Design and Efficiency Analysis of Operational Scenarios for Space Situational Awareness Radar System

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ABSTRACT

In order to perform the surveillance and tracking of space objects, optical and radar sensors are the technical components for space situational awareness system. Especially, space situational awareness radar system in combination with optical sensors network plays an outstanding role for space situational awareness. At present, OWL-Net(Optical Wide Field patrol Network) optical system, which is the only infra structures for tracking of space objects in Korea is very limited in all-weather and observation time. Therefore, the development of radar system capable of continuous operation is becoming an essential space situational awareness element. Therefore, for an efficient space situational awareness at the current state, the strategy of the space situational awareness radar development should be considered.

The purpose of this paper is to analyze the efficiency of radar system for detection and tracking of space objects. The detection capabilities are limited to an altitude of 2,000 km with debris size of 1 m^2 in radar cross section (RCS) for the radar operating frequencies of L, S, C, X, and Ku-band. The power budget analysis results showed that the maximum detection range of 2,000km can be achieved with the transmitted power of 900 kW, transmit and receive antenna gains of 40 dB and 43 dB, respectively, pulse width of 2 ms, and a signal processing gain of 13.3dB, at frequency of 1.3GHz. The required signal-to-noise ratio (SNR) was assumed to be 12.6 dB for probability of detection of 80% with false alarm rate 10^{-6}. Through the efficiency analysis and trade-off study, the key parameters of the radar system are designed. As a result, this research will provide the guideline for the conceptual design of space situational awareness system

1. INTRODUCTION

The need to secure technology for Space Situational Awareness (SSA) is on the rise to protect the safety of the people and space assets from space hazards. The main mission for space situational awareness system is to build the surveillance and tracking capacity of space objects that are likely to re-enter the Earth, or collide with satellites and space debris. Especially, the knowledge of position and orbits of all space objects is one of the most important aspects of SSA [1]. During the last years radars have provided very powerful information for space object observation, compared to that obtained by other observational sensors. Radar system provides high detection probabilities at Low Earth Orbit (LEO) by two-way distance due to the active illumination of the object with electromagnetic radio wave energies. Besides its important properties is independent of the meteorological and daytime conditions. Radar performances, suited to space situational awareness, are required for the verification of orbital systems, and risk assessment of re-entering space objects [2]. Especially, in LEO orbits (up to 2,000 km), the most suitable option is to use ground-based radar [2][3].

Currently, the United States Space Surveillance Network (SSN) consists of a worldwide network of space surveillance sensors with radars, optical telescopes and space based space surveillance satellites. And upgrade the SSN is also planned to add the most powerful radar sensor, space fence system, S-band radar which will be capable of tracking about a large number of small space objects. Space Fence is expected to allow detectable returns from the smaller size objects and to provide a greater number of observations with which to compile a more accurate and complete catalog [1][4]. Furthermore, to modernize legacy capabilities was begun such as the Eglin FPS-85 radar, the Haystack radar and GLOBUS II [5].

In Europe, the European Space Agency (ESA) started a space situational program from 2009, including the future radar system to detect and survey all objects of a size in the order of one decimeter in LEO [6][7][8]. In France, the bistatic radar system, GRAVES (Grand Rseau Adapt la Veille Spatiale) is operated by the air force. The Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR) commissioned by the Federal Government the German Space Administration (DLR) is developing new phased-array radar to monitor space objects in the LEO. This project, called as German Experimental Surveillance and Tracking Radar (GESTRA), will support the German space Situational Awareness Center to generate a catalogue of orbital data for objects at altitudes of less than 3000 km [8].

In Korea, according to the preparedness plan for space hazards, the development of space situational awareness system is considered. At present, OWL-Net (Optical Wide-Field patrol Network) with five small wide-field telescopes in the world is the only one space situational awareness infrastructure.

In this paper, through the analysis for radar performance, the efficiency of radar system for detection and tracking of space objects is studied. The analysis was performed using radar parameters of the reference systems and the power budget design and simulations was described.

