High-resolution radar imaging of space objects

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ABSTRACT

In view of the increasing number of space objects, comprehensive high-quality space surveillance becomes ever more important. Radar is a powerful tool that, in addition to detection and tracking of objects, also enables spatially high-resolution imaging for satellite characterization independent of daylight and most weather conditions. Together with the technique of Inverse Synthetic Aperture Radar (ISAR), very high-resolution and distance-independent two-dimensional images can be obtained. Advanced high-performance radar imaging of space objects is a complex and demanding task, touching many technological and signal processing issues.

Therefore, besides theoretical work, the Microwaves and Radar Institute of German Aerospace Center (DLR) has developed and constructed an experimental radar system called IoSiS (Imaging of Satellites in Space) for basic research on new concepts for the acquisition of advanced high-resolution radar image products of objects in a low earth orbit. This paper provides an overview of the principles of high-resolution imaging of satellites using ground-based ISAR. Furthermore, an overview of the experimental radar system IoSiS is provided, along with a brief outline of the planned system concept of IoSiS-Next Generation. Latest measurement results of real space targets demonstrate the capability of the system and the potential for future radar-based space surveillance using centimeter-resolution imaging radars. New to the field of radar-based imaging of space objects, comprehensive simulation results show how accurately a space target can be imaged in three dimensions using the new intended imaging concept realized using multi-static imaging geometries.

1. INTRODUCTION

Every year the European Space Agency (ESA) publishes a comprehensive Space Environment Report containing the evolution of objects in orbit around earth [7]. Fig. 1 shows the number of regularly tracked objects in space. Right from the beginning, the number of functionless objects, i.e. space debris, exceeds the number of operating satellites, i.e. payloads. Furthermore, in recent years there has been a notable increase in the number of unidentified objects, underscoring the growing necessity for a tool for object characterisation. It should be noted that the much higher number of smaller pieces of space debris estimated by the ESA is not taken into account in this diagram. Furthermore, the rate of new satellites or spacecraft launched each year remained constant over decades until approximately 2010. Consequently, space situational awareness (SSA) played a secondary role, being driven primarily by military interests. However, due to the start of the new millennium as well as the beginning of the New Space era, the number of spacecraft and corresponding future space debris has increased dramatically since about 2010.

Therefore, several years ago, the German Aerospace Center (DLR) started comprehensive theoretical analyses and the construction of an experimental radar system, called IoSiS (Imaging of Satellites in Space) [1] [2]. The research focus here is on imaging, which is why IoSiS does not yet have a tracking capability. The research with IoSiS supports the investigation of a future multifunctional radar-based imaging system with the idea of a new concept in satellite imaging. In contrast to existing systems, the concept envisages the use of a larger number of smaller, spatially distributed apertures that are suitable for bi- and multi-static as well as true three-dimensional imaging.

Fig. 2 illustrates the principal components of the IoSiS system. It comprises a steerable reflector antenna with a 9-meter transmit (Tx) antenna in a Cassegrain configuration and two separate directly fed receiving (Rx) antennas, together with the radar electronics in a nearby container. Both receive antennas have a diameter of 1.8 m. So far, the measurement results discussed in this paper are based on only one receiving channel. The second receive antenna or channel, respectively, was used for multi-channel imaging studies. In present implementation of the IoSiS system, the DLR advanced multi-purpose X-band radar system GigaRad is used [6]. Furthermore, the radar is capable of utilising

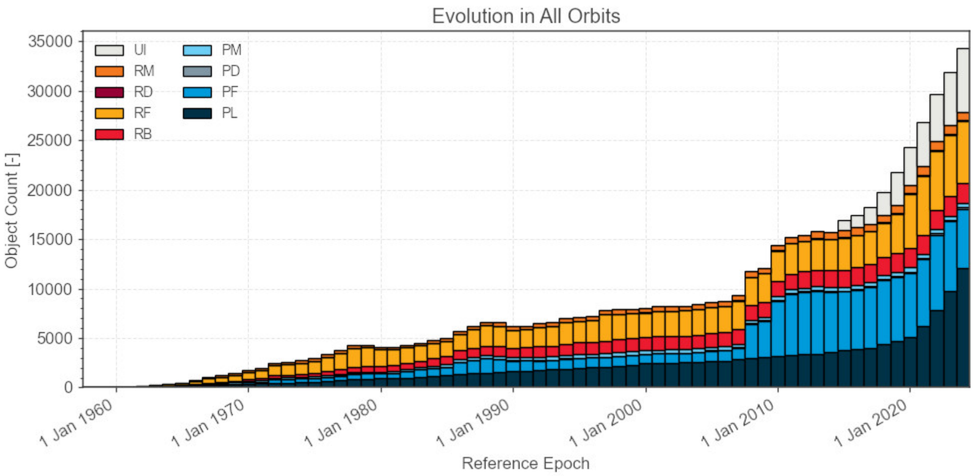

Fig. 1: Number of regularly tracked space objects [7].
UI: Unidentified, RM: Rocket mission related object, RD: Rocket debris, RF: Rocket fragmentation debris, RB: Rocket body, PM: Payload mission related object, PD: Payload debris, PF: Payload fragmentation debris, PL: Payload

