DIGITAL BEAM-FORMING ANTENNA OPTIMIZATION FOR REFLECTOR BASED SPACE DEBRIS RADAR SYSTEM

A. Patyuchenko, M. Younis, G. Krieger

German Aerospace Center (DLR), Microwaves and Radar Institute, Muenchner Strasse 20, 82234 Wessling, Germany,
Email: anton.patyuchenko@dlr.de

ABSTRACT

Ground based space debris radar system utilizing a multi-beam reflector antenna and digital beam-forming techniques allows a tracking of target within a large angular segment and supports the realization of an advanced Track While Scan mode characterized by a large search volume and simultaneous high detection and capture probabilities.

This paper considers the concept and the main operational principles of the ground based space debris radar system using the reflector antenna with multiple digital feed elements. The paper is particularly focused on the impact of antenna parameters on the overall space debris radar performance.

1. INTRODUCTION

Space Situational Awareness (SSA) has to guarantee the safe and stable space environment reducing the risk of collision with space debris to its minimum. The level of this risk is highly dependent on the availability of reliable and operationally flexible sources of information. The main source for space debris at Low Earth Orbit (LEO) region, which is of a particular importance, is various ground based radars. Many of these radar systems are based on the reflector antenna characterized by a high directivity and a low side lobe level. Nevertheless the reflector based systems are limited in terms of technical and physical parameters [1]. In particular, their limits are in the mechanical steering required to track the objects and in the search volume defined by the half-power beamwidth.

This paper considers an innovative concept of the reflector ground based space debris detection system using multiple channels and utilizing Digital Beam-Forming (DBF) techniques [2], [3]. This system is capable of tracking a target within a large angular segment with more flexible mechanical steering requirements and allows the realization of an advanced Track While Scan mode characterized by a large search volume. However from [2] and [3] it is evident that the reflector antenna parameters, such as its gain, aperture shape and size as well as a feed system, have a strong impact on the main overall system performance, in particular, on the beam steering angular range, the number of returned echo pulses and the detection probability of the radar system.

The main purpose of the paper is to consider an optimization of the reflector antenna parameters to yield the improved operational flexibility and advanced technical capabilities of the DBF space debris radar system. An impact of the antenna design on the overall system performance is considered.

The first part of the paper starts with a description of the novel reflector based DBF space debris radar and its main operational principles. The main advantages of the system compared to the conventional radar are discussed. In the second part of the paper the reflector antenna is considered in more detail. Various system performance aspects are discussed and their dependence on the antenna design parameters is estimated. The last part of the paper contains a description of the system prototype - a multi-channel DBF radar demonstrator. The paper concludes with a short summary.

2. DBF SPACE DEBRIS RADAR CONCEPT

In this section the main concept and operational principles of the reflector based DBF radar are presented. Its functional advantages compared to the classical radar case are discussed.

A simplified structure of the novel radar system based on the reflector antenna with multiple digital feed elements is depicted in Fig. 1 a). The DBF reflector based radar consists of a parabolic dish antenna and an array of primary feeds positioned in the focal plane. The circuitry of the feed system shown in Fig. 1 b) is composed of primary antennas each connected to a Transmit/Receive (TR) module. The receive part is represented by an RF chain consisting of switches, LNAs, band-pass filters and ADCs. In the transmit part a conventional analog configuration is used.