2. RADAR PERFORMANCE ANALYSIS

The trade-off options for ground-based radar such as tracking concept, radar type, sensitivity & altitude, frequency band, search volume and radar location [3]. There are generally two types of radar configuration in monostatic and bistatic systems. The monostatic is configured as both transmitter and receiver in the one station, whereas in a bistatci radar transmitting and receiving antennas are separated by a large distance. A transmitter is placed at one site and the associated receiver is placed at the other site. Target detection is similar to that of monostatic radar: target illuminated by the transmitter and target echos detected and processed by the receiver [9]

For monostatic Radar, the received power, P_r is expressed as:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^3 L_s} \left(\frac{|F|^4}{L_p} \right) \frac{\sigma}{R^4} G_p \qquad (1)$$

where P_t is peak power of the transmitter, G_t transmitter antenna gain, G_r receiver antenna gain, λ wavelength, σ radar cross section(rcs), L_s the total system losses, L_p the propagation loss due to the absorption of the electromagnetic wave by O_2 and H_2O molecules in the atmosphere which is dependent on the used radar frequency, $|F|^4$ propagation factor is defined by $F = \left| \frac{\vec{E}}{\vec{E_0}} \right|$ which is ratio of actual and free space electric field, R radar range to the target, and G_p is the signal processing gain which is usually pulse integration.

Noise Power, P_n is expressed as

$$P_n = k T_s B_n \qquad (2)$$

where k is the Boltzmann's constant(1.38×10^{-23} J/K), T_s is the system noise temperature which is usually defined as $T_s = T_0 F$, where T_0 is 290K and F is the receiver noise factor, and B_n is the receiver's noise bandwidth. The noise figure of the receiver, NF is expressed as NF = 10log10 (F) in dB unit. It is noticed that the noise factor F is different from propagation factor |F|.

The signal-to-noise ratio is defined as

$$\mathrm{SNR} = \frac{P_r}{P_n} \qquad (3)$$

Let define the radar constant K, which is determined by the hardware subsystem of the radar system, be

$$\mathrm{K} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^3 P_n L_s} \qquad (4)$$

The radar equation can be expressed in terms of SNR and radar constant K as follows:

$$\mathrm{SNR} = \mathrm{K} \frac{\sigma}{R^4} G_p \qquad (5)$$

Alternatively, the radar range is expressed as

$$R_{max} = \sqrt[4]{K \frac{\sigma}{SNR_{min}} G_p} \qquad (6)$$

where R_{max} is maximum radar range and SNR_{min} minimum SNR.

Radar Cross Section(RCS) is dependent on the used radar frequency and target size which is usually assumed by the conductive sphere with radius, r. Theoretically, the RCS of a sphere is differently calculated in three scattering regions: Rayleigh, Mie, and Optical [10].

In the space situational awareness radar systems, NASA SEM(Size Estimation Model) is commonly used for the RCS calculation which is based on the measurement results in the frequency range of 2.4 GHz – 18 GHz (S, C, X, Ku band). NASA SEM curves are calculated as follows [11]:

$$\mathrm{x} = \sqrt{\frac{4z}{\pi}}\ \text{, for z > 5, Optical Region} \qquad (7a)$$

$$\mathrm{x} = \sqrt[6]{\frac{4z}{9\pi^5}}\text{, for z < 0.03, Rayleigh Region} \qquad (7b)$$

$$\mathrm{x} = \mathrm{g(z)}\text{, for 0.03 < z < 5, Mie Resonance Region} \qquad (7c)$$

In Mie resonance region, the smooth function g(z) can be expressed by using curve fitting.

We defined the reference performance as a starting point to analyze the detection capabilities of 1 m size in diameter at 2,000 km. The radar parameters for the reference are as follows. For all the frequency band as considered in this paper, the peak transmit power P_t = 100 kW, the transmit and receive antenna gains $G_t = G_r$ = 40 dB, the transmitted pulse width τ = 1 ms with an unmodulated waveform, the receiver system noise temperature T_s = 290°K and the noise figure NF = 3 dB, the patter propagation factor |F| = 1, the system loss L_s = 6 dB, and the atmospheric attenuations are assumed to be a constant value above the troposphere(~ 85 km). The calculated atmospheric attenuations are 1.2 dB, 1.5 dB, 1.7 dB, 2.4 dB, and 5.5 dB for frequencies of 1.3 GHz, 3.0 GHz, 5.5 GHz, 10 GHz, and 16.7 GHz, respectively [9]. And a single pulse SNR_1 is defined for RCS = 1 m^2 at the range R = 1,000 km. For all frequencies, RCS = 1 m^2 corresponds to a diameter of 113 cm.The antenna gain and 3 dB beamwidth can be estimated by the following formula for a phased-array antenna with a element spacing of $\lambda/2$ [9].

