Future Radar-Based SSA Capabilities Facing the New Space Race

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ABSTRACT

The number of spacecraft and corresponding amount of future space debris has increased dramatically since about 2010. Consequently, existing SSA capabilities and technologies have become progressively overstrained and insufficient to provide authorities and decision makers with adequate information. It must be assumed that within the next decade a new military space race will evolve. There will be many players, since space technology is becoming more and more available at low cost on open markets. Hence, modern technologies have to be developed for highly advanced SSA. This paper introduces the present IoSiS radar system and shows various imaging results of spacecraft in lower Earth orbit, predominantly the ISS as a large and complex object. Furthermore, the basic ideas of the new radar concept are outlined and accompanied by simulations of expected capabilities. The intention of this paper is not to analyse and explain these issues on a highly scientific level, but rather to characterise in a straightforward way the current situation, future requirements, present technologies, and a possible future concept for radar-based SSA, focusing on radar imaging and not tracking approaches.

1.0 INTRODUCTION

The last and first space race was carried out exclusively between superpowers the United States of America and the Soviet Union, beginning in the 1950s and lasting until the downfall of the Iron Curtain in the early 1990s. Beginning with exclusively military ambitions, the activities ultimately evolved further to civilian applications in Earth observation, communication, navigation, and radio, while other nations joined the market successively. However, the rate of new satellites or spacecraft each year kept constant over decades until about 2010. Consequently, Space Situational Awareness (SSA) played a secondary role, driven mostly by military interest. The start of the new millennium is considered to be the beginning of the New Space era: the epoch in which space technology has become heavily commercialised and many start-ups have been founded, offering plenty of new capabilities for spacecraft, payload, launch, operation, and applications [1], [2], [3]. Hence, the number of spacecraft and the corresponding amount of future space debris has increased dramatically since about 2010. Consequently, existing SSA capabilities and technologies have become progressively overstrained and insufficient to provide authorities and decision makers with adequate information. In parallel, it turns out that in addition to the classical military branches like the army, air force, and navy, new battlefields will or already have been built up in cyberspace and outer space. In the recent Ukraine war, a new class of military technology – massive drone-based operations – has been added to classical warfare. Hence, it must be assumed that within the next decade a new military space race will evolve as well. The large difference, compared to the ancient space race, will be the number of players including, besides the classical two, populous potent nations like China, India, and many others all around the globe [1], [2], [3], since space technology is becoming more and more available at low cost on open markets.

This predicted new and completely different situation of outer space usage and corresponding harassment, either by space debris or a multitude of unknown spacecraft, requires the development of new technological paths for reliable and responsive SSA. Microwave radar, and especially imaging radar, is the fundamental frame of present and of course future SSA [4], [5], [6]. Ref. [4] reports the long tradition of US MIT Lincoln Laboratory in radar SSA, starting in the 1950s with radar tracking and continuing with the introduction of large-dish technology in the 1960s. Since then, various range profiling and Inverse Synthetic Aperture Radar (ISAR) imaging radars from C to W band have been built and operated as a service and for research. Widespread use of X-band and in the last decade of W-band in the HUSIR system has allowed a constant increase in spatial resolution, which is theoretically now up to about 2 – 3 cm for the HUSIR-W system. The use of large-dish technology with diameters of up to 30 – 40 m, leading to a very high sensitivity, has even made possible ISAR imaging of geosynchronous satellites. Besides radar imaging technology, a very nice overview of long-term data collection and analysis using the HUSIR-X radar system is outlined in Ref. [5], underlining the need for Earth-based radar SSA. Ref. [6] provides a comprehensive treatment of past and planned large-dish radar SSA in Germany and an idea for Europe. Since the 1990s, the TIRA system has been contributing to imaging radar SSA in the Ku band using a 34 m antenna. Current spatial resolution is expected to be below 10 cm. The imaging system is currently upgraded to Ka band for improved spatial resolution and fully-polarimetric imaging capabilities.

Besides its long heritage, large-dish radar technology always requires very high surface accuracies of the dish especially at higher frequencies, since proper separation of transmit and receive sections of the radar is a challenge due to the one-antenna approach. Although present radar technology based on large-dish antennas is already powerful, it does not provide for all future demands in Earth-based spacecraft analysis. Here, very high spatial resolution, three-dimensional imaging, and multi-static radar echo analysis will be the benchmark for information quality, besides many other benefits of modern and future-oriented radar system design.

