

Design of a Radar Based Space Situational Awareness System

Toni Liebschwager

*University of Federal Armed Forces, Munich, Germany
toniliebschwager@web.de*

Dr.-Ing. Thomas Neff

German Aerospace Center, Oberpfaffenhofen, Germany

Univ.-Prof. Dr.-Ing. Roger Foerstner

University of Federal Armed Forces, Munich, Germany

ABSTRACT

Existing SSA-Networks in most cases consist of sensors which originally were not designed for the purpose of detecting or tracking space debris and active satellites. Furthermore there are different kinds of sensors in use which makes it even more complicated to handle all generated data. Therefore it is reasonable to create a network consisting of homogenous sensors. Technologies that are available for detection and tracking of objects (e.g. optical sensors or radar) will be discussed. Focal point will be on operational availability and reliability. It will be shown that Phased Array Radars are the most reasonable technology to be used while creating a sensor network consisting of homogenous sensors. This paper entails to present a proposal for a network of Phased Array Radars configured for this purpose. The system is intended to detect and track objects that are at least as small as objects that can currently be found in the US SSN catalogue. Furthermore potential hazards in different orbits will be evaluated and discussed to optimize the system on these areas. The system is supposed to be able to create an own object catalogue. Therefore perseverative tracking and required capacity will also be considered.

On the basis of these considerations the paper shows how to lay-up such a radar-system starting from scratch. Criteria for detection and tracking of objects will be determined. This part of the work contains aspects like choosing the frequency band or tracking-frequencies for different sizes of objects. In the next step the locations for the sensors will be chosen. Based on thoughts about infrastructure it is plausible to place the radar systems on existing observation sites. By analyzing simulations with different numbers of sensors and / or locations several feasible approaches for such a Space Situational Awareness Network will be presented in this paper.

1. INTRODUCTION

Since the beginning of modern space flight in 1957, the number of artificial objects orbiting the earth steadily increased. More and more objects ask for additional Space Situational Awareness (SSA). One important aspect of SSA is knowledge of position and orbits of all potential harmful objects. The size of objects that have to be detected and tracked due to their potential to catastrophic collisions can be obtained by using the NASA Breakup Model. [1] If the energy to mass ratio exceeds 40J/g, a collision might imply a loss of the satellite. As it can be seen in Fig. 1 the risk for collisions is highest in sun synchronous orbits at a height of about 900 km.

ESA MASTER-2009 Model
3D spatial density distribution vs. S.D. Altitude and S.D. Declination
Global Average: $0.2245E-07$ [1/km³]