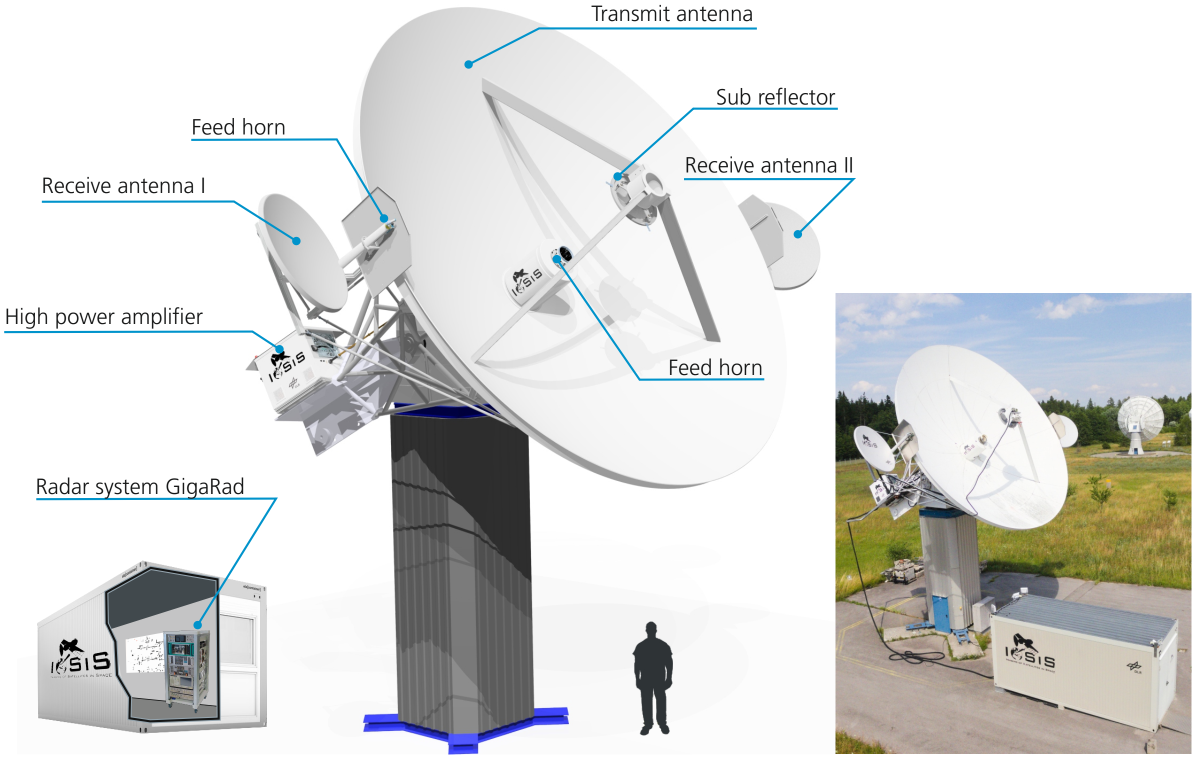

Fig. 2: The IoSiS system comprises a 9-meter transmit antenna and two 1.8-meter receive antennas. The main radar electronics are located in a nearby container. The photograph depicts the experimental IoSiS satellite imaging radar, which has been installed at the DLR Weilheim campus in Germany.

arbitrary transmit signals [3]. The Tx channel of the radar is connected to a high-power amplifier (HPA) located on the rear side of the main dish, which itself feeds the feed horn via rectangular waveguide. Thus, the Cassegrain antenna configuration allows a short and low loss connection between the HPA and the antenna feed. The Rx antennas are connected via low-noise amplification and optical cabling to both Rx channels of GigaRad. Table 1 shows the basic system parameters of the IoSiS radar as used for ISAR imaging operation. Here the maximum possible instantaneous bandwidth allows range resolution up to 34 mm. Presently the pulse repetition frequency (PRF) is limited to 200 Hz. However, a new timing unit, currently under development, will enable a varying PRF with more than one traveling pulse per round trip time and hence an increased PRF.

Table 1: Basic parameters of the IoSiS radar system.

Parameter	**Symbol**	**Parameter value**	**Unit**
Center frequency	f_c	10.2	GHz
Bandwidth	B	4.4	GHz
Range resolution	Δr_{range}	34	mm
Pulse duration	τ_{pulse}	45	μs
PRF	prf	200	Hz

2. FUNDAMENTALS OF RADAR-BASED IMAGING OF SATELLITE

The combination of a fixed ground-based microwave radar and a moving object on a specific orbit fulfills the requirement for the ISAR imaging geometry, as illustrated in Fig. 3. The requisite synthetic aperture is generated by the proper motion of the objects. In this context, R_B stands for the range at the beginning of the imaging process, while R_E refers to the range at the end of the process. In the latter two-dimensional radar image, the azimuth direction, represented by S_{az}, and the range direction, represented by S_R, are the two dimensions of interest. The third dimension, indicated with S_{el}, cannot be resolved using a single radar system on the ground. In order to achieve a spatial resolution in the S_{el} direction, it is necessary to employ at least one additional, spatially separated receiver on the ground for interferometric imaging. Alternatively, a number of receivers are required for the purpose of conducting real three-dimensional radar imaging. The latter is described in greater detail in the section which presents a simulation result of a three-dimensional imaging process of a satellite.