Several years ago, DLR began investigating new imaging radar system concepts for advanced SSA. Besides comprehensive theoretical analysis, an experimental radar system has been developed and constructed, called IoSiS – Imaging of Satellites in Space. IoSiS is an X-band system providing theoretically of up to 35 mm spatial resolution. It offers two receive channels by separated transmit and receive antennas, providing various operational modes [7], [8].

2.0 THE IOSIS RADAR SYSTEM

The basic idea behind IoSiS was the intention to provide experimental capabilities for very high-performance radar imaging of spacecraft, in addition to theoretical investigations. Furthermore, practical experience is fundamental when exploring complex technological systems and concepts, including not only hardware and algorithms for data processing, but also practical handling of operation and data collection. It should be noted that the IoSiS radar system is not intended for the detection of space debris or similar tasks.

The experimental setup of IoSiS is realised at DLR facility Weilheim, as shown in Figure 1. For transmit (TX), an existing dish antenna of 9 m diameter was reconfigured. (The dish antenna was formerly was used as a second redundancy antenna for the launch control and early commissioning phase of spacecraft.) For receive (RX) two smaller antennas of 1.80 m diameter were tied on both sides with the TX antenna, on one hand for highly improved decoupling of TX and RX while using the identical positioning system, and, on the other hand for being still able to separate TX and RX antenna for research purposes. IoSiS is an X-band radar working from 8.0 – 12.4 GHz, but due to interference reasons with nearby communication systems a bandwidth of only 2.8 GHz is actually used. IoSiS operation is permitted by the national German telecommunication authority Bundesnetzagentur for experimental purposes.

The radar electronics are built largely on digital technology, providing the generation of arbitrary TX signals while sampling the full bandwidth on RX in the time domain. Furthermore, two independent TX and two independent RX channels are available, where at present only one TX channel is used. Nevertheless, wave polarisation experiments can be executed, recording simultaneously one co-polar and one cross-polar signature for TX and RX.

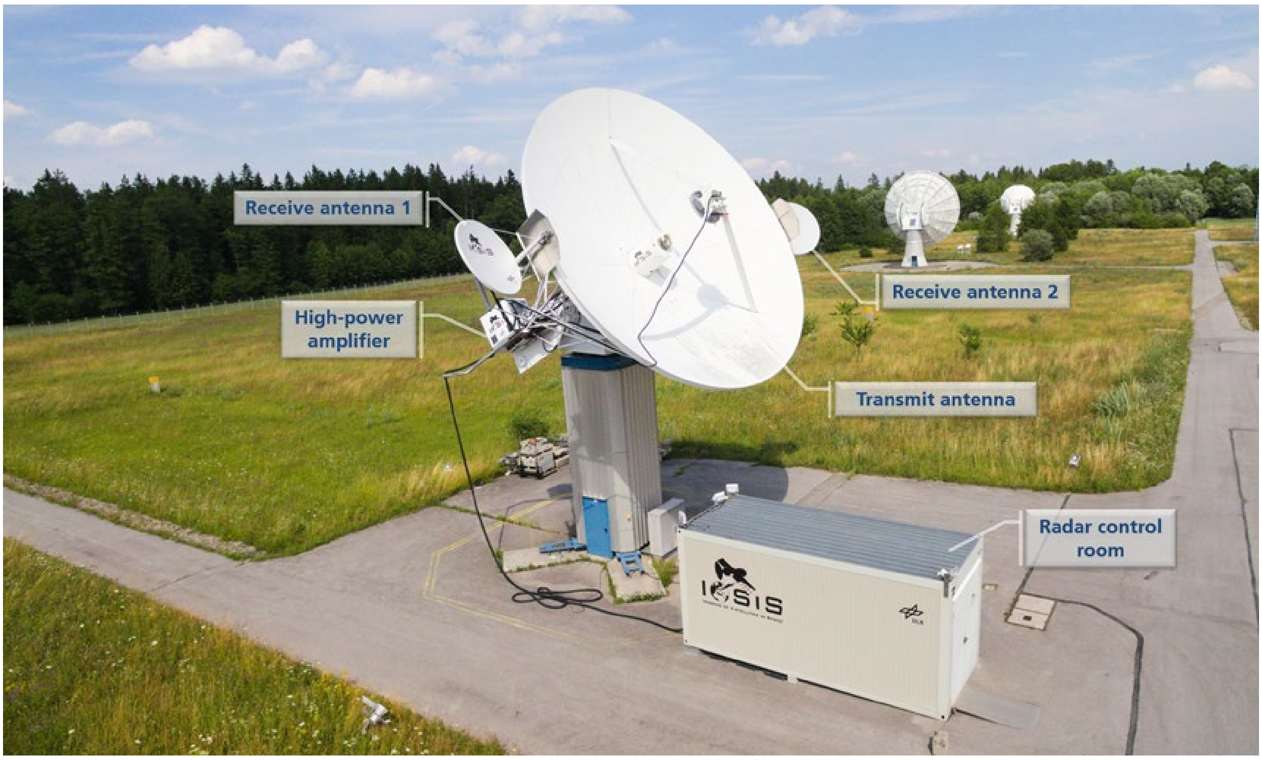

Figure 1: Photograph of the IoSiS imaging radar system located at DLR facility Weilheim, Germany. The facility is otherwise used for space communication and control of spacecraft.