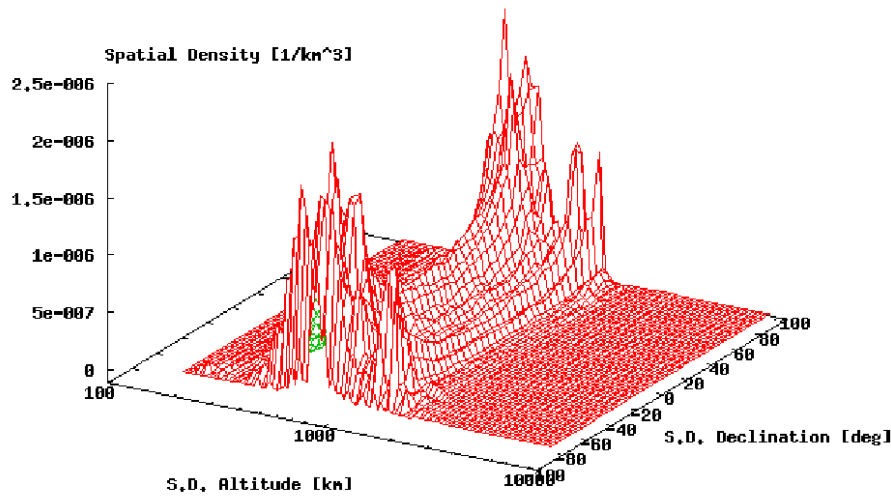


Fig. 1. Spatial Density of Objects

In such an orbit the energy to mass ratio for a sphere hitting a satellite with a mass of 1000 kg exceeds this value at a size of about 7 cm assuming it is made out of aluminium. Therefore it is reasonable to detect and track even smaller objects as they can cause serious damage to a satellite. There are different technologies that can be used to observe objects in this orbit region: telescopes, radars with mechanical steering and Phased Array Radars. Due to the dependency on light and weather it is not reasonable to use telescopes for the network, as their operational availability is not satisfying at all. When deciding for Phased Array Radars or mechanical ones we have to consider the large amount of objects that have to be observed. As their number exceeds 60,000 in the size regime of 5 cm and above, radars with mechanical steering reject. Conventional Phased Array Radars may also have trouble observing a large amount of objects simultaneously, so it was decided to analyze the potential of Digital Beamforming (see also Fig. 5).

2. ANALYZING FIELD OF VIEW AND MAXIMUM RANGE

Before getting started with parameters of the radar system, its Field of View (FoV) and maximum range have to be evaluated, as they are major design drivers. The system is supposed to be able to detect objects up to a height of 2,000 km. This height was set reflecting the fact, that it includes all orbits of possible LEO missions. The maximum range of the radar required to observe this height is a function of the maximum elevation of the system. Fig. 2 shows the relation.

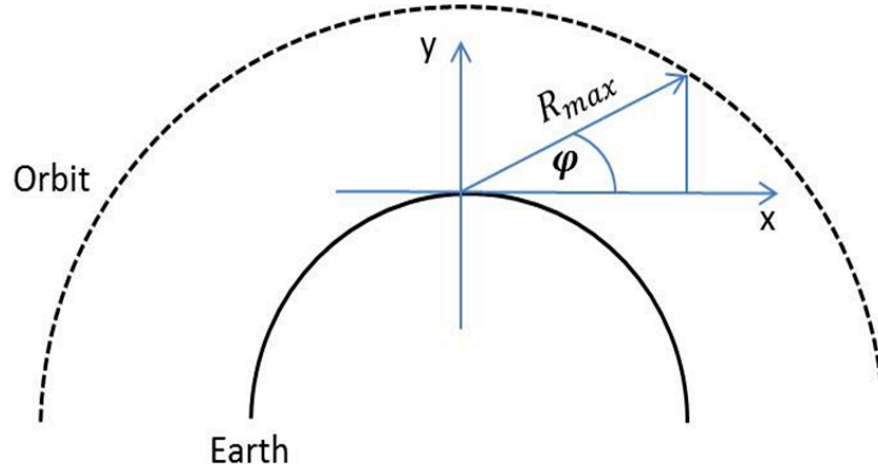


Fig. 2. Analyzing Maximum Range

The required range for different elevations has been calculated. Minimum elevations have been assumed with 5° . So 30° coverage in elevation leads to a maximum elevation of 35° . Tab. 1 shows the required range of the sensor for different maximum elevations.

Tab. 1. Required Range as a function of Elevation

Maximum Elevation	Required Range
25°	3,367 km
35°	2,890 km
45°	2,549 km

As one can see, there are big differences (about 800 km) for different elevations. An additional range of about 800 km makes a big difference when analyzing the corresponding SNR.

To analyze the impact of changing the FoV, location and viewing direction of the sensor, simulations for different locations and FoVs have been performed. It can be shown that only one hemisphere has to be simulated, also the longitude of a sensor has no impact on the observation performance. [2] The object environment was simulated by taking a TLE catalogue (epoch July 2013). All objects were propagated for a period of about 10 days. Fig. 3 shows the number of observable objects for a sensor with a maximum range of 4,000 km 20° coverage in elevation and azimuthal coverage of about 60° , pointing south. As one can see, best locations are in latitudes between 10° and 25° .

