A Concept for an Advanced Reflector-Based Space Surveillance Radar

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I. INTRODUCTION

The Space Situational Awareness (SSA) has to guarantee the safe and stable space environment. The level of the SSA is highly dependent on the availability of reliable and operationally flexible sources of information about the space debris. The continuous increase of the space debris volumes is a many sided problem which nowadays poses more and more stringent requirements on the technical capabilities of the SSA sources including radar, optical and in-situ detection and measurement systems.

Low Earth Orbit (LEO) is the region of a particular importance due to the manned space missions taking place there. As the main SSA source for LEO serve various ground based radars. The considerable part of these radar systems is 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 the multiple digital channels and utilizing Digital Beam-Forming (DBF) techniques. The original idea of the concept is based on the spaceborne Synthetic Aperture Radar (SAR) combining a reflector antenna with a digital feed array for the first time suggested in [2] and considered in more details in [3], [4] and [5]. This system is capable of tracking a target within a large angular segment without mechanical steering of the antenna and allows the realization of an advanced Track While Scan (TWS) mode characterized by a large search volume. This paper considers a concept and main operational principles of this system.

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 the novel reflector based DBF space debris detection radar and its main operational principles. Afterwards the pros and cons of the system are discussed and compared to the conventional radar case. The last part of the paper presents a description of the system prototype – a multi-channel DBF radar demonstrator. 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.

Operational Modes

There are two main types of observations used by the conventional radars to detect and track the space debris [1]: 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 finding new non-cataloged objects and a rough estimation of an object size and orbit data. Target directed observation is conducted in a tracking operational mode; here the antenna pointing direction is changing as the target moves so that the target remains for a long period within a half-power beamwidth. This mode requires initial input data and it is used to obtain characteristics and orbit data of cataloged objects with higher accuracy.

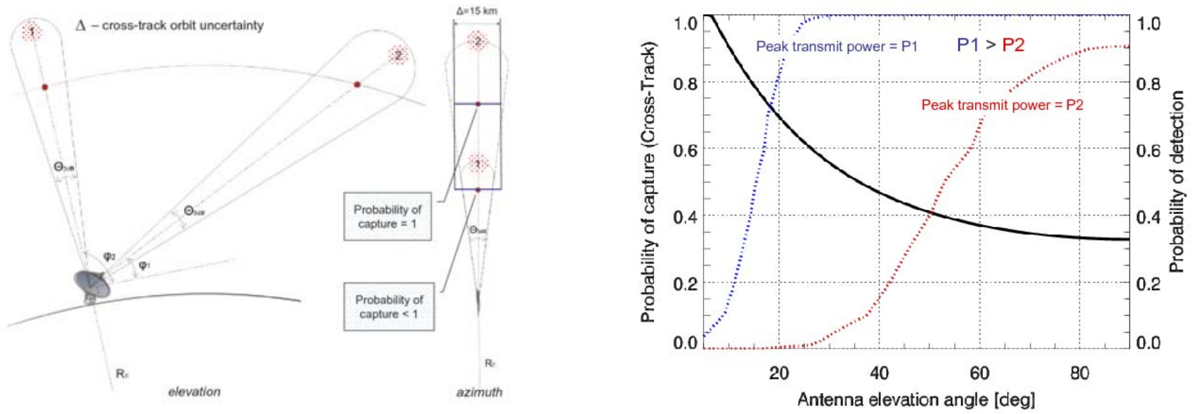

Fig. 1. Geometrical representation of a cross-track capture probability (left). Probability of capture for the given cross-track orbit uncertainty (solid line) and probability of detection (dotted lines) as a function of an antenna elevation angle (right).

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, *Δ*, both specified for the given direction at the location of the target. The antenna pattern spatial extension in turn is defined by its half-power beamwidth, Θ_{3dB}, and the slant range to the target. Geometrical representation of the capture probability in a cross-track direction is shown in Fig. 1 (left).

Impact of a Varying Antenna Elevation Angle

Comparing beam 1 and 2 shown in Fig. 1 (left) for antenna elevation angles φ_1 and φ_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 corresponds to the lower free space attenuation and thus to the higher detection probability. This is demonstrated in Fig. 1 (right) where the detection and capture probabilities are plotted as a function of the antenna elevation angle.

Impact of the Operational Frequency

Both the half-power beamwidth, Θ_{3dB}, and the gain, *G*, of the antenna have an impact on the capture probability as well as on the detection probability. The larger their values are the higher are the corresponding probabilities.

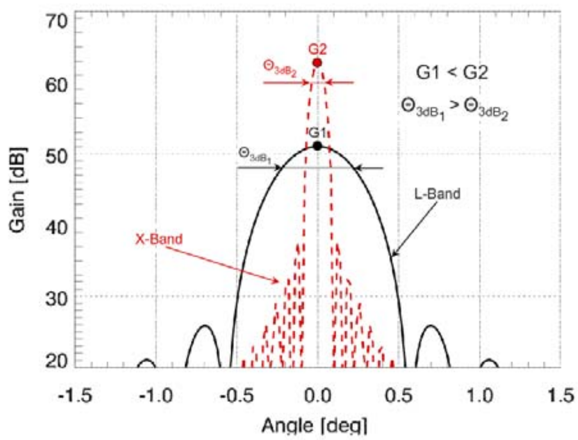

Fig. 2. Reflector antenna patterns: solid line – L-Band system, dashed line – X-Band system.

