimating the minimal time to cross the survey zone according to its characteristics.
Figure 12 shows that lower angular speed are obtained for low elevation values.

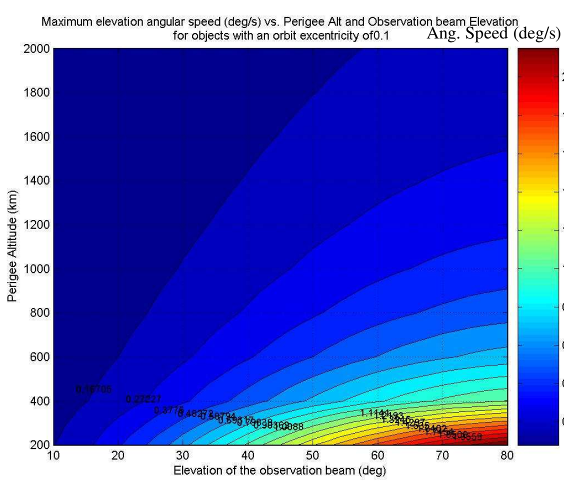

Figure 12 – Maximum angular speed vs. elevation of a LEO object and its perigee altitude

On the other hand, the problem for high altitude objects is to be detected. The main driver for detection is distance. It can be reduced by searching for objects at high elevation, as geometry can show quite simply.
So a trade off has to be found to be able to detect well both low and high altitude objects.

2.1.3.3. Dynamic distribution of the objects

The number of objects simultaneously in the FOR at a given moment can be an important parameter (cf. *Figure 13*).
For Track While Scan (TWS) radars, it will define the processing load that has to be sustained. For Active Tracking (AT) radars, it defines the number of tracks that have to maintained, and thus the time load of the radar.

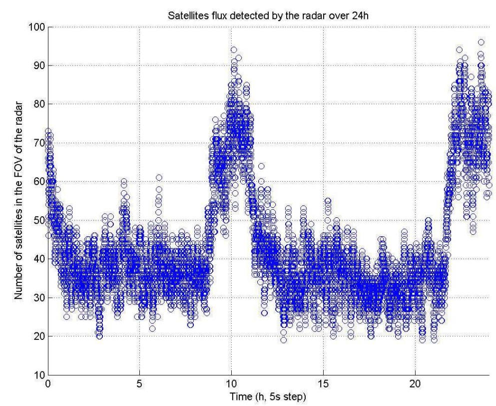

Figure 13 – Number of objects in the FOR (Radar position at latitude 45°, longitude 0°, 180° azimuth opening, minimum elevation 20°, elevation aperture 20°, reference range on -20 dBm² 3500km, 24h simulation of the NORAD catalogue)

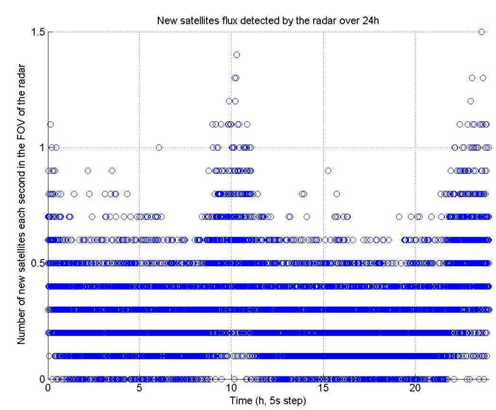

Figure 14 – Number of new objects in the FOR (Radar position at latitude 45°, longitude 0°, 180° azimuth opening, minimum elevation 20°, elevation aperture 20°, reference range on -20 dBm² 3500km, 24h simulation of the NORAD catalogue)

The number of new objects in the FOR is another important parameters, giving the number of new objects to acquire. (cf. *Figure 14*)

On *Figure 13* and *Figure 14*, the peaks of objects correspond to Fengyun-1C debris (ID between 30000 and 33000).
This peak may be levelled down with time. NORAD database is biased for the moment. Considering there are other debris on other orbits not yet detected, the mean true level of objects density may be intermediate between the lower one and this peak.

Based on simulations with Onera's tool S4 and post-processing on MATLAB, models have been proposed to show the behaviour of the number of objects and new objects in the FOR wrt. its characteristics.
The results are given for the NORAD catalogue.

