

# Reflector-Based Digital Beam-Forming Radar System for Space Debris Detection

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**Abstract**—The paper considers a novel radar system concept for space debris detection based on a reflector antenna and utilizing digital beam-forming techniques. The main operational principles of the system are discussed. First, a classical radar system and its performance aspects are considered. Then in terms of the considered aspects, the performance enhancements of the novel digital beam-forming radar are demonstrated.

## I. INTRODUCTION

Space debris or orbital space junk created by human is a many-sided problem which is becoming more and more critical nowadays. Man-made space debris poses a risk to ordinary unmanned spacecraft in Earth orbit, also the population of debris is growing and the probability of collisions that could lead to potential damage will consequently increase. It has, however, now become common practice to consider the collision risk with orbital debris in planning satellite missions [1]. So the detection of space debris today is a prudent and necessary activity in conjunction with implementation of some debris mitigation measures towards preserving the safe and stable space environment.

Detection of the space objects located in the most populated Low Earth Orbit (LEO) region of 800-1000 km is performed using various ground based radar systems. The majority of the systems use a reflector antenna chosen for its high directivity and a low side lobe level. However there are limitations of the radar measuring systems which are generally of physical and technical nature [2]. In particular the performance of the reflector based systems is limited in terms of a mechanical steering of the antenna required in tracking mode as well as a limited search volume predefined by the half-power beamwidth.

This paper presents an innovative concept of the ground based radar system for space debris detection using a reflector antenna with multiple feed elements and utilizing digital beam-forming (DBF) techniques. The concept originates from the novel idea of a spaceborne Synthetic Aperture Radar (SAR) system combining a reflector antenna with a digital feed array for the first time suggested in [3] and considered in more details in [4], [5] and [6]. This system is capable of tracking a target within a large angular segment without mechanical steering and allows advanced Track While Scan mode characterized by a large search volume. This paper considers a conceptual design of the novel system and discusses its main advantages.

The paper starts with a description of the classical ground based radar, its basic performance aspects and parameters. The discussion is followed by the introduction of a concept of the novel reflector based DBF radar and its main operational principles. Afterwards the main advantages of the novel system compared to the conventional radar are described. The paper concludes with a short summary.

## II. CONVENTIONAL RADAR FOR SPACE DEBRIS DETECTION

In this section operational principles and particular performance aspects of the classical reflector based radar are considered.

### A. Operational Modes

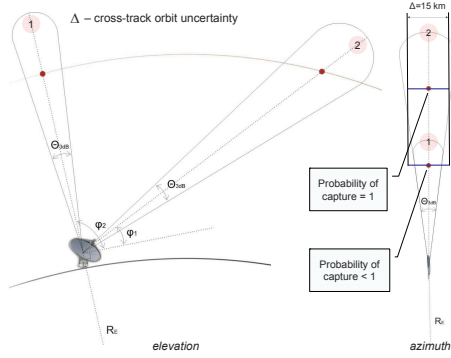
There are two main types of observations used by the conventional radars to detect and track the space debris [2]: volume directed observation and target directed observation. Volume directed observation is performed in a beam-park operational mode when an antenna is pointed in a fixed direction which allows to find new non-cataloged objects and roughly estimate an object size and orbit data. Target directed observation is conducted in a tracking operational mode where the antenna pointing direction is changing as the target moves such that the target remains for a longer period within a half-power beamwidth. This mode requires initial input data and is used to obtain characteristics and orbit data of cataloged objects with higher accuracy.

### B. Capture and Detection Probabilities

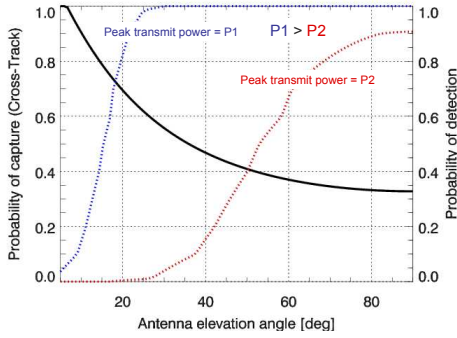
Probability of a target capture is directly proportional to the observation volume and defined as the ratio of the antenna pattern spatial extension to an object's orbit uncertainty,  $\Delta$ , both specified in the given direction at the location of the target. The antenna pattern spatial extension in turn is defined by its half-power beamwidth,  $\Theta_{3dB}$ , and the slant range to the target. Geometrical representation of the capture probability in a cross-track direction is shown in Fig. 1 a).