Considering the relation of these parameters to the operational frequency, *f*, expressed in (1) [6], we note their inverse interdependence illustrated in Fig. 2 where the radiation patterns of L-band and X-band reflector systems are compared.

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

where γ is the parameter defined by the shape and the illumination of the reflector surface, α 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.

Performance of the Conventional Radar

In order to illustrate the above described performance aspects let us consider the 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 (2) [6]:

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

where τ is the pulse length, σ is the Radar Cross Section (RCS), λ 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 RCS was computed according to (2) for L- , S- and X-band systems using a single pulse for target detection. The minimum required signal-to-noise ratio, SNR_{min}, is *11 dB* allowing a detection probability of *99 %* and a false alarm probability of *1 %* [6]. 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 $\varphi = 5°$.

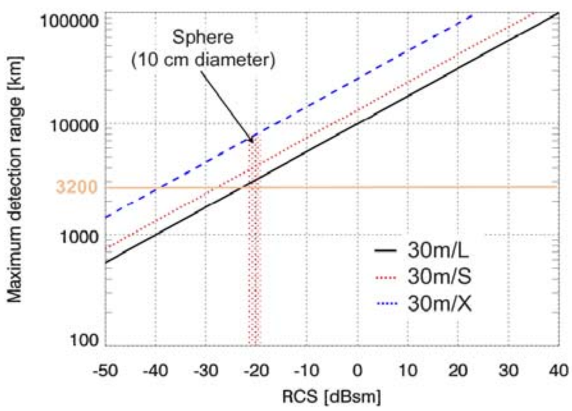

Fig. 3. Maximum detection range as a function of Radar Cross Section (RCS) for the L-, S- and X-Band classical radar systems based on the *30 m* reflector antenna and operated in a single pulse mode.

From the obtained results we can see that the largest maximum detection range is achieved at the X-Band with the 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* ($\varphi = 90°$), 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.

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.

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 covering 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.

IV. ASPECTS OF THE IMPROVED DBF RADAR PERFORMANCE

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 an antenna. The example of antenna patterns shown in Fig. 5 is given for the 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°* requiring no mechanical steering. Meanwhile the corresponding classical radar, which has the HPBW of only *0.36°*, would require the mechanical steering to track the target within the given angular range.

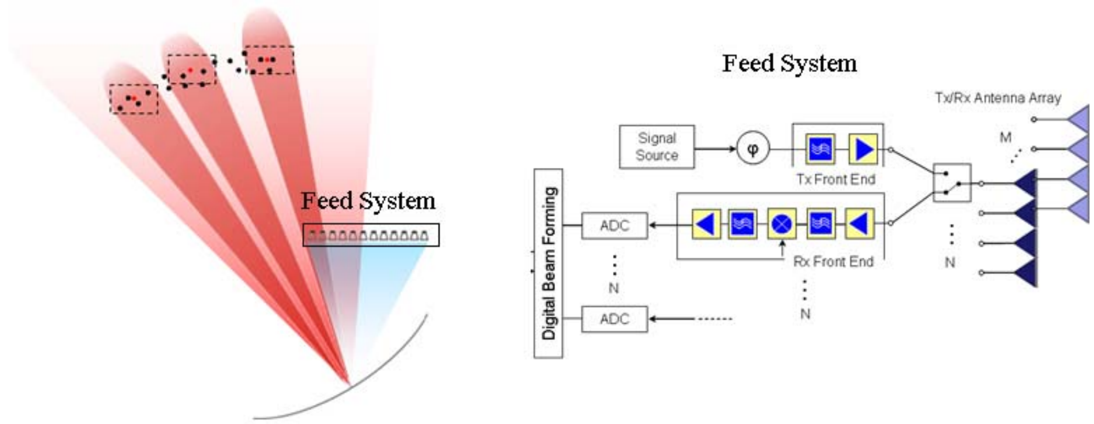

Fig. 4. Simplified architecture of the reflector based DBF radar system: the reflector dish with a schematically depicted feed system (left) and the structure of the digital feed system circuitry (right).