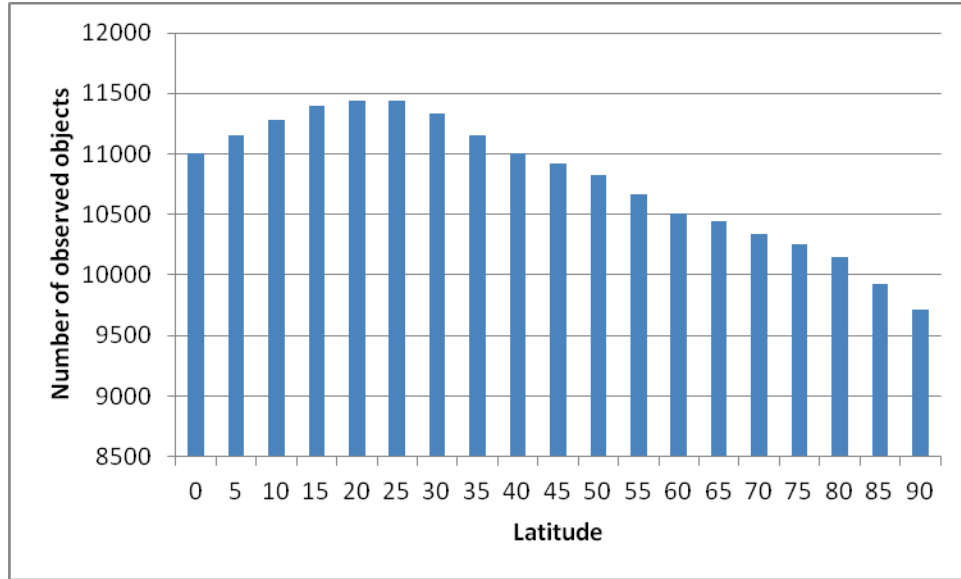


Fig. 3. Observable objects depending on latitude

An important parameter for observability is the time span an object is residing in the sensor's FoV. Therefore this parameter has to be optimized. Increasing the azimuthal coverage leads to longer dwell times, increasing coverage in elevation has negligible effects on this. But as Fig. 4 shows, even 60° azimuthal coverage lead to pleasing dwell times.

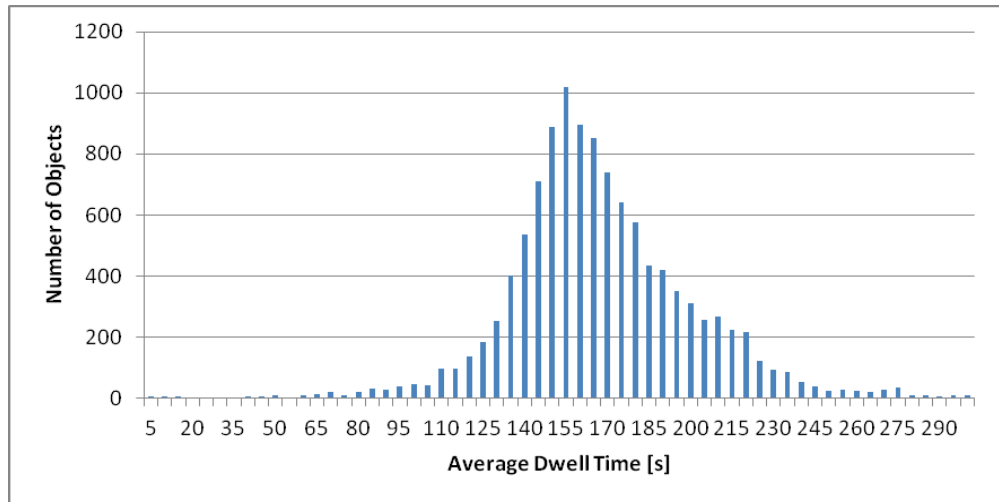


Fig. 4. Average dwell times with 2,500 km range, 60° azimuthal coverage, 20° coverage in elevation, 20° latitude

These dwell times lead to high integration gains as Digital Beamforming is used so that the object is observed all the time by a receiving beam. With a pulse repetition frequency of 47 Hz and an assumed dwell time of 100 s, 37 dB integration win can be gained.