2.1.3.3.1. Number of objects in the FOR

The general model for the estimation of the number of satellites in the survey zone for the NORAD population is given in Eq. 2

$$NbSatSurveyZone = ceil\left(\begin{array}{l} \alpha \\ + \beta \cdot \left(A_{Az} + B_{Az} \cdot \left(AzOp - 150 \right) \right) \\ \cdot \left(\dfrac{a\tan\left(\dfrac{Range}{R\mathrm{Re}f} \right)}{a\tan\left(\dfrac{2500}{R\mathrm{Re}f} \right)} + \dfrac{R\mathrm{Re}f}{2500} - \dfrac{R\mathrm{Re}f}{Range} \right) \\ \cdot e^{-\frac{(ElevMin-20)}{Elev\mathrm{Re}f}} \cdot \sqrt{\left(\Delta Elev / 20 \right)} \end{array} \right) \quad (2)$$

with AzOp = azimutal aperture given in degrees [100°;180°]
Range = the range of the radar on a -20dBm² object given in km [750km; 3500km]
ElevMin = the elevation of the lower bound of the survey zone given in degrees [15°; 60°]
ΔElev = the elevation aperture of the survey zone given in degrees [10°; 40°]
ceil(x) is the function giving the upper integer value

The parameters of the model are given with respect to the northern latitude of the radar:

LatRadar	α	β	A_{Az}	B_{Az}	RRef	ElevRef
30	3	0.9	78	0.24	440	25
35	5	0.917	79	0.25	440	25
40	7	0.9	81	0.26	440	25
45	8	0.889	82	0.32	450	25
50	7	0.88	86	0.35	460	25
55	6	0.875	90	0.37	470	25
60	8	0.875	90	0.43	480	25

2.1.3.3.2. Number of new objects in the FOR

The mean number of new satellites can roughly be described by a similar model than the number of satellites, except there is a negligible (and thus neglected) dependency on elevation aperture. Cf. Eq.3

$$\overline{NbNewSatSurveyZone} = \max\left(MinValue, \left(\begin{array}{l} \alpha \\ + \beta \cdot \left(A_{Az} + B_{Az} \cdot \left(AzOp - 150 \right) \right) \\ \cdot \left(\dfrac{a\tan\left(\dfrac{Range}{R\mathrm{Re}f} \right)}{a\tan\left(\dfrac{2500}{R\mathrm{Re}f} \right)} + \dfrac{R\mathrm{Re}f}{2500} - \dfrac{R\mathrm{Re}f}{Range} \right) \\ \cdot e^{-\frac{(ElevMin-20)}{Elev\mathrm{Re}f}} \end{array} \right) \right) \quad (3)$$

with AzOp = azimutal aperture given in degrees [100°;180°]
Range = the range of the radar on a -20dBm² object given in km [750km; 3500km]
ElevMin = the elevation of the lower bound of the survey zone given in degrees [15°; 60°]

The parameters of the model are given with respect to the northern latitude of the radar, with MinValue = 0.06:

Lat Radar	α	β	A_{Az}	100x B_{Az}	RRef	Elev Ref
30	0.005	0.95	0.230	0.09	420	35
35	0.005	0.95	0.244	0.09	410	35
40	0.010	0.94	0.250	0.1	405	35
45	0.010	0.93	0.265	0.11	400	35
50	0.015	0.91	0.285	0.13	400	35
55	0.025	0.90	0.310	0.15	400	35
60	0.030	0.90	0.343	0.17	420	35

Concerning the maximum number of new satellites at a given time, the most important parameter for the flux of new objects is the minimum elevation of the survey zone. Range (0.15/1000km) and azimuth aperture (0.15/30°) have low linear effect, except in the case of "exotic" combinations. Its aperture has only few effects on the maximum number of new satellites.

Using the same model with other values for the parameters, we can get the maximum number of new objects in the survey zone, with MinValue = 0.4:

Lat Radar	α	β	A_{Az}	B_{Az}	RRef	Elev Ref
30	0.08	0.94	1.10	0.002	300	75
35	0.10	0.92	1.13	0.002	290	75
40	0.10	0.91	1.18	0.002	280	75
45	0.10	0.90	1.20	0.002	270	75
50	0.12	0.90	1.22	0.002	260	75
55	0.15	0.890	1.24	0.003	250	75
60	0.20	0.875	1.27	0.004	250	75