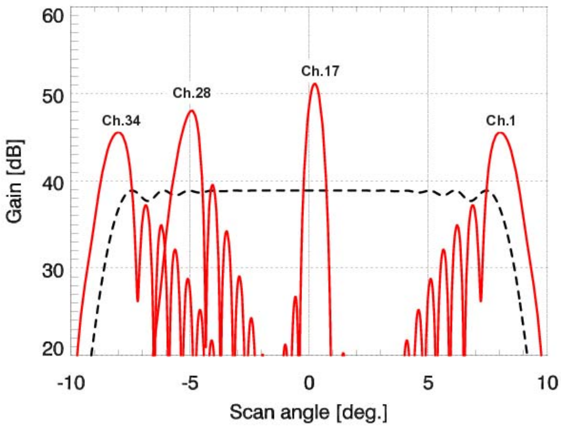

Fig. 5. Transmit antenna patterns of an L-Band reflector based DBF radar system with *34* digital feed channels using a *30 m* reflector dish: solid lines – a single channel is activated, dashed line – all channels are activated.

Advanced Operational Modes

Another particular characteristic of the novel system is the independent digital channels carrying the received 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.

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.

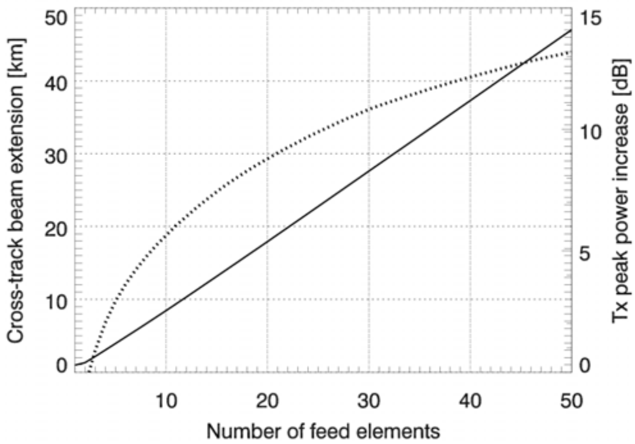

Fig. 6. Cross-track beam extension (solid line) and the required increase of the Tx peak power relative to the case of the classical radar with a single feed element operated in a single pulse mode (dotted line) as a function of the number of feed elements.

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 feeds 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 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.

V. PROTOTYPE DEVELOPMENT

In the framework of the development of advanced operational modes for the space debris system the multichannel DBF radar demonstrator was designed in the Microwaves and Radar Institute at German Aerospace Center. The simplified architecture of the demonstrator which is currently under development is depicted in Fig. 7. The initial architecture has *1* transmit channel and *8* receive channels (note that only *4* receive channels are shown in Fig. 7). The further increase of the channels number is possible due to the flexibility and modular structure of the system's architecture.

The radar prototype is based on the cPCI form-factor allowing the maximum data throughput of 400 MB/s; however, the new AXIe standard, available in the end of 2011, will allow the maximum data throughput of around 2 GB/s per digital channel. The prototype will be used to develop and test 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 of the future reflector based space debris detection and tracking system.

VI. 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 [1]. With the new 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.

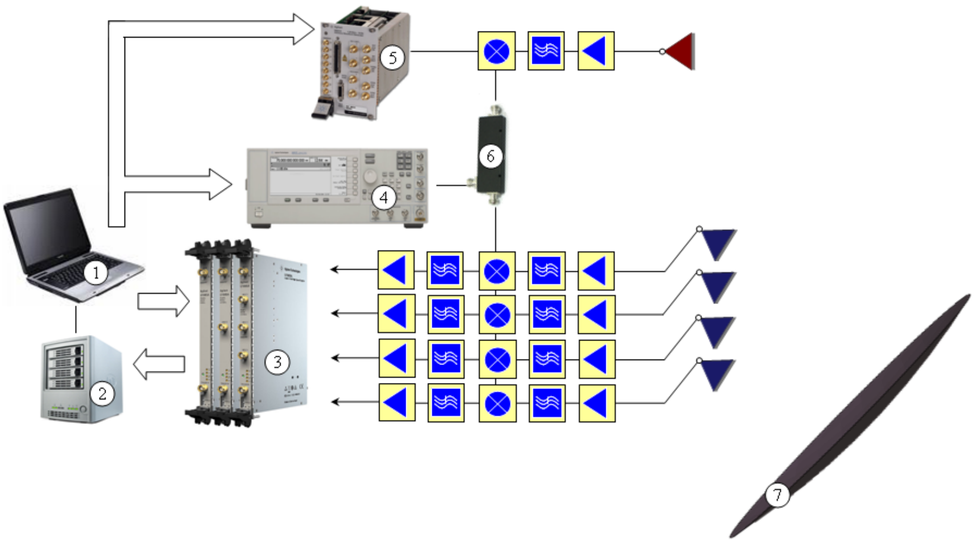

Fig. 7. Multichannel DBF Radar Demonstrator: 1 – personal computer, 2 – data storage device, 3 – analog-to-digital converters (ADC) with an embedded PC, 4 – Analog Signal Generator, 5 – Arbitrary Waveform Generator (AWG), 6 – coupler, 7 – reflector antenna.

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 be further developed and tested using the multi-channel DBF radar demonstrator which is currently under development. This 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 the space debris detection is a promising concept allowing a higher operational flexibility and an improved performance compared to the conventional reflector based radars.

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