Considering a sufficiant Signal-to-noise ratio (SNR) the spatial resolution is range independent when using the inverse synthetic aperture radar technique. The range resolution is determined by the radar system bandwidth and the azimuth resolution results from the integration angle. The range resolution of the subsequent ISAR image can be calculated as follows:

$$\Delta r_{range} = \frac{c_0}{2B} \tag{1}$$

Here c_0 is the speed of light and B the radar system bandwidth. It shows that the achievable range resolution Δr_{range} depends only on the radar system bandwidth. The larger the bandwidth the better becomes the achievable spatial resolution in the radar image in the range direction. In the second spatial direction, the so-called azimuth direction, the spatial resolution can be calculated by:

$$\Delta r_{azim} = \frac{c_0}{4 f_c sin(\frac{\varphi_{SA}}{2})} \tag{2}$$

Here f_c is the radar center frequency and φ_{SA} the azimuth integration angle corresponding to Fig. 3. Considering a fixed radar transmit frequency, large integration angles are mandatory for a high spatial resolution in azimuth direction.

It is essential that the satellite path is known with great precision in order to ensure that the antenna is correctly aligned during the pass, given that IoSiS does not currently possess the capability to track automatically. A steerable antenna system provides the capacity for wide azimuth scanning, which is necessary for achieving high azimuth resolution. Concurrently, the integration time of observation is extended, resulting in an enhancement of the SNR in the radar image. The fundamental prerequisite of an ISAR imaging method is the alteration in the viewing angle observed from the satellite. Moreover, the radar pulses along the synthetic aperture must be acquired coherently, as the phase information is essential for processing the ISAR image. This implies that the radar transmitter and receiver operate with the same reference phase. When the transmitter and receiver are in close proximity in a quasi-monostatic arrangement, coherence can be achieved with relative ease. However, when both the transmitter and receiver are situated at a considerable distance to achieve bi-static imaging geometries, achieving coherence represents a significant challenge. This research topic of synchronisation is addressed in the IoSiS – Next Generation System described in section 4.

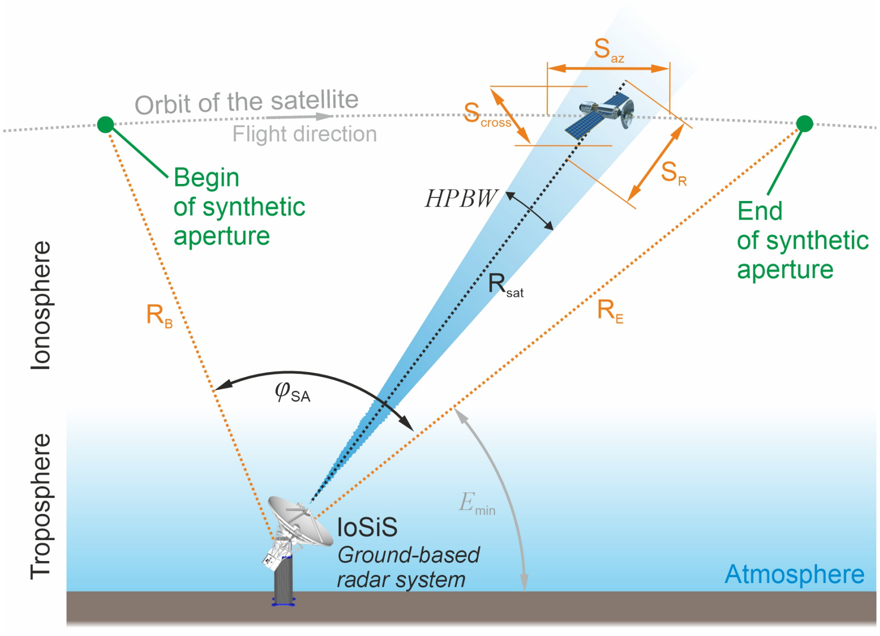

Fig. 3: Imaging geometry of a ground-based inverse synthetic aperture radar (ISAR). The tracking antenna illuminates a satellite along its orbit path and collects coherently radar echos. Afterwards the image is processed based on the acquired radar echos.

3. MEASUREMNT RESULTS

The following two sections present and analyse two measurement results obtained using the IoSiS system. Firstly, there will be a demonstration of how an accurate evaluation of the structure of a space object can be achieved. In this instance, a three-dimensional model of the object of interest is employed for the purpose of comparing the object's structural characteristics. Nevertheless, the example serves also to illustrate the difficulties inherent in interpreting radar images, which evolve in a manner distinct from that of optical images, which are well-known to the human eye. Secondly, the importance of spatial resolution is illustrated by a measurement of the solar panels belonging to the International Space Station (ISS).

3.1 Analysing the structure of a space object

Fig. 4 shows a radar image of the ISS. A substantial number of components of the ISS exhibit a pronounced backscatter behaviour, including the habitat modules, the primary truss segment and the distinctive reflections associated with the heat radiators. However, not all components of the ISS are discernible in the radar image. In particular, the solar arrays are oriented in a manner that precludes their visibility. The structure at the end of each solar panel is the only identifiable feature, which allows the position of the panel to be determined. The image was processed using 6400 pulses, which, based on the geometry of the measurement, corresponds to an integration angle of 22.2°.