The radar imaging is performed by applying the principle of Inverse Synthetic Aperture Radar (ISAR). Here, the radar transmits modulated pulses towards the target of interest while keeping it inside the main lobes of the antennas by steering those according to the *a priori* known orbit path. The reflected pulses are coherently recorded, and, after the data acquisition, a two-dimensional image is formed offline by a back-projection algorithm. The generated radar map represents a highly spatially resolved representation of the target's backscattering properties according to its shape, geometry, and reflectivity. More details about the IoSiS system are reported in Refs. [7], [8].

3.0 IOSIS IMAGING RESULTS

At present, due to limited TX power (it peaks at several kilowatts), only targets in the inner Low Earth Orbit (LEO) domain with distances of around 800 km can be imaged with sufficient Signal-to-Noise Ratio (SNR). In terms of radar, a rewarding target for SSA research is the International Space Station (ISS), since it has a huge size of about 108 m in length and is a highly complex object with fine structures. The ISS typically orbits the Earth at an altitude of 390 – 430 km above ground, offering sufficiently "short" distance to the IoSiS radar even in off-zenith directions.

Figure 2 shows a photograph and a comparison of different spatial resolution of radar images of the whole ISS and a zoomed area. First, the immense difference in information content between the two illustrated resolutions stands out, especially for the zoomed sections. It should be noted that even 50 cm spatial resolution nowadays is at the technological edge of many existing Earth observation radar satellites and is not achieved by all of them. However, when images in Earth observation have a size of several kilometres, even a few meters of spatial resolution give the impression of detailed information. Here, where the image is size about 100 m in diameter, 50 cm spatial resolution only allows the coarse structure of the ISS to be recognised. The zoomed section in that case only recognises a backscattering structure, but provides no further detail. The images of the 5 cm resolution, i.e., a factor of ten times higher, enable the identification of fine details, even in the zoomed section. Note, that in azimuth direction even higher resolution was achieved when processing larger observation angles, i.e., a larger synthetic aperture [8].