$$\mathrm{G} \approx \pi N \eta \qquad (8)$$

$$\theta_{3dB} \approx \frac{100}{\sqrt{N}} \qquad (9)$$

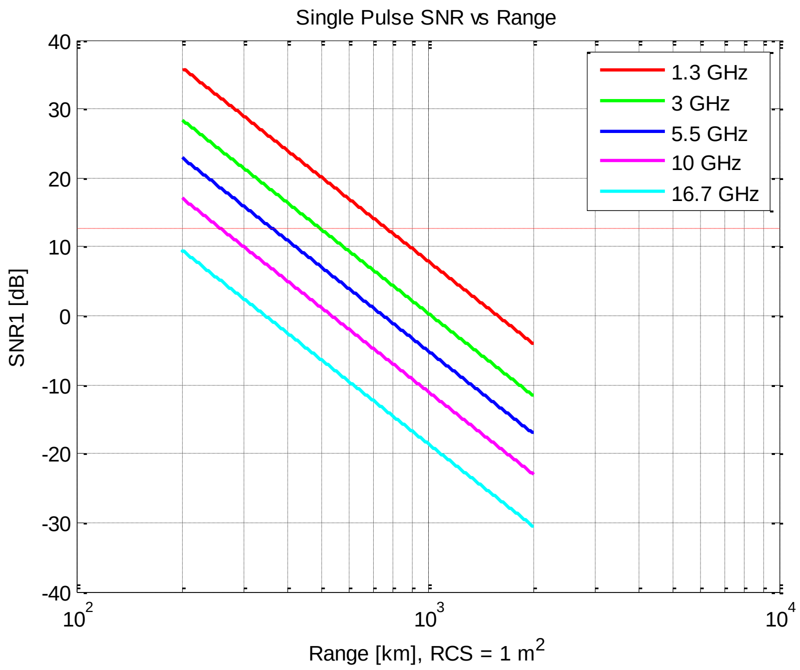
where θ_{3dB} in degree, N is number of elements, and η is antenna efficiency.
When the antenna efficiency η = 0.65 and N = 5,000, the antenna gain is 40 dBi with beamwidth of 1.4°. The peak transmit power P_t of 100 kW can be obtained with a single element power P_0 of 20 W, Pt = N x P_0.
The probability of detection P_d can be calculated in terms of a single pulse SNR_1 and probability of false alarm P_{fa}. They are approximately related as follows [10];

$$P_d = 0.5 \cdot erfc\left(\sqrt{-ln(P_{fa})} - \sqrt{SNR + 0.5}\right) \qquad (10)$$

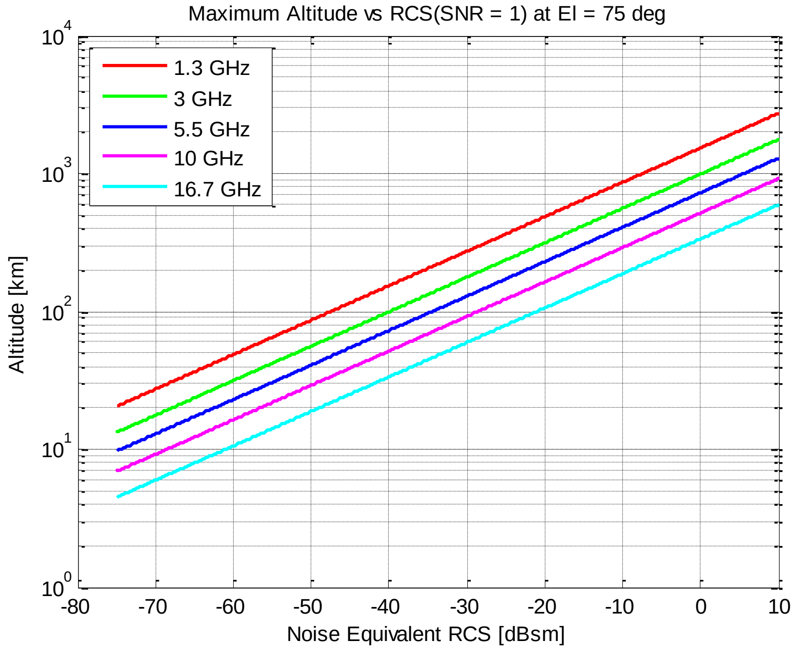
The required SNR for P_d = 80 % is SNR_{req} = 12.6 dB with $P_{fa} = 10^{-6}$.

Fig.1 shows the simulated graphs using the reference parameters. The frequency dependency is pronounced for the same parameters. However, the radar systems with higher frequency have some advantages such as reduced hardware dimensions and detection of smaller target size in some applications due to shorter wavelength.