A detailed representation of the forward section of the ISS is presented in Fig. 5. For purposes of comparison, a three-dimensional computer-aided design (CAD) model of this section is also provided in the illustration [5]. The section comprises a cylindrical module measuring 11 metres in length, which is equipped with an attached experimental facility. The radar image indicates the presence of minute structures on the cylindrical surface of the module, exhibiting a parallel alignment with the longitudinal axis. The scattering of the incident field by these structures results in a plastic impression of the tube in the radar image, which serves as an excellent illustration of the manner in which a cylindrical structure is displayed in a radar image in comparison to an optical image.

In the upper part of the image, it is evident that strong reflections from other cylindrical modules are present, arranged in a configuration that is almost perpendicular to the radar's line of sight. In addition, the so-called exposed facility shows pronounced backscattering characteristics in the lower part of the image. The radar image shows that the exposed facility consists of a complex structure that differs from the CAD model. The radar image also makes it possible to identify the various smaller containers used for the experiments. As indicated by the orange rectangle, it is easy to see that a container was obviously docked to the lower left slot during the measurement, whereas the CAD model does not show this container. This is just an example, but it illustrates the kind of information that can be extracted from a high-resolution radar image. Given the huge amount of space debris, the identification of changes based on the characterization of the structural composition of space objects, as illustrated, would facilitate characterization, identification or detection of structural damage to the satellite

3.2 Significance of spatial resolution

The ISAR technique enables very high resolution imaging of objects in space, independent of the distance. The achievable spatial resolution depends on the bandwidth of the radar system and the azimuth integration angle, as described above. The resolution is a significant factor in the ability to identify or characterise the imaged object. Earth observation radar satellites have a spatial resolution of several metres to half a metre. In the domain of satellite imaging, this level of resolution is long way off for a comprehensive characterisation of the observed object. An increase in resolution by a factor of at least ten enables the gathering of well-focused radar images with high levels of detail. Nevertheless, this ambitious objective of achieving an exceptionally high resolution presents a number of challenges. It is essential to consider the potential sources of error that may be either non-existent or insignificant in lower resolution images. These include, for example, atmospheric distortions, frequency Doppler shifts and inaccuracies in imaging geometry and phase stability.

The importance of spatial resolution is illustrated in Fig. 6. The presented measurement results show the solar panel of the ISS at four distinct spatial resolutions. The images were subjected to a processing procedure that resulted in the generation of a cell with square resolution. This means that the resolution in both directions, range and azimuth, is the same for each image, except for the last, highest resolution image, for which all available radar data were processed, resulting in a significantly higher resolution in the azimuth direction. Given the strong dependence of the SNR on the azimuth integration angle, the dynamic range of each image is adjusted in order to optimise the visibility of the solar panel.

In the first image the solar panel can only be identified with considerable difficulty due to an image resolution of only 50 cm. However, the grid structure that supports the solar panels displays a pronounced backscatter effect. In this case the radar system bandwidth is $B = 300\ MHz$ and the azimuth integration angel is $\varphi_{SA} = 1.6^\circ$ resulting in a spatial resolution of 50 cm. In consideration of the limited azimuth integration angle, the integration gain is notably low, resulting in a pronounced background noise. Increasing the resolution to 20 cm, which corresponds to a bandwidth of $B = 750\ MHz$ and an azimuth integration angle of $\varphi_{SA} = 4^\circ$, more details of the solar panels become visible and the background noise is reduced. With a resolution of 10 cm, corresponding to a bandwidth of $B = 1.5\ GHz$ and an azimuth integration angle of $\varphi_{SA} = 8^\circ$, the image quality can be further improved significantly. The grid structure situated at the center of the solar panels has been resolved in great detail. Additionally, the horizontal lines positioned on the left and right of the grid structure have been separated, which indicates that the image displays not one but two solar panels that are perfectly aligned behind each other. In the highest resolution image with a spatial resolution of 3 x 6 cm ($B = 2.7\ GHz$, $\varphi_{SA} = 27^\circ$), the background noise is further suppressed and the image is reproduced with greater clarity than in the previous images.