3. ANALYZING REQUIRED RADAR PARAMETERS

First parameter to be set is the wavelength of the signal. As considered before it is important to detect and track objects down to sizes of 5 cm. In this size regime, long wavelengths perform very poor. [3] This can be shown using an example a sphere with a diameter of 5 cm. Tab. 2 shows the results for different wavelengths.

Tab. 2 RCS of a sphere with diameter of 5 cm

Band	UHF	X-Band	W-Band
Wavelength [m]	0.7	0.03	0.003
RCS [dBsm]	-44.51	-27	-27

The RCS is increasing with decreasing wavelengths till reaching its maximum value of -27 dBsm. This value can already be gained with a wavelength of 0.03 m. Shorter wavelengths do not contribute to better results.

It has been shown that there are two different FoVs that could deliver satisfying performances for realizing the sensor network. Now we have to analyze which of them can be realized in a more economical way. Therefore several budgets have been calculated.

To ensure that all objects passing the sensor's FoV can be detected and tracked, Digital Beamforming has to be used. The concepts proposes to "build" the entire Field of View out of several smaller beams. Fig. 5 shows the concept, the beams formed by the subarrays are colored red, the resulting FoV is colored blue.

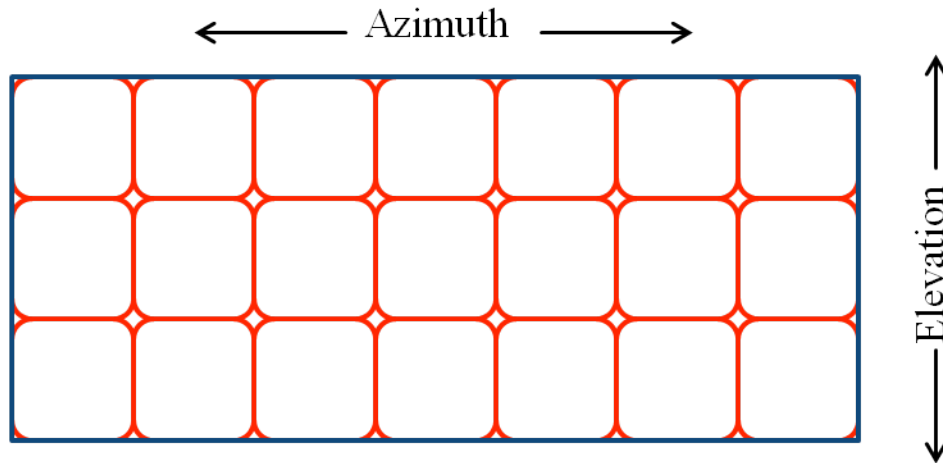


Fig. 5 Covering the Field of View

This concept leads to an increased receiving antenna gain as all T/R modules are used for this purpose. The more transmission beams are used, the better gets the SNR. But as more transmission beams lead to higher power consumption of the system, a reasonable number and size has to be found. It has been found out that 3 dB beamwidths of about 1.5° lead to good results. When covering 40° in elevation and 60° in azimuth there is a need for at least 1,080 subarrays forming these beams. The system is supposed to create signals with a duration of 1.3 ms. With a PRF of 47Hz and 50 W maximum power of a transmission module this leads to an average power of approximately 3 W for each T/R module. Higher PRFs are hard to implement because it takes about 20 ms till the signal returns from a target in a distance of 2,500 km.

Tab. 3 Sensor with 2,500 km maximum range and 3 dB beamwidth of 1.5°

Parameter	Value [dB]	Weighting	Contribution [dB]
Average Power	42,83	1	42,83
Antenna gain (transmitting)	41,52	1	41,52
Antenna gain (receiving)	71,86	1	71,86
Wavelength	-15,23	2	-30,46
RCS	-27	1	-27
Integration win	37	1	37
Compression win	64	1	64
4π	10,99	3	-32,97
Range	63,98	4	-255,92
Boltzmann constant	-228,6	1	228,6
Noise temperature	30	1	-30
Receiver bandwidth	93	1	-93
Losses	20	1	-20

Sum

-3,54 dB

A SNR of -3,54 dB is a good start for further analyzes, as losses have been considered very high. Also a RCS of -27 dBsm is very pessimistic as most realistic objects will provide better results.