The reference performances are summarized in Table 1 for all frequencies. As can be seen in Table 1, the more transmitted power and antenna gain will be necessary as increasing the frequency. However, the increases of power and antenna gain are challenging problems for relevant frequency band, in which some technical compromise must be made, for example, low power and high gain. For debris detect radars in the world, a single pulse SNR_1 at 1,000 km is as large as 50 dB [12].



(a) Single pulse SNR_1 versus target ranges.



(b) Target altitude versus RCS when $SNR_1 = 1$.

(c)

Fig. 1 Reference performances: (a) single pulse SNR_1 vs range, (b) altitude vs RCS when $SNR_1 =1$ for various frequencies (P_t = 100 kW, $G_t = G_r$ = 40 dB_i).

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Table 1. Reference Performances as frequencies

	L-band	S-band	C-band	X-band	Ku-band
Frequency[GHz]	1.3	3.0	5.5	10.0	16.7
Wavelength[cm]	23.08	10	5.45	3.0	1.8
SNR_1[dB] @1,000 km	8.06	0.5	-5	-10.86	-18.4
Range[km] @SNR_1= 0 dB	1,950	1,029	752	535	347
Altitude[km][1]	1,532	991	724	516	334
Add SNR[dB][2] @R = 2,000km	16.6	24.14	29.6	35.5	43

Note 1 : Antenna beam elevation is assumed to be 75°.

Note 2 : Additional SNR is required to detect target RCS of 1 m^2 at 2,000 km with threshold SNR of 12.6 dB.

The power budget has been designed based on the reference performance analysis by taking into account the practical radar components. In this design, L-band frequency is considered. For the other frequency bands, the similar way can be applied. This method is very useful for designing the radar systems.

The radar system is assumed to a phased-array type which has many advantages compared to the conventional radars with large parabolic antenna.

The power budget design is summarized in Table 2 as an example. While the transmit antenna gain G_t is fixed to 40 dB, a single element power P_0 is increased from 20 W to 100 W which delivers total peak power of 500 kW. In this frequency, the achieved element power is about 1 kW in GESTRA system [8]. As far as the number of phased-array elements, transmit and receive elements are 360,000 and 86,000 in S-band, respectively [4]. The receive antenna is usually separated from the transmit antenna with the increased gain for bistatic or close monostatic operations.

The signal processing techniques are very important in radar systems. The most commonly used method is pulse integration, coherent or noncoherent. The coherent integration is very difficult to implement. In space debris detection radars, the used number pulses are 16 or 64 for the noncoherent integration which gives the processing gains of 9.5 dB and 13.3 dB, respectively [10].

The radar pulse width τ is an another important parameter. The transmitted average power P_{av} is related by $P_{av} = P_t \times \tau \times prf$, where prf is pulse repletion frequency. The longer the pulse width τ, the higher the average power P_{av}.

Finally, SNR margins have to be assured taking into account unmodeled losses. In this design, 10 dB margin is assumed. The individual increment of components may be accompanied by high costs. Therefore, the cost and performance must be compromised.

Table 2. An Example Power Budget Design for L-band
(The detection capability of RCS = 1 m^2, R = 2,000 km with SNR_{req} = 12.6 dB)

Parameters	Relative Gain[dB]	Remarks
Transmit Power, Pt	7	Pt = 500 kW with P_0 = 100 kW,
Transmit antenna Gain, Gt	0	Gt = 40 dB @N = 5,000
Receive antenna Gain, Gr	3	N = 10,000, separate Rx antenna
Signal Processing Gain, Gp	13.3	64 pulse Integration(noncoherent)
Pulsewidth Control	3	Average power is increase by 2 ms
SNR Margins	10	Taking into account unmodeled losses
Total Increases	26.3	P_d = 80 %, $P_{fa} = 10^{-6}$

The design parameters are applied for radar equation and the simulation results are shown in Fig. 2 for RCS of 1 m^2 and are summarized in Table 3, in detail, for various RCSs. The maximum range of 2,000 km can be achieved for target size of 1 m^2 with the transmitted power of 900 kW. One can easily estimate the detection capabilities in terms of range and target size in diameter with reference to Table 3. For a range of 1,000 km and a target diameter of 50 cm, for example, SNR is 27.3 dB at P_t = 500 kW. This SNR value is greater than the detection threshold value of 22.6 dB (blue dotted line in Fig. 2). Therefore, this target size can be detected at 1,000 km for given parameters. But, if the range may be extended to above 1,000 km, the higher SNR will be needed which leads to higher power and gain. The additional SNR will be 12 dB by doubling the range since SNR is inversely proportional to fourth power of the range.