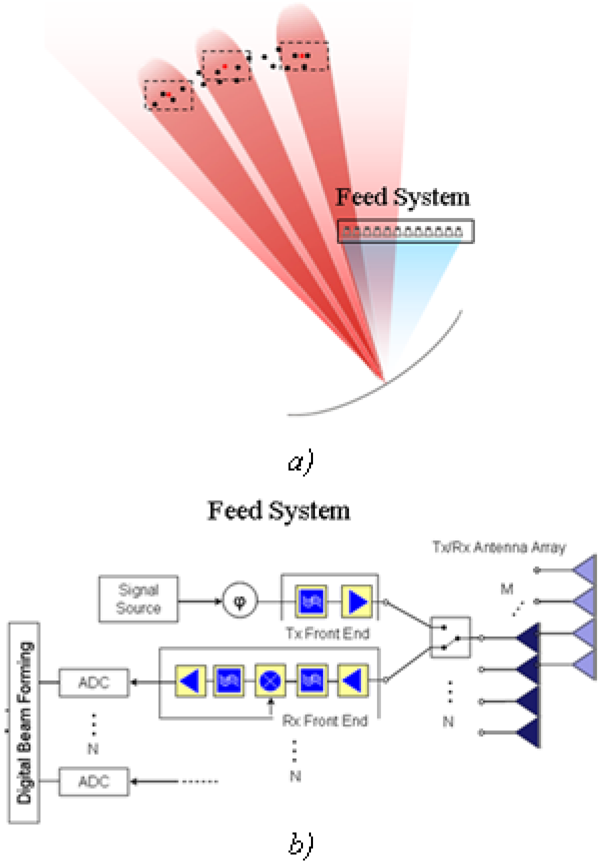

Figure 1. Simplified structure of the reflector based DBF space debris radar: a) schematic representation of the system tracking multiple targets simultaneously; b) feed system structure with its circuitry.

Activation of a single feed element results in a narrow high gain beam illuminating a fixed volume in space. Activating different digital channels one can illuminate different angular ranges as demonstrated in Fig. 2 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 covering a larger volume with a lower gain as shown in Fig. 2 by the dashed line. Thus capabilities of such system allow illumination of a large volume in space on transmit and scanning of this volume digitally by switching and combining the feed elements on receive.

Multiple independent digital channels, carrying the received data, make the realization of advanced operational modes possible. These modes could be represented by a complex Track While Scan mode combining volume and target directed observations together in a more efficient way using various digital processing algorithms. The used digital beam-forming techniques translated into 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

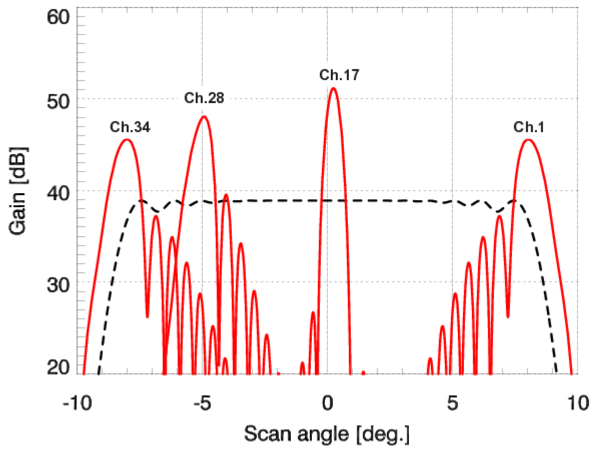

Figure 2. Transmit antenna patterns of an L-Band reflector based DBF radar system with 34 digital feed channels using a 30 m reflector dish: a single channel is activated (solid lines), all channels are activated (dashed line).

time required to acquire an orbital parameter set of a defined number of objects. The general system structure with multiple beams tracking several targets simultaneously is schematically shown in Fig. 1 a).

3. ANTENNA DESIGN AND DBF RADAR PERFORMANCE

In this section parameters characterizing the performance of the DBF space debris radar are discussed and their relation to the reflector antenna design is given.

3.1. Scanning range

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 relaxing the requirements imposed on the mechanical steering of the antenna.

The example of antenna patterns shown in Fig. 2 is given for the L-Band DBF radar using a $30m$ reflector dish with 34 digital channels. Such system can perform a digital scanning over the angular range of around $16°$ requiring no mechanical steering. Meanwhile the corresponding classical radar having the HPBW of only $0.36°$ would require the mechanical steering to track the target within the given angular range.

However due to the simultaneous activation of several elements on transmit, which is required to illuminate a large space area, the antenna gain decreases and this leads to the reduction of a Signal-to-Noise Ratio (SNR) level for the received pulses resulting in a lower probability of detection. One of the possible ways to keep the same probability of detection with the increased number of feed channels is to increase SNR or the peak transmit

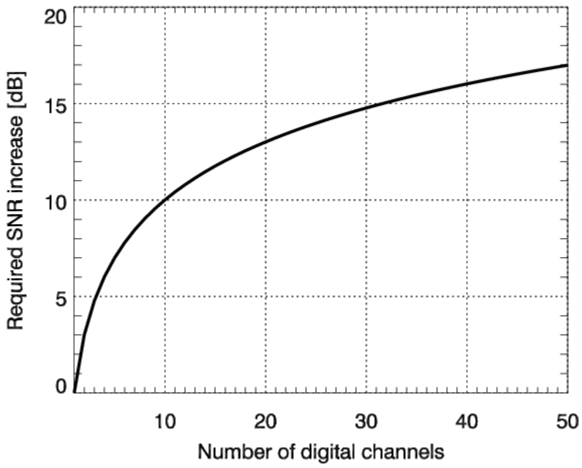

Figure 3. Required increase in the SNR level as a function of the number of digital feed channels. The data is obtained for the L-Band reflector with an aperture diameter of $D = 30\,m$.