4. Locating Proper Sensor Sites

As it has been shown, best sensor locations can be found between 10° and 25° latitude. The proposed sensor type requires a lot of infrastructure. So it is easier to build them near existing sensor sites, as these offer most necessities. To evaluate the most plausible sites, all existing SSA sensor sites have been analyzed. [4] With the proposed type of sensor it is possible to build up the network with just two or three sites. That is why it is very important to distribute them as equal as possible around the globe. Sites in Maui and Tenerife fit the demands very well. A third sensor site than has to be located in longitudes between 110° and 120°. Best infrastructural conditions might be found in Australia as there is no large SSA sensor in this longitudes existing yet. Perth has been assumed as a proper location as infrastructural requirements should be able to be fulfilled. Table 4 shows the chosen locations for the sensors.

Tab. 4 Simulated Sensor Sites

Location	Longitude	Latitude
Tenerife	-16.51	28.3
Maui	-156.257	20.7085
Perth	115.63	-31.52

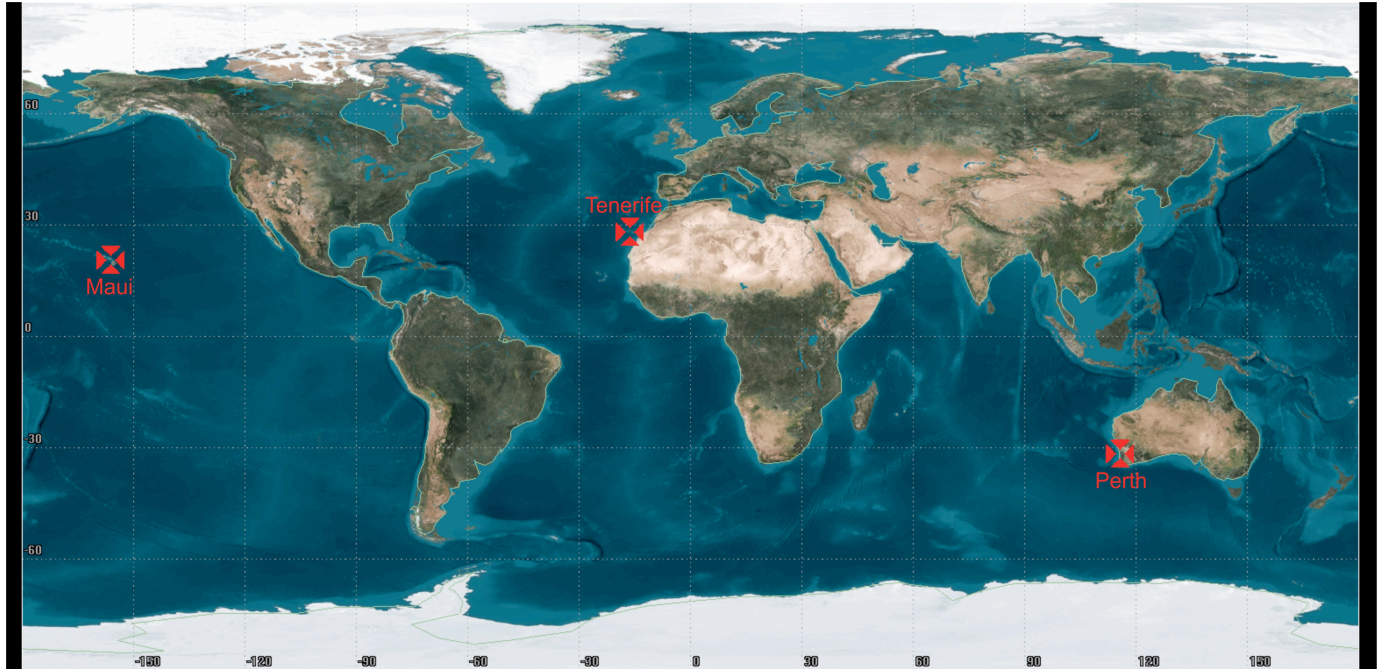


Fig. 6. Proposed Sensor Locations

These locations have been analyzed single and each possible combination. It is important not to consider only the observed objects but to analyze the correlated objects as the system is supposed to build up an object catalogue. Criteria for a successful correlation of an object were set to at least one observation every 24 hours with a minimum dwell time of about 10 seconds. [2] Tab. 6 shows the correlated TLE object population for different heights of perigee.