2.1.3.3.3. Mean duration of visibility

The general model for the estimation of the mean duration of successive visibility (given in seconds) is given in Eq. 4:

$$MeanDurationVisi = ceil\left(\begin{array}{l}\alpha \\ + \beta \cdot \left(A_{Az} + B_{Az} \cdot (AzOp - 150)\right) \\ \cdot \left(\dfrac{a\tan\left(\dfrac{Range}{RRef}\right)}{a\tan\left(\dfrac{2500}{RRef}\right)} + \dfrac{RRef}{2500} - \dfrac{RRef}{Range}\right) \\ \cdot e^{-\frac{(ElevMin-20)}{ElevRef}} \cdot \sqrt{\left(\Delta Elev / 20\right)}\end{array}\right) \quad (4)$$

with AzOp = azimutal aperture given in degrees [100°;180°]

Range = the range of the radar on a -20dBm² object given in km [750km; 3500km]

ElevMin = the elevation of the lower bound of the survey zone given in degrees [15°; 60°]

ΔElev = the elevation aperture of the survey zone given in degrees [10°; 40°]

The parameters of the model are given with respect to the northern latitude of the radar:

LatRadar	α	β	A_{Az}	B_{Az}	RRef	ElevRef
30	5	0.94	130	0.33	210	40
35	4	0.95	130	0.33	210	40
40	2	0.95	130	0.30	210	40
45	0	0.96	128.6	0.26	210	40
50	0	0.97	128	0.26	210	40
55	0	0.97	128	0.25	210	40
60	0	0.98	128	0.25	210	40

2.1.3.3.4. Associated requirements

On the basis of these models, some requirements can be established in order to ensure the radar will withstand the load associated to the objects it can detect.
The radar system shall be able to maintain the tracks of the objects detectable in its tracking zone.
The radar system shall be able to detect and acquire at least the mean number of new objects per second corresponding to its configuration.

2.1.3.4. Importance of the revisit time

Revisit time is the delay between two consecutive identical positions of the FOV while scanning the survey zone.
Related to the geometric characteristic of the survey zone, it defines the possible number of detectable plots.
Consecutively, it defines the cumulated probability of detection of the object, since it is given by:

$$Pd_{Cumul} = 1 - \left(1 - Pd_{Plot}\right)^{NbPossibleDetections}$$

This is especially important in the case of an active tracking radar, since the survey zone is generally smaller than in the case of a TWS only radar. The aim is just to get a first plot in order to initiate the tracks.
For a TWS radar, it should enable to get the minimum number of plots needed to get a track whose accuracy is sufficient to correlate it to the previous and next tracks of the same object.

2.2. Performance requirements

2.2.1. Cataloguing requirements

The radar system shall be able to provide the data to build the catalogue from cold start.
On the basis of the experience of an existing system (GRAVES), considering the tracking and cataloguing process, it is assumed that at least 4 plots separated by at least 3 seconds are needed every 24 hours to maintain the tracks.
The delay between the plots aims to get a minimum angular movement in order to have sufficient information for the orbitographic filter.
The catalogue is expected to be built within 7 days.

2.2.2. Detection requirements

First step before cataloguing objects is to be able to detect them, thanks to the survey function.
Using the same technique as in §2.1.2.3 and on *Figure 8*, we can define drivers for the choice of the reference range needed to detect a given part of the population, taking into account some degrees of freedom.
(Caution, these are only clues for the choice, also showing trends. Exact simulation are needed to get the exact results)

Table 15 gives the minimal range (or equivalent altitude) on a -20 dBm² target to get a given part of the NORAD population for different elevation values of the beam (radar located in Spain). The mean value of the elevation in the survey zone is to be considered in order not to be too constraining, taking into account all the hypothesis. This does not take into account the true probability of detection, but only a 0/1 logic on stationary targets, so it is a bit pessimistic. Once again, it gives trends and interesting order of magnitude, especially on the cost of the upper percents.

The detection range cannot be set at this point in order to let a degree of freedom to the radar specialist during the concepts design phase. Thus, the reference range shall be given in the next phase as the range for a -20 dBm² RCS object following a Swerling 3 target model with a probability of detection of 90% on a single plot.
Objectives have been set for the cumulated probability of detection (aiming the survey+AT concepts)

Concerning Probability of False Alarm, AT concepts can use confirmation dwell to avoid starting a false tracks and TWS concepts can deal with them through post-processing association algorithms. So it has been set to a reasonable value: the Probability of false alarm (Pfa) of the detection function of the Radar System shall not exceed Pfa = 10^{-4} for one dwell.

One requirement concerns the instrumented range: the radar shall be able to detect objects up to an altitude of 2000km.

The requirement for the accuracy has been defined in the SOW[1] for the study as an entry technical requirement.
The requirement has been released for step D only.