1) *Impact of a varying antenna elevation angle:* Comparing beam 1 and 2 shown in Fig. 1 a) for antenna elevation angles  $\phi_1$  and  $\phi_2$  respectively and considering an object at orbit height  $h$ , we can see that the target capture probability is decreasing with an increasing antenna elevation angle due to the decreased slant range to the target and thus a reduced beam

extension at the target's position. However, the shorter slant range reduces the free space attenuation and thus increases detection probability. This is demonstrated in Fig. 1 b) where the detection and capture probabilities are plotted as a function of the antenna elevation angle.



(a)



(b)

Fig. 1. a) Geometrical representation of a cross-track capture probability. b) Probability of capture for the given cross-track orbit uncertainty (solid line) and probability of detection (dotted lines) as a function of antenna elevation angle.

2) *Impact of an operational frequency:* The half-power beamwidth,  $\Theta_{3dB}$ , and the gain,  $G$ , of the antenna have an impact on the capture and detection probabilities as well. The larger their values the higher the corresponding probabilities. Considering the relation of these parameters to the operational frequency,  $f$ , expressed by (1) [7], we note their inverse interdependence illustrated in Fig. 2 where the radiation patterns of L-band and X-band reflector systems are compared.

$$\Theta_{3dB} = \frac{\gamma \cdot c_0}{D \cdot f}; G = \alpha \cdot \left(\frac{\pi D f}{c_0}\right)^2 \quad (1)$$

where  $\gamma$  is the parameter defined by the shape and the illumination of the reflector surface,  $\alpha$  is the net efficiency,  $f$  is the operational frequency,  $D$  is the diameter of the reflector and  $c_0$  is the speed of light.

Taking this into account, we come to the conclusion that classical reflector based radar systems operated at lower frequencies can be generally characterized by a higher capture

probability, and thus by a larger observation volume, but a lower detection probability compared to the systems operated at higher frequencies assuming the same Tx power.

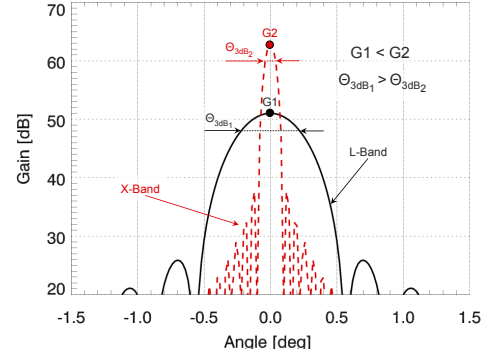


Fig. 2. Reflector antenna patterns: solid line - L-Band system, dashed line - X-Band system.

### C. Performance of the Conventional Radar

In order to illustrate the above described performance aspects let us consider a classical ground based radar for space debris detection using a 30 m reflector antenna with a single feed element. We would like to estimate its performance in terms of the maximum detection range for the given detection probability and its beam extension for the given target position at different frequency bands.

The performance of the system is estimated using a simplified range equation given for a monostatic pulsed radar expressed by [7]:

$$R_{max} = \left( \frac{\tau G^2 \sigma \lambda^2 P_t}{(4\pi)^3 k T_s L \cdot SNR_{min}} \right)^{1/4} \quad (2)$$

where  $\tau$  is the pulse length,  $\sigma$  is the Radar Cross Section (RCS),  $\lambda$  is the wavelength,  $P_t$  is the transmit peak power,  $T_s$  is the system noise temperature,  $L$  is the overall loss factor including the atmospheric attenuation,  $SNR_{min}$  is the minimum required signal-to-noise ratio for detection of a target defined for a certain false alarm and detection probabilities.

The maximum detection range as a function of Radar Cross Section (RCS) was computed according to (2) for L-, S- and X-band systems using a single pulse to detect a target. The minimum required signal-to-noise ratio,  $SNR_{min}$ , is assumed to be 11 dB allowing a detection probability of 99 % and a false alarm probability of 1 % [7]. The obtained results are presented in Fig. 3. Here the RCS values in the range of  $-18$  to  $-22.5$  dBsm correspond to a metallic spherical object with a diameter of 10 cm illuminated at the corresponding frequency bands. The considered target is orbiting the Earth at the distance of 1000 km and assumed to be non-fluctuating. The range of 3200 km measured from the ground antenna to the target is equivalent to the antenna elevation angle of  $\phi = 5^\circ$ .