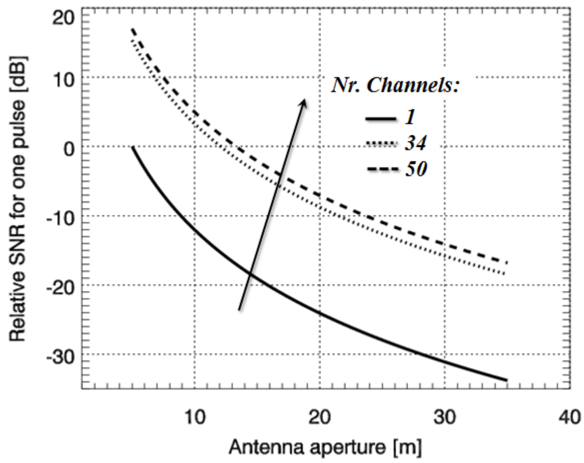

Figure 4. Required SNR decrease for one pulse as a function of aperture diameter (single pulse operation) relative to a single feed system with a diameter $D = 5\,m$: 1 channel (solid line), 34 channels (dotted line), 50 channels (dashed line).

power of the system. The required increase in SNR level as a function of the number of digital channels is shown in Fig. 3.

Another way to sustain the level of the detection probability is to activate the feeds on transmit sequentially illuminating the required region in 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.

3.2. Signal-to-Noise Ratio

Signal-to-Noise Ratio is expressed by [4]:

$$SNR = P_r/P_n \tag{1}$$

where P_n is the level of the receiver noise, which determines the minimum level of the received signal power P_r that can be detected. The received power P_r is given by the radar equation expressed in its rudimentary form by:

$$P_r = \frac{P_t \cdot G_{tx} \cdot G_{rx} \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 R^4} \tag{2}$$

where σ is the Radar Cross Section (RCS), λ is the wavelength, P_t is the transmitter power, G_{tx} and G_{rx} are the antenna transmit and receive gain and R is the distance to the target. The level of the received power, P_r, and thus the level of the SNR, is directly proportional to the reflector gain given by:

$$G = \kappa \cdot \left(\frac{\pi D}{\lambda}\right)^2 \tag{3}$$

where κ is the aperture efficiency and D is the aperture diameter.

Using equations (1), (2), and (3) we can compute the required decrease in the SNR level for a single pulse resulting in the same reference probability as a function of a varying antenna aperture diameter. Required decrease in SNR relative to the reference case corresponding to the single feed system with a diameter of $D = 5\,m$ is shown in Fig. 4 as a function of the antenna diameter and the number of digital channels.

From Fig. 4 we can conclude that the increase of the aperture size relaxes the requirement on the minimum peak transmit power while the increase in the number of digital channels imposes more stringent requirements on the SNR for one pulse which can be compensated, for example, increasing the aperture size.

3.3. Number of returned echoes per beam

In order to increase sensitivity of a radar system a multipulse operation is employed. A target in orbit illuminated by a burst of pulses reflects them back over a period of time it remains within the field of view of the antenna system. At the receiver side the returned echo pulses are integrated and this results in the improved detection due to the increased level of the total energy received from the target.

The number of returned echoes depends on the half-power beamwidth (HPBW) of the antenna and a target time within the beamwidth:

$$N = \frac{\Theta_{3dB}\,(h + R_E)\, f_{PRF}}{v} \tag{4}$$

where Θ_{3dB} is the HPBW of the antenna, h is the orbit height of the object, R_E is the Earth radius, f_{PRF} is the

Pulse Repetition Frequency (PRF) and v is the velocity of the object.

Since the HPBW, Θ_{3dB}, is proportional to the diameter of the reflector antenna via:

$$\Theta_{3dB} = \epsilon \frac{\lambda}{D} \tag{5}$$

where ϵ is the function of shape and illumination of the reflector surface, one can relate the number of received echoes to the antenna aperture size. The number of received echo pulses for a single beam as a function of antenna diameter is shown in Fig. 5. The results are obtained for a target orbiting the Earth at the height of $1000\,km$ illuminated in the beam-park mode with a fixed antenna elevation angle of 25° at L-Band by a pulse train at a PRF rate, f_{PRF}, of $10\,Hz$, $50\,Hz$ and $100\,Hz$.