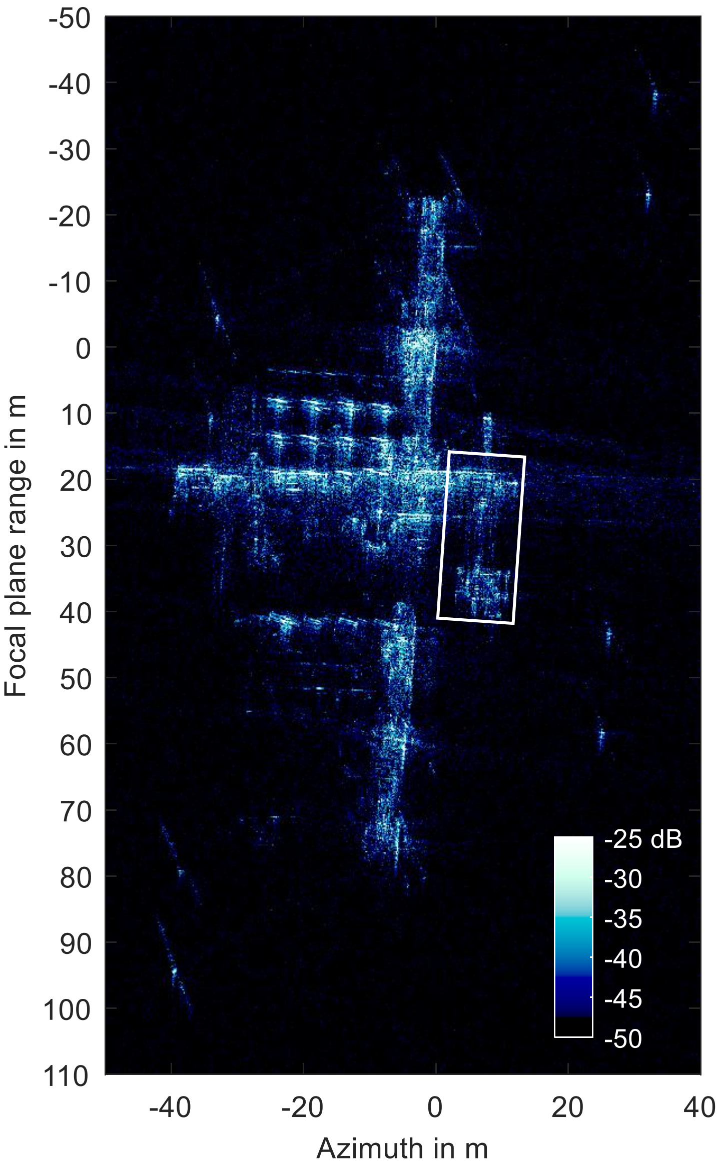

Fig. 4: Measured ISAR image of the ISS.

4. IOSIS-NEXT GENERATION

The experimental IoSiS 1st generation system described above has made it possible to carry out fundamental research into high-resolution satellite imagery. The project has facilitated the acquisition of knowledge regarding the handling of the various error sources inherent to the imaging process, the configuration of the radar system hardware, and, lastly, the verification of the image processing algorithms developed and implemented during this phase of the project. Furthermore, the system comprised two receiving channels, thereby facilitating research in the domain of multi-channel imaging of objects in space, encompassing both hardware and software algorithms. However, the antenna system employed in the 1st Generation system was a relatively antiquated communication antenna with a mechanical accuracy that is inadequate for operations in the X band. The inaccuracy of the reflector shape is resulting in a notable reduction in antenna gain. Furthermore, the insufficient pointing accuracy is limiting the length of the synthetic aperture