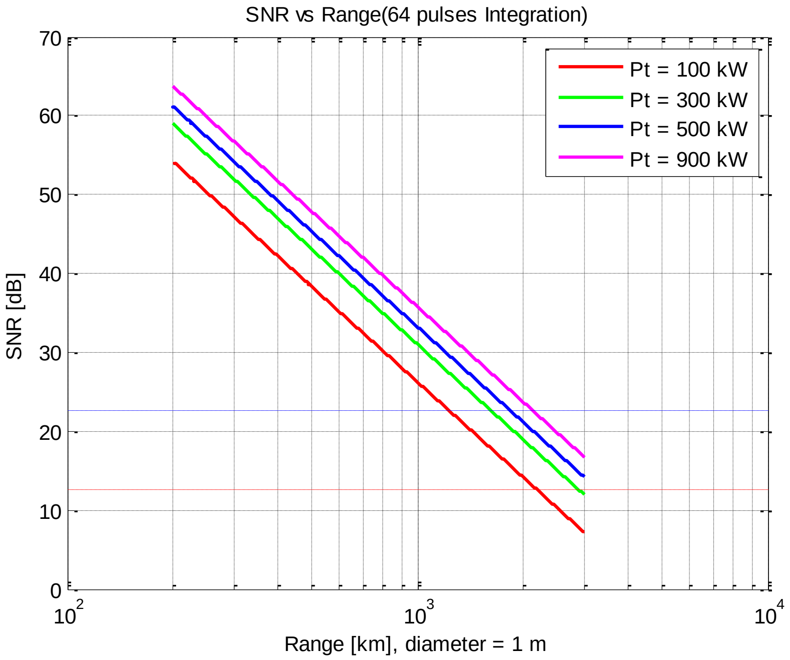

Fig. 2 SNR versus Range for a target diameter of 1 m varying transmitted power
(the red and blue dotted lines are 12.6 dB and 22.6 dB, respectively)

Table 3 SNR versus target diameter for various transmitted power at 1,000 km
(f = 1.3 GHz, G_t = 40 dB, G_r = 43 dB, G_p = 13.3 dB, τ = 2ms)

Diameter(cm)	5	10	50	100
RCS(dBsm)	-27.07	-21.0	-7.07	-1.05
SNR @1000 km				
Pt = 100 kW	0.305	6.38	20.3	26.32
Pt = 300 kW	5.08	11.15	25.08	31.1
Pt = 500 kW	7.3	13.36	27.3	33.3
Pt = 900 kW	8.85	15.9	29.85	35.87

3. CONCLUSIONS

The efficiency and performance of radar system for detection and tracking of space objects are simulated to analyze the detection capabilities in terms of frequencies, the transmitted power and target size in diameter. Current radar technology offers two principal types of system: systems with mechanically steered reflector antennas and phased-array antennas. A continuous space situational awareness can be reliably guaranteed by high performance ground based phased array system. So, for an efficient space situational awareness system at the current status, the relevant strategy is necessary. The analysis for the detection capabilities of the radar system can provide the guideline for the consideration of the development of the space situational awareness radar. The phase-array radars have the advantages conventional radars about the tracking capability with an electronically beam-steering and tracking multiple objects, simultaneously. The higher the transmitted power and antenna gain, the longer the detection range and small size of space objects. Therefore, the detection performances are heavily dependent on the radar system hardware. In the simulation, a simple radar signal processing of noncoherent pulse integration was applied. The power budget analysis results showed that the maximum detection range of 2,000km can be achieved with the transmitted power of 900 kW, transmit and receive antenna gains of 40 dB and 43 dB, respectively, pulse width of 2 ms, and a signal processing gain of 13.3dB, at frequency of 1.3GHz. The required signal-to-noise ratio (SNR) was assumed to be 12.6 dB for probability of detection of 80% with false alarm rate 10^{-6}. In order to further improve SNR, coherent signal processing techniques will be necessary in the base band such as pulse compression, constant false alarm rate (CFAR) detector, and other advanced algorithms which usually require the system complexity and higher cost. Through the efficiency analysis and trade-off study, the key parameters of the radar system are designed. This results will be expected to be used for the conceptual design of space situational awareness radar system.

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