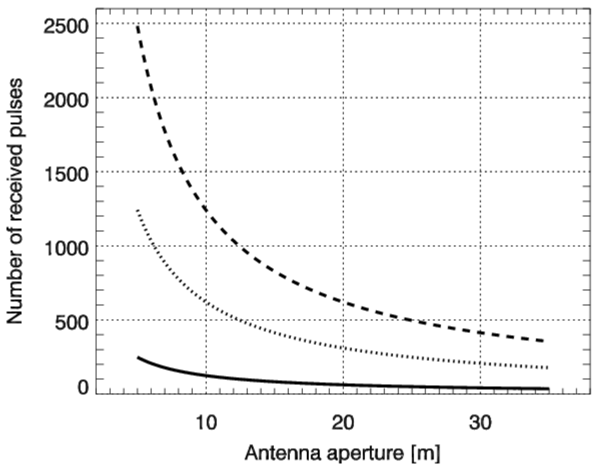

Figure 5. Number of received echo pulses for a single beam as a function of a reflector diameter: $f_{PRF} = 10\,Hz$ (solid line), $f_{PRF} = 50\,Hz$ (dotted line), $f_{PRF} = 100\,Hz$ (dashed line).

3.4. Integration of the returned echoes per beam

In practice the pulse integration effect in the multi-pulse mode is achieved using energy storage elements. Due to a non-constant phase between transmitted and received pulses the pulses are integrated non-coherently. The improvement achieved by this integration is identified as an integration efficiency expressed by [4]:

$$E(n) = \frac{SNR_1}{n \cdot SNR_n} \tag{6}$$

where SNR_1 is the SNR for a single pulse operation and SNR_n is the SNR for a single pulse with the integration of n pulses resulting in the same probability of detection and a false alarm rate.

The parameter $n \cdot E(n)$ representing the decrease in the required SNR for one pulse with non-coherent integration of n pulses relative to the single pulse operation [4] is shown in Fig. 6 as a function of number of integrated pulses and compared to the coherent case when $n \cdot E(n) = n$.

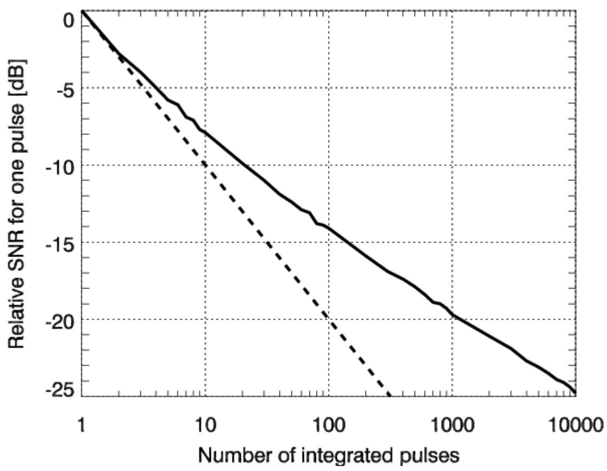

Figure 6. Decrease in the required SNR for one pulse with a non-coherent (solid line) and coherent (dashed line) integration of n pulses relative to the single pulse operation as a function of number of integrated pulses. Linear detector, $p_d = 0.9\,\%$, $p_{fa} = 10^{-4}$.

Using equations (4), (5) and (6) one can relate the required decrease in SNR for one pulse (relative to the single pulse operation) with the aperture diameter assuming that all returned echo pulses, n, are non-coherently integrated. The given dependence for a single beam without taking into account the gain increase is shown in Fig. 7 by black lines for different values of PRF, f_{PRF}.

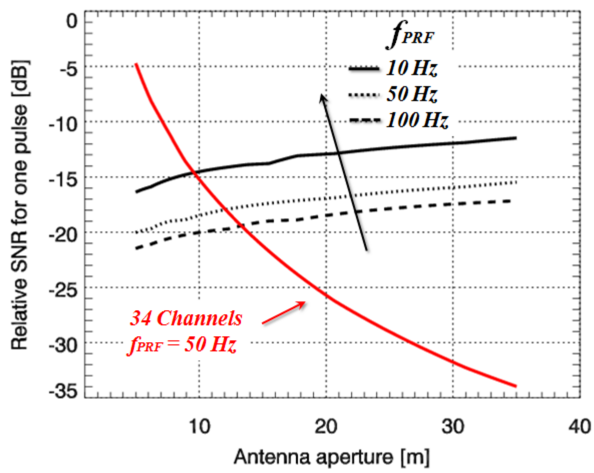

Figure 7. Required SNR decrease for one pulse as a function of aperture diameter relative to the single pulse operation for different values of f_{PRF} without taking into account the increase in gain (black lines). Red line represents the total required decrease in SNR for one pulse for the system with 34 digital channels operated in a multi-pulse mode with $f_{PRF} = 50\,Hz$ relative to the single-pulse reference system with $D = 5\,m$.