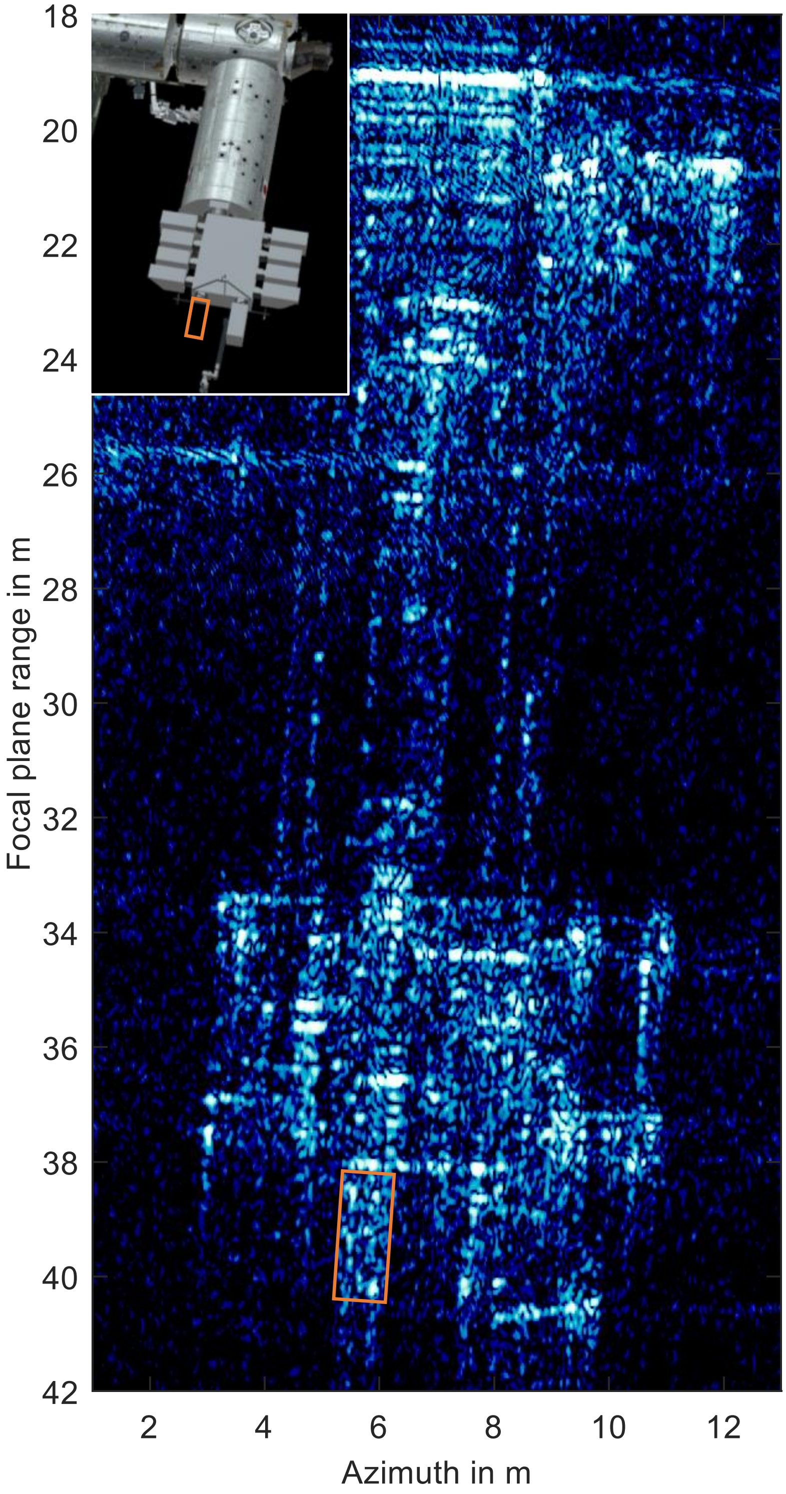

Fig. 5: Enlarged illustration of the image section highlighted in Fig. 4 in comparison with the 3D CAD model of this section of the ISS.

integration angle and, consequently, rendering the subsequent measurements highly unreliable. In order to overcome these circumstances and to extend the possibilities of research, especially in the field of multi-channel and multi-static

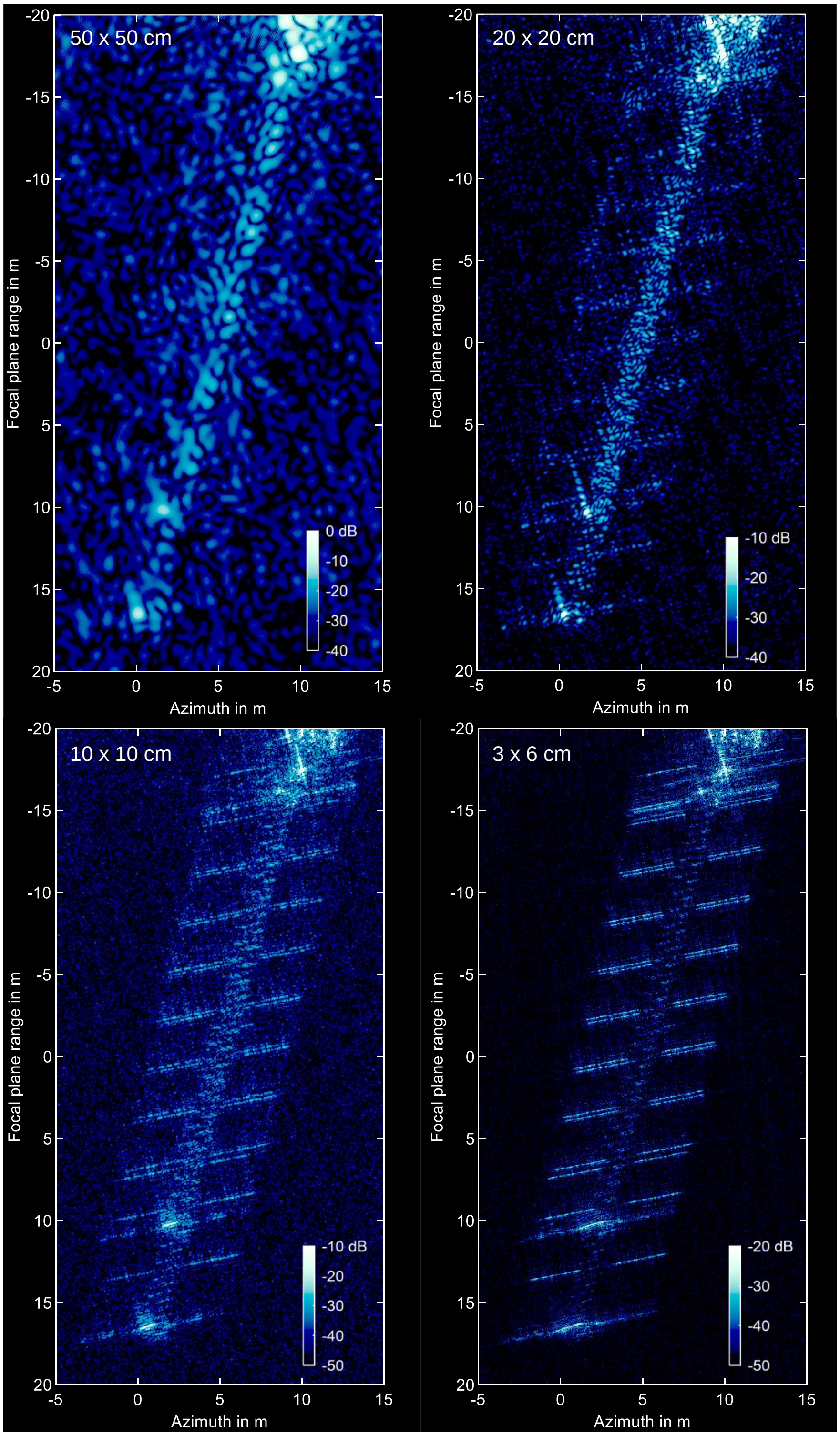

Fig. 6: Solar panel of the ISS imaged with the IoSiS radar system.

imaging of objects in space, the DLR initiated the planning of the IoSiS – Next Generation facility.