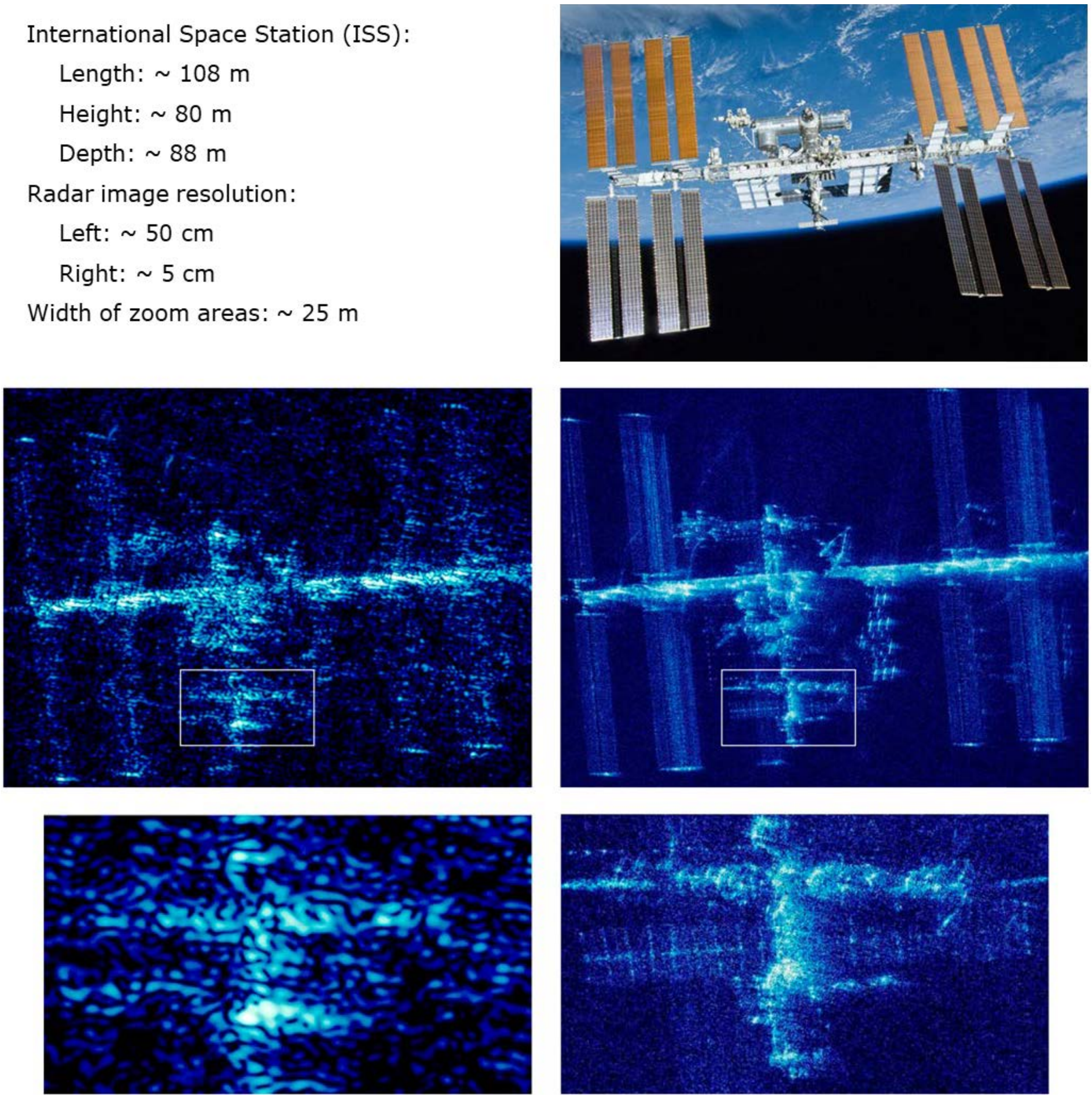

Figure 2: (Top right) Photograph of the ISS (source: NASA); (middle left) IoSiS radar image result of the whole ISS and a zoomed area for 50 cm spatial resolution; (middle right) as before, but for a spatial resolution of 5 cm. The white rectangle in both radar images of the whole ISS represents the zoomed area shown below. The photograph may vary in line of vision and may not contain all structures of the ISS being present during radar observation and vice versa.

Figure 3 shows a comparison of part of the high-resolution section and a roughly corresponding warped photograph of that detail. Note that the perspectives do not really fit to each other, and an attempt was made to warp the photograph such that it roughly fits to the radar perspective for better comparison. The comparative analysis clearly shows details like the metallic supporting structure of the solar panels and some further attached extensions to the cylindrically shaped habitat area. However, a more detailed interpretation is hard to make for two reasons. First, the ISS state at radar observation and at the moment of photography do not fit for sure, and hence, the ISS is most likely differently configured with respect to the main structures. Secondly, and more importantly, the ISS has a very distinctive three-dimensional complex structure (see dimensions indication in Figure 2), which is compressed into a two-dimensional world by classic ISAR imaging. Since classic radar imaging performs a range by azimuth image, structures may appear at an unexpected location in the image because of their actual shift in elevation and range to the radar. In contrast, an optical image is an azimuth by elevation map where the location of a structure appears at the correct offset angle or position with respect to the image centre, neglecting for the moment possible slight distortions by the focusing optics. This circumstance is not so dominant in radar Earth observation, since there the imaged area can often be considered as a two-dimensional structure given the typical size of the images.

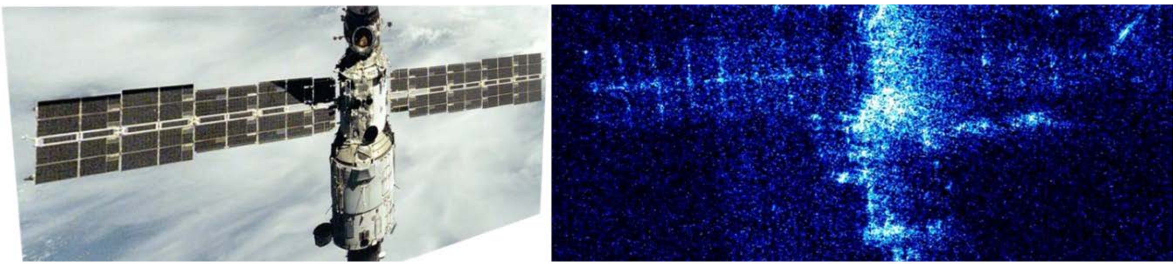

Figure 3: (Left) Warped photograph of the Zwezda Service Module of the ISS (source: NASA); (Right) Section of the high-resolution radar image from Figure 3-1 roughly fitting to the photograph. The photograph may not contain all structures of the ISS being present during radar observation and vice versa.