From the obtained results we can see that the largest maximum detection range is achieved at X-Band with the

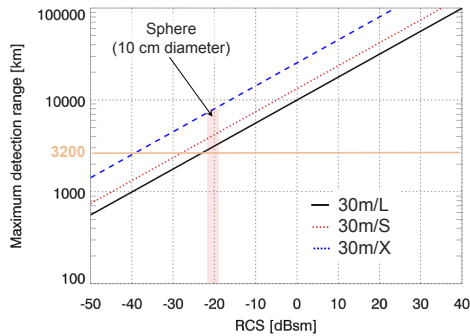


Fig. 3. Maximum detection range as a function of Radar Cross Section for L-, S- and X-Band classical radar systems based on the 30 m reflector antenna and operated in a single pulse mode.

assumption that the transmit peak power, system noise temperature and overall losses are the same for all three systems. Evaluating the cross-track beam extension at the distance of 1000 km ( $\phi = 90^\circ$ ), we obtain 0.96, 5.3 and 9.38 km for X-, S- and L-Band correspondingly. Thus, the X-Band system having the largest maximum detection range allows the lowest probability of capture for the given orbit uncertainty.

### III. CONCEPT OF THE REFLECTOR BASED DBF RADAR SYSTEM

The above presented performance parameters achieved by the classical radar can be improved by using a novel radar system based on the reflector antenna with multiple digital feed elements. In this section the main concept and operational principles of the reflector based DBF radar are presented, and its advantages compared to the classical radar are discussed.

#### A. System Concept

A simplified structure of the system is depicted in Fig. 4. It consists of a parabolic dish, an array of primary antennas located in the focal plane, a feed system circuitry and a digital control system. Each feed antenna is connected to a Transmit/Receive (TR) module. The receive part is represented by a switch, a low noise amplifier, a band-pass filter, and an analog-to-digital converter. In the transmit part a conventional analog configuration is used.

#### B. Operational Principles

Activation of a single element results in a narrow high-gain beam illuminating a certain volume in space. Activating different digital channels one can illuminate different angular ranges as demonstrated in Fig. 5 where antenna patterns are plotted for various activated channels (solid lines). On the other hand, combination of several channels results in the formation of a wider antenna pattern allowing to cover a larger volume with a lower gain as shown in Fig. 5 by the dashed line. Thus, capabilities of the new system allow to illuminate a large volume in space on transmit and on receive scan the region of interest digitally by switching and combining the feed elements.

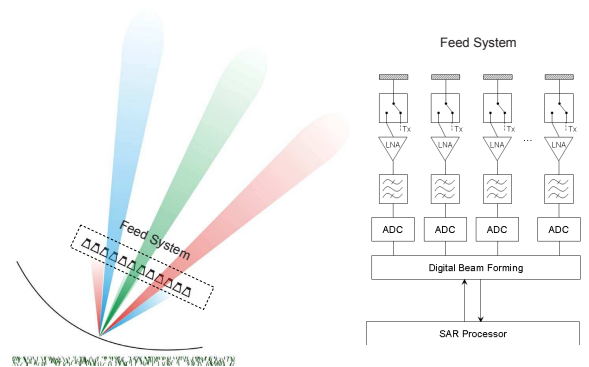


Fig. 4. Simplified architecture of the reflector based DBF radar system: the reflector dish with a schematically depicted feed system (left) and the structure of the digital feed system circuitry (right).

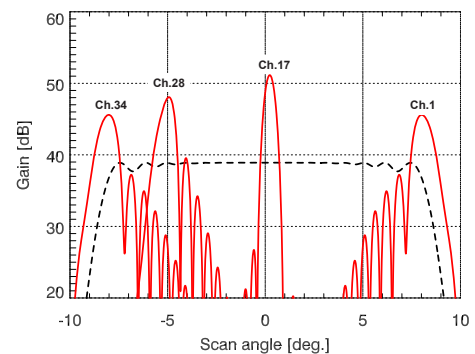


Fig. 5. Transmit antenna patterns of an L-Band reflector based DBF radar system with 34 digital channels using a 30 m reflector dish: solid lines - a single channel is activated, dashed line - all channels are activated.