From the obtained results it follows that the increase in the reflector diameter leads to the higher SNR required for one pulse due to the less number of returned echo pulses caused by the reduced HPBW. On the other hand the large diameter results in higher system gain, Fig. 4, which in turn allows the reduction of the peak transmit power. The total required decrease in SNR for one pulse for the system with 34 digital channels operated in a multi-pulse mode with $f_{PRF} = 50\,Hz$ relative to the single-pulse reference system with $D = 5\,m$ is shown in Fig. 7 by the red line.

4. PROTOTYPE DEVELOPMENT

Within the frame of research activities aimed at the development of the DBF techniques and advanced operational modes for the reflector based space debris radar system a multichannel DBF radar demonstrator is designed in the Microwaves and Radar Institute at German Aerospace Center (DLR). The simplified architecture of the prototype is depicted in Fig. 8. The initial architecture has 1 transmit channel and 8 receive channels (note that only 4 receive channels are shown in Fig. 8 for simplicity). The further increase of the channels number is possible due to the flexibility and modular structure of the system architecture.

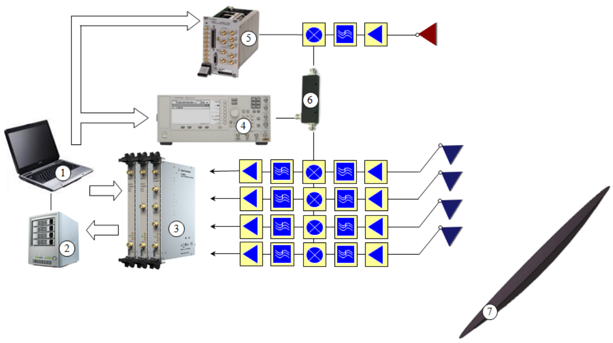

Figure 8. Multichannel DBF Radar Demonstrator: 1 - *personal computer,* 2 - *data storage device,* 3 - *analog-to-digital converters (ADC) with an embedded PC,* 4 - *Analog Signal Generator,* 5 - *Arbitrary Waveform Generator (AWG),* 6 - *coupler,* 7 - *reflector antenna.*

The radar prototype is based on the cPCI form-factor allowing the maximum data throughput of $400\,MB/s$; however, the new AXIe standard will allow the maximum data throughput of around $2\,GB/s$ per digital channel. The prototype will be used to develop and to test the advanced operational modes as well as their functional capabilities and limitations. The demonstrator system gives a possibility to gain the knowledge and experience the value of which cannot be underestimated during the implementation phase of the future DBF space debris radar system.

5. CONCLUSION

The innovative ground based space debris radar system using the reflector antenna with multiple digital feed elements is considered in this paper. The system has a number of advantages compared to the conventional reflector based radars [1]. With this radar a target can be tracked within a large angular range relaxing the requirements for the mechanical steering of an antenna. Multi-beam capability of the novel system and availability of multiple digital channels with independent data make the realization of an advanced Track While Scan mode characterized by a large search volume possible.

Considering the main reflector antenna parameters it was shown that they have a strong impact on the the overall space debris radar performance. The paper discussed the functional dependence of the main system performance parameters on the antenna aperture diameter and the number of digital feed channels. In particular the beam steering angular range, the number of returned echo pulses and the detection capabilities of the radar system were considered. On the basis of the obtained results the optimum antenna design for the DBF radar system yielding the improved performance can be defined according to the requirements imposed on a particular system. The system prototype being currently under development will allow to advance the ongoing studies on innovative DBF techniques and system operational modes and enhance them with the experimental results.

The realization of the new generation DBF reflector based space debris radar system, with a higher operational flexibility and an improved performance compared to the conventional reflector based radars, will allow to secure the space environment reducing the risk of collision with space debris to its minimum.

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