2.2.3. Tracking requirements

This is the example of the will to open the possibilities for the design of the radar, through the choice of the strategy to collect information. In order to perform the survey mission, the radar must carry out a survey function (~detection) and a tracking function (~plots gathering) (cf. definitions in the glossary §1.1).
Previous studies have only considered passive tracking (Track While Scan, TWS). We are also considering Active Tracking (AT).
Yet, the designed radar remains a survey asset. It is designed so that the accuracy of the tracks is only sufficient to be able to correlate them in order to build the catalogue. But it may not be sufficient to ensure other missions, such as high accuracy tracking for collision avoidance for instance. Other dedicated assets, cued on the basis of the information of the catalogue, will be needed to perform specific related missions:

- Accurate collision risk avoidance ensured by high accuracy (radar or optical) tracking asset(s).
- Imagery possible thanks to imaging radar(s) or optical means.
- …

The tracking requirements shall not restrict the possibility between these two possible modes, and shall be valid for both cases.
In the TWS case, since tracking is ensured on the base of the survey plots, detection and tracking shall be considered as a single function and the requirements associated to both shall be fulfilled. The most restrictive one shall be considered.

Here also, to keep the degree of freedom, the reference range shall be given in the next phase as the range for a -20 dBm² RCS object following a Swerling 3 target model with a probability of detection of 90% on a single plot.

Table 15 – Minimal Range on a -20 dBm² target to get a given part of the NORAD population for different elevation values of the beam (radar located in Spain)

Elevation	20°		30°		40°		50°		60°	
PourcObject	Altitude km -20dBm²	Range km -20dBm²	Altitude km -20dBm²	Range km -20dBm²	Altitude km -20dBm²	Range km -20dBm²	Altitude km -20dBm²	Range km -20dBm²	Altitude km -20dBm²	Range km -20dBm²
99	1230	2505	1300	2144	1600	2207	NA	NA	NA	NA
98	1130	2341	1170	1955	1200	1693	1270	1571	NA	NA
97	1060	2224	1070	1807	1090	1548	1150	1428	1220	1373
96	1020	2156	1030	1748	1040	1482	1060	1320	1130	1274
95	980	2087	990	1687	1000	1429	1020	1272	1070	1207
90	840	1841	870	1504	880	1268	880	1103	900	1019

Concerning Probability of False Alarm for tracking, it can be less restricting than the one for survey. Indeed, TWS concepts will have to fulfil the most restrictive one. Since AT concept will only try to track already detected objects and since false tracks may only be initiated on false survey plots (with higher Pfa), the risk to have several successive false plots forming a track is negligible. So the Probability of false alarm (Pfa) of the detection function of the Radar System shall not exceed Pfa = 10^{-3} for one dwell.

The requirement for the accuracy has been defined in the SOW[1] for the study as an entry technical requirement.
The requirement has been released for step D only.

2.3. Other requirements

2.3.1. Data transfer, interfaces and treatment: impact on system design

It is important to define the radar system, its limits and the data it will exchange with the other elements. It can impact system design.
These links are shown on both *Figure 16* and *Figure 17*, corresponding to different architectures depending on the tracking technique.
The radar system shall be composed of one or more radar sensors.
The radar system output data shall be tracks, as a set of linked plots supposed to belong to the same observed object.
The radar system shall be able to transfer all the output data to the data centre.
The radar system shall be able to store all the measurements and tracking data for at least 7 days.
The radar elements shall be able to get and exploit a catalogue of the orbiting objects from the data centre. (it is not mandatory, but may be useful in the case of active tracking)

2.3.2. Power supply

The radar system elements needs in energy shall be compatible with power grid supply capability and/or power stations capability.

2.3.3. Meteorological conditions

The radar system elements shall survive to the worst conditions known for the location site.
They also shall be able to work in bad conditions.
It is important to define these conditions: they can impact the logistics studies, but also performances (through accuracy…) and general design (high temperature would enhance the constraints on cooling devices)