4.1 System description

Fig. 7 provides an illustration of the principal components of the IoSiS-NG facility, which is to be located on the campus of the DLR ground station in Weilheim. Two 7-meter full-motion Cassegrain antennas will be employed, wherein the initial configuration will utilize one antenna for transmission and the other for receiving. This configuration will facilitate a high degree of isolation between the transmission and receiving paths, which is particularly crucial when operating at higher frequencies. The entire facility is designed with a high degree of flexibility, allowing for experimental usage. In addition, the facility will comprise a third, smaller receive-only antenna that can be positioned flexibly, enabling the use of measurement geometries with arbitrary base lengths. This also allows for comprehensive research and investigations into synchronizing distributed receiver systems.

The facility comprises a building which includes the radar control room as well as a laboratory area where the radar hardware will be placed. The latter also allows the assembly and repair of high frequency radar components for research purposes. The construction of the infrastructure is scheduled to commence in 2025 and is expected to take a minimum of two years to complete. Subsequently, the principal components of the X-band radar system, which is currently employed in the IoSiS 1st generation system, will be incorporated into the new facility and integrated into the antenna systems. As previously stated in the initial sections of this document, the future IoSiS system will progressively comprise a series of distributed apertures, which will facilitate comprehensive multi-static imaging and eventually enable the acquisition of three-dimensional images. The forthcoming IoSiS-NG represents a significant advance towards the challenging destination that has been identified. In the next section, a simulation result is discussed that demonstrates the performance of an imaging system that uses distributed receiving apertures.

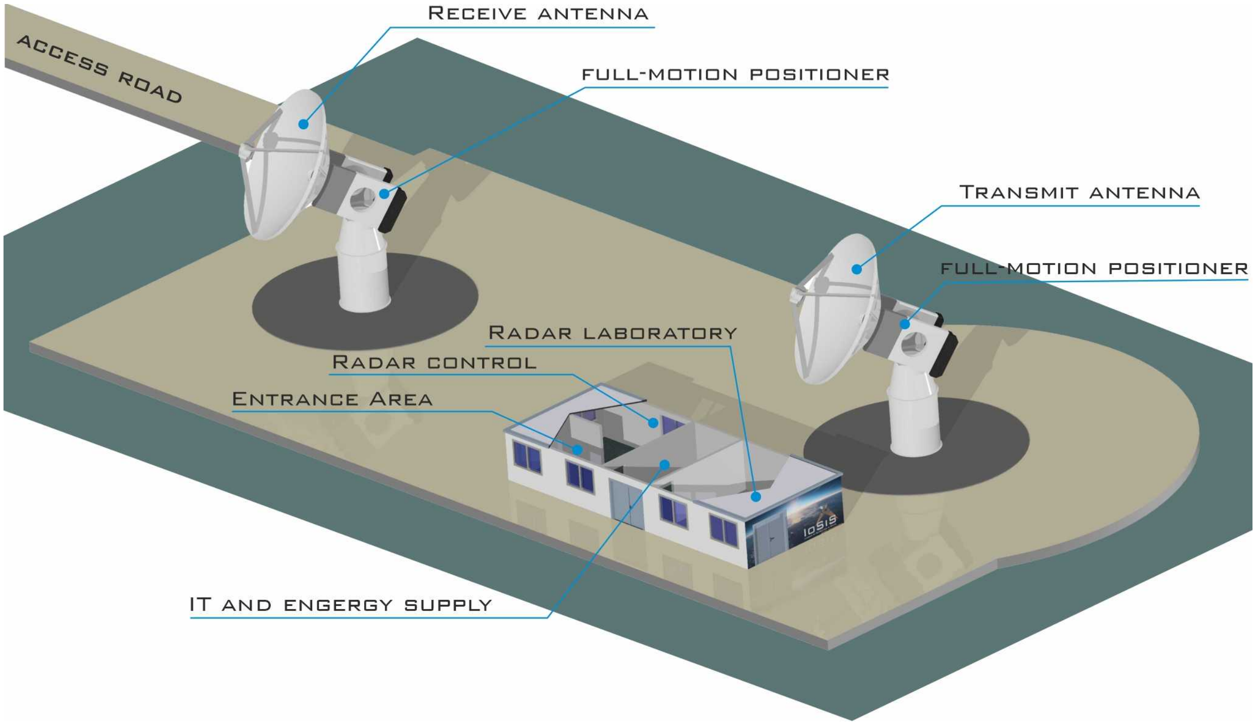

Fig. 7: CAD illustration of the future IoSiS - Next Generation facility.

4.2 Simulation results of a mulit-static radar using distributed apertures

A radar system comprising a single transmitter and receiver is capable of providing a two-dimensional representation of the scene under observation. This signifies that a three-dimensional target is projected onto a two-dimensional image plane. It is evident that the superposition of scatterers on the image plane results in a loss of information. In order to resolve the scattering in the third dimension and thus overcome this problem of information loss, a radar aperture must be created in the third dimension. In the case of imaging of a satellite in space, this extension of the aperture must be aligned perpendicular to the orbit of the satellite.

Fig. 8 shows the simulation results of a three-dimensional imaging geometry consisting of one transmitter and 140 receivers evenly distributed along a baseline with a maximum extension of 30 km. The satellite is equipped with two large solar panels on both sides and three angled, flat antennas. As envisaged in the future IoSiS system, the radar frequency is assumed to be 96 GHz together with a bandwidth of 8 GHz, resulting in an image with a resolution of a few centimeters.