## IV. ASPECTS OF THE IMPROVED DBF RADAR PERFORMANCE

This section discusses the main advantages of the novel reflector based DBF system compared to the classical space debris radar presented in Section II.

#### A. Relaxed Requirements for Mechanical Steering

The main feature of the novel system is the availability of narrow high-gain multiple receive beams and a wide low-gain transmit beam. This allows to relax the requirements imposed on the mechanical steering of an antenna. The example of antenna patterns shown in Fig. 5 is given for an L-Band DBF radar using a 30 m reflector dish with 34 digital channels. Such a system can perform a digital scanning over the angular range of around  $16^\circ$  requiring no mechanical steering. Meanwhile the corresponding classical radar, which has the HPBW of only  $0.36^\circ$ , would require the mechanical steering of the antenna to track the target within the given angular range.

### B. Advanced Operational Modes

Another particular characteristic of the novel system is the digital channels with independent data. It allows a development and realization of advanced operational modes which could be represented by a complex Track While Scan mode combining volume directed and target directed observations together in a more efficient way using various digital processing algorithms. The used digital beam-forming techniques translated to the advanced operational modes would allow effective tracking of several targets simultaneously over a large angular range which would in turn reduce the total measurement time required to acquire an orbital parameter set of a defined number of objects. The improved efficiency of the novel system can be in particular expressed in terms of a better capture probability at high operational frequencies.

### C. Improved Capture Probability

As shown in Fig. 5, the reflector based DBF radar is capable of covering a large volume in space with multiple high gain beams thus ensuring high capture probability at high operational frequencies. Taking as an example an X-Band DBF radar system utilizing a 30 m parabolic reflector with 48 digital channels and comparing its cross-track beam extension at the distance of 1000 km with the classical radar case the coverage is increased by a factor of 45. However the novel system has a lower detection probability compared to the classical system operated at the same power. The reason is a lower gain on transmit due to the simultaneous activation of several feed elements.

One of the possible ways to keep the detection probability on the required level is to increase the total supplied power to compensate for the gain reduction. Let us consider the above described X-Band DBF radar with a variable number of feed elements. In Fig. 6 the required increase of the total transmit power relative to the classical radar system with a single feed element in a single pulse operation mode is shown as a function of the number of feeds by the solid line. One can see that the increase of the feed number leads to the increase of the required total power. At the same time the larger number of elements leads to a larger cross-track beam extension which is demonstrated in Fig. 6 by the dotted line for the slant range of 1000 km, which eventually results in a better capture probability.

Another way to sustain the level of the detection probability is to activate the elements on transmit sequentially illuminating the required region is space by narrow high-gain beams. In this case the system must be able to generate pulses with a higher pulse repetition frequency compared to the classical radar case and thus higher average power is required.

### V. CONCLUSION

The new ground based radar system using the reflector antenna with multiple digital feed elements for space debris detection is considered in this paper. The system has a number of advantages compared to the conventional reflector based radars for space debris detection [2]. With the new system a

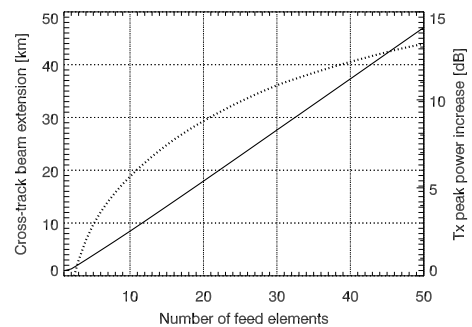


Fig. 6. Cross-track beam extension (solid line) and the required increase of the Tx peak power relative to the case of the classical radar with a single feed element operated in a single pulse mode (dotted line) as a function of the number of feed elements.

target can be tracked within a large angular range relaxing the requirements on the mechanical steering of an antenna. Multi-beam capability of the novel system and availability of multiple digital channels with independent data make possible the realization of an advanced Track While Scan mode characterized by a large search volume. Comparing basic performance parameters of the conventional reflector based space debris radar it was shown that the novel DBF system operated at the same frequency band achieves higher probability of target capture while still can have an unchanged detection probability.

This paper discusses a general system concept which will eventually open a wide number of further problems requiring deliberate investigations. Overall results of the current work showed that a combination of the reflector antenna with a digital feed array to be used for a space debris detection is a promising concept allowing to obtain higher operational flexibility and an improved performance compared to the conventional reflector based radars.

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