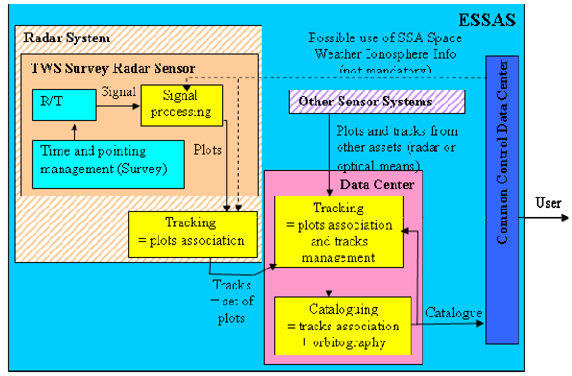

Figure 16 – Description of the interfaces for a "TWS" survey radar system

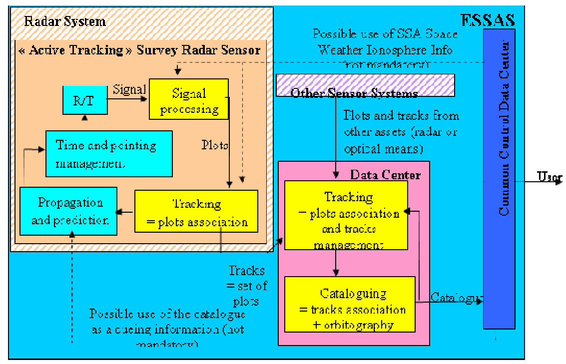

Figure 17 – Description of the interfaces for an "Active Tracking" survey radar system

2.3.4. Electromagnetic legislation

The transmitting frequency band(s) must be chosen among the available frequencies in UHF band in Europe:
- 430-440 MHz
- 1215-1400 MHz
- 3100-3300 MHz

2.3.5. Electromagnetic security

The security of the staff and of the population living near the radar elements must be ensured. Thus, European legislations apply in order to define the size of the restricted areas, on the ground and in the air.
Special attention shall be paid to side lobes to limit the emitted power in direction of the ground.

2.3.6. Logistics and availability requirements

In order to ensure the 99% availability in a year (out of the scheduled maintenance periods) during 20 years, logistics studies have to be undertaken. Particularly, The level of redundancy of the critical elements (transmitters,…) shall be evaluated, as well as their Mean Time Between Failure (MTBF) in order to define the Mean Time Between Critical Failure (MTBCF) for the whole system and the Mean Time To Repair (MTTR).

2.4. Requirements managament

In order to ensure traceability, all the requirements defined through theses studies have been written using a specific presentation.
The definition flag is composed of:
- Information on the type of statement (requirement, objective, test)
- a number
- a reference to the document where the requirement has been defined
- an indication word for the subject of the requirement
- an indication about the steps concerned by the requirement

A title can be given to the requirement.
References to other requirements can be given if the current one enables to cover or fulfil another one. The text of the requirement can then be detailed, closed by an end flag.
A comment can be added after the end flag, and the verification mean shall be given.

A set of tests have been defined to ensure the coverage of the different requirements.

In order to keep this paper clear and easier to read, the requirement management presented here has not been used in this paper, but is in use for the whole study.

Tools exist or can be created and can be used to manage the requirements and their derivatives in the different reports that will be written.
The proposed numbering principles allow using lexical analysis tools. For instance, VBA scripts can be developed to build the requirements/tests trees. ChiasTek Reqtify tool is also a possible tool.

3. CONCLUSION

A large part of this paper has been devoted to present the various constraints and their impact on the radar system:
- Propagation issues, impacting accuracy and link budget.
- Population considerations, impacting all the system requirements. Thus, a lot of trade-offs need to be done. They have to be robust to the variation of the population of objects. Indeed, the SOW[1] requirements refer to various populations (NORAD-based catalogue for step F and Master-2005 for step U) that are not absolutely consistent together. NORAD is based on observations by radars, whereas Master-2005 is simulated and contains objects whose minimum size is 1 cm. Moreover, NORAD catalogue contains 2007 Chinese ASAT test debris, Master-2005 does not.
- Other constraints, related to legislation (frequency allocation), security, availability, interfaces, meteorology… impacting the whole system have been taken into account.
- Mission related requirements also impact the whole system. The need for a minimal periodic dwell-time impacts the detection and tracking requirements.

On the basis of the analysis of these phenomenons, a set of requirements has been derived, associated to different tools and considerations aiming to ease the design of possible concepts.

As a first part of a radar system study, all this should help radar specialists to propose and study some radar concepts, by relating all this information through the radar link budget equation, adding technological knowledge and time-load or processing-load considerations.

REFERENCES

[1] Statement of Work – Definition of Ground Segment Requirements for a UHF Radar for the ESSAS - GRST-STU-SYS-SOW-1001-OPS-GS Issue 1.0 - 5th of August 2008
[2] Analysis of design options of a large ground-based radar for Europe's future Space Surveillance System - H. Krag et al. – IAC-08-A.6.5.04