The four results shown here show the satellite from four different angles of view, as indicated in the diagram. The white contour of the satellite situated at the center of each image represents the backscattering behaviour of the satellite that was employed for the simulation. This backscatter map of the satellite was determined with the aid of a simulation tool that was developed in-house [4]. Each image is comprised of three radar images, which represent the maximum projection in each spatial direction. This methodology allows for the satellite to be observed from three sides in each of the four images. The selected viewing angles of 0°, 45°, 90° and 135° are arbitrary and can be modified during the post-processing of the gathered multi-static radar data. Nevertheless, irrespective of the manner in which the three-dimensional backscatter map of the satellite is digitally rotated, the areas situated at the upper centre will remain invisible due to their position within the radar shadow during the measurement. This is due to the fact that the satellite was assumed to be stabilized during the simulation, which meant that the satellite maintained the same orientation to the earth throughout the pass, as is the case for operational satellites [8]. Nevertheless, the results are an impressive demonstration of the performance and capabilities of a multi-static millimeter-wave radar.

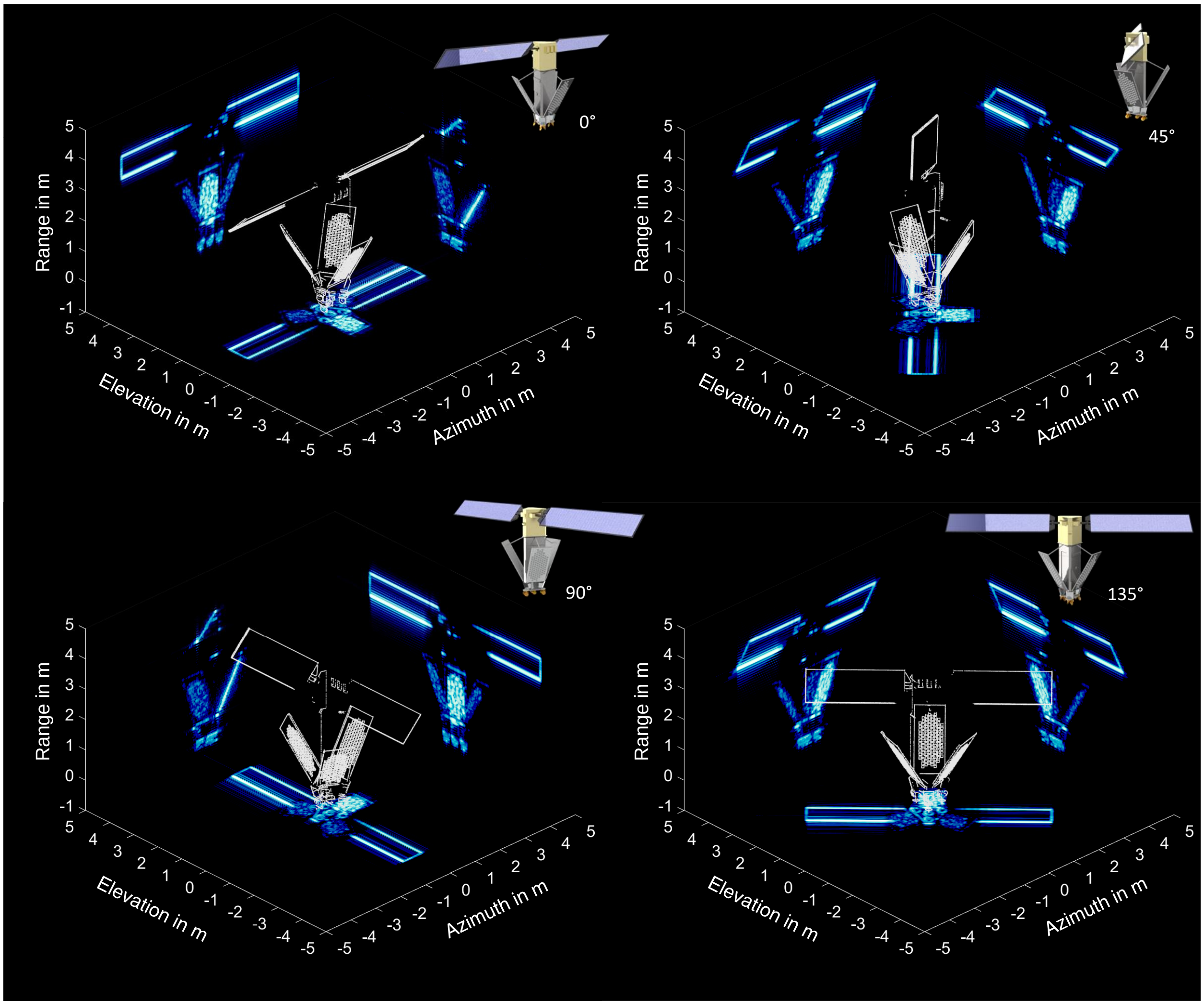

Fig. 8: Simulation results of a multi-static satellite imaging radar concept utilizing a single transmitter and 140 receivers in the W band.

5. ACKNOWLEDGEMENT

The authors thank Martin Häusler and his colleagues from the DLR satellite ground station for supporting this research.

6. FUNDING INFORMATION

This work has been partially supported by Federal Office of Bundeswehr Equipment, Information Technology and In-Service Support. This work has been partially supported by Bavarian Ministry of Economic Affairs, Regional Development and Energy.

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