Tab. 5. Correlated Percentage of TLE-Population

Locations	Percentage of population with height of perigee			
	<2,000 km	<1,500 km	<1,000 km	<500 km
Maui-Perth	89.6%	90.1%	89.4%	52.1%
Maui-Tenerife	89.7%	90.2%	89.5%	51.9%
Perth-Tenerife	89.6%	90.1%	89.3%	51.6%
Maui-Perth-Tenerife	90.8%	91.2%	90.6%	58.8%

As one can see the results under 500 km differ from those above. To examine the reasons for this, the results were also analyzed referring the excentricity. Table 6 shows the results.

Tab. 6. Correlated objects concerning excentricity

Excentricity	Percentage of correlated objects			
	Maui-Perth	Maui-Tenerife	Perth-Tenerife	Maui-Perth-Tenerife
0	99.7%	99.7%	99.7%	99.8%
0.05	99.6%	99.4%	99.3%	99.7%
0.1	97.8%	97.8%	98.3%	98.7%
0.15	81.2%	81.2%	84.1%	87.0%
0.2	82.3%	77.2%	86.1%	97.5%
0.25	67.9%	71.7%	67.9%	84.9%
0.3	50.0%	55.0%	55.0%	75.0%
0.35	45.0%	40.0%	35.0%	80.0%
0.4	11.8%	29.4%	17.6%	64.7%
0.45	27.3%	22.7%	25.0%	54.5%
0.5	9.2%	9.2%	8.2%	35.7%
0.55	5.5%	8.2%	6.4%	13.6%
0.6	6.3%	12.5%	8.8%	22.5%
0.65	4.7%	6.8%	2.9%	10.6%
0.7	0.4%	1.3%	0.2%	1.7%
0.75	1.0%	2.0%	1.0%	3.0%
0.8	0.0%	0.0%	0.0%	0.0%
0.85	0.0%	0.0%	0.0%	0.0%

As one can see the network's performance is best at near circular orbits. Nearly all missing objects have elliptical orbits. These orbits are hard to observe when using only a small number of sensors with limited range as the objects pass the sensor's FoV very seldom. The differences between the scenarios with two or three sensor sites are very small. The benefits of a third sensor therefore have to be denied.

The risk due to missing some objects in elliptical orbits is pretty small, as there is only a small number of objects in such orbits. Therefore this paper suggests a network consisting of two sensor sites in Maui and Tenerife. These sites are chosen as infrastructural requirements can be fulfilled best there.

5. CONCLUSION

A radar based sensor network using DBF with two sites located on Maui and Tenerife is able to detect and track almost all objects in the size regime down to 5 cm in near circular objects. Important parameters of the system are shown in Tab. 7.

Tab. 7. Important Parameters of the System

Parameter	Value
Wavelength	0.03 m
Average power	20.74 MW
3dB beamwidth of subarray	1.5°
Maximum Range	2,500 km
Coverage in Azimuth	60°
Coverage in Elevation	40°
Size of the array	48 m*32.4 m

6. REFERENCES

- 1 Sakuraba, K.: *Investigation and Comparison between New Satellite Impact Test Results and NASA Standard Breakup Model*, In: International Journal of Impact Engineering, 2007.
- 2 Krag, H.: *Designing a large ground-based RADAR for Europe's future Space Surveillance System*; In: Deutscher Luft- und Raumfahrtkongress 2008; P. 1287-1296.
- 3 Skolnik, M.: *Introduction to Radar Systems*, Mc Graw-Hill, Boston, 2001.
- 4 Weeden, B.; Cefola, P.; Sankaran, J.: *Global Space Situational Awareness Sensors*, 2010.