The only way to solve this problem satisfactorily is the performance of true three-dimensional radar imaging. A suitable concept for doing this is outlined later. Furthermore, it should be mentioned that many object details may be non-visible to classic mono-static radar, e.g., when the incident electromagnetic wave is not reflected back towards the radar, but in other directions. This information gap may be filled by the same imaging concept as proposed for the three-dimensional imaging, enabling now multi-static radar.

Besides very high-resolution ISAR imaging of spacecraft, the analysis of the timely evolution of high-resolution range profiles may already be very useful. This is especially valid when the spacecraft has periodically moving segments within its structure, or when the whole spacecraft rotates or tumbles while following its orbital path. Figure 4 illustrates a set of measured consecutive radar range profiles of an old rocket stage.

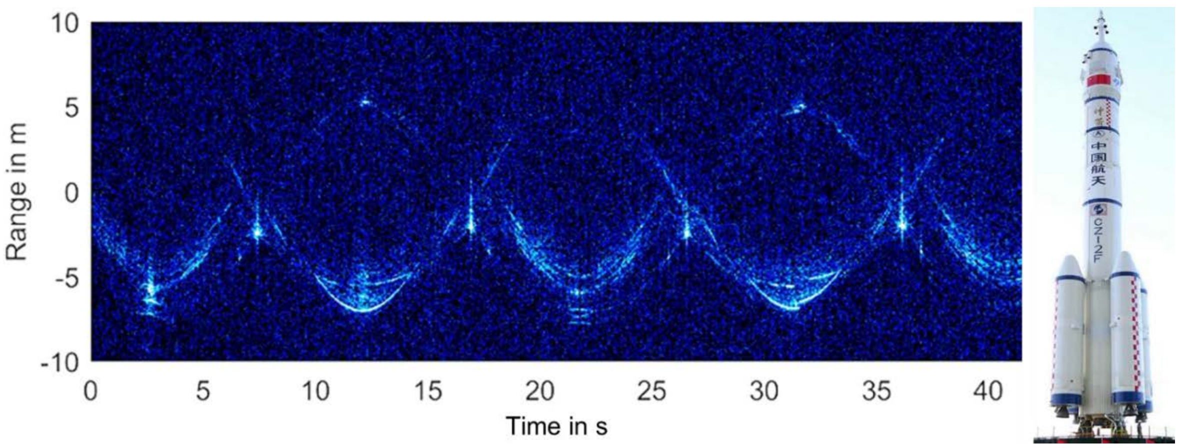

Figure 4: IoSiS range profiles of a rotating or tumbling rocket stage of a Long March 2F rocket from People's Republic of China, being decayed in 2021. On the right a photograph of the whole rocket is shown (source – Wikipedia https://en.wikipedia.org/wiki/Long_March_2F).

The radar image has a range resolution again in the several centimetre range while no focusing has been applied in azimuth direction. Hence, the range profiles are just strung together according to their order in time. What is remarkable is the periodic signature in time, where roughly two sinusoidal signatures with a period of about 20 s and a "phase shift" of about 180° can be observed. This can be explained by the roughly cylindrical shape of the stage, when considering the body structure of the whole rocket in Figure 4, whose top and bottom structures reflect the waves back to the radar when they are almost perpendicularly oriented to the wave incidence. Hence, the echoes from the top and bottom structure appear at half of the period at around 10 s repetition, where the side facing the radar of course produces much higher reflections. The two sides, top and bottom, can also be discriminated by their range signature, where one side probably represents the engine exhaust of the stage and the other the connection part to the next stage. ISAR imaging in that case was not possible, since the pulse repetition frequency used was not sufficient with respect to the tumbling rate of the rocket stage.

4.0 FUTURE RADAR MAPPING OF LEO SPACECRAFT

Although IoSiS can already produce very high-performance imaging of inner LEO spacecraft, on-going research at DLR shows that future SSA requires new concepts in terms of radar imaging capabilities and modes. Following early ideas on innovative and game-changing designs, a study was carried out a few years ago, resulting in a new concept based on "distributed antenna apertures" instead of single large-dish solutions. Figure 5 illustrates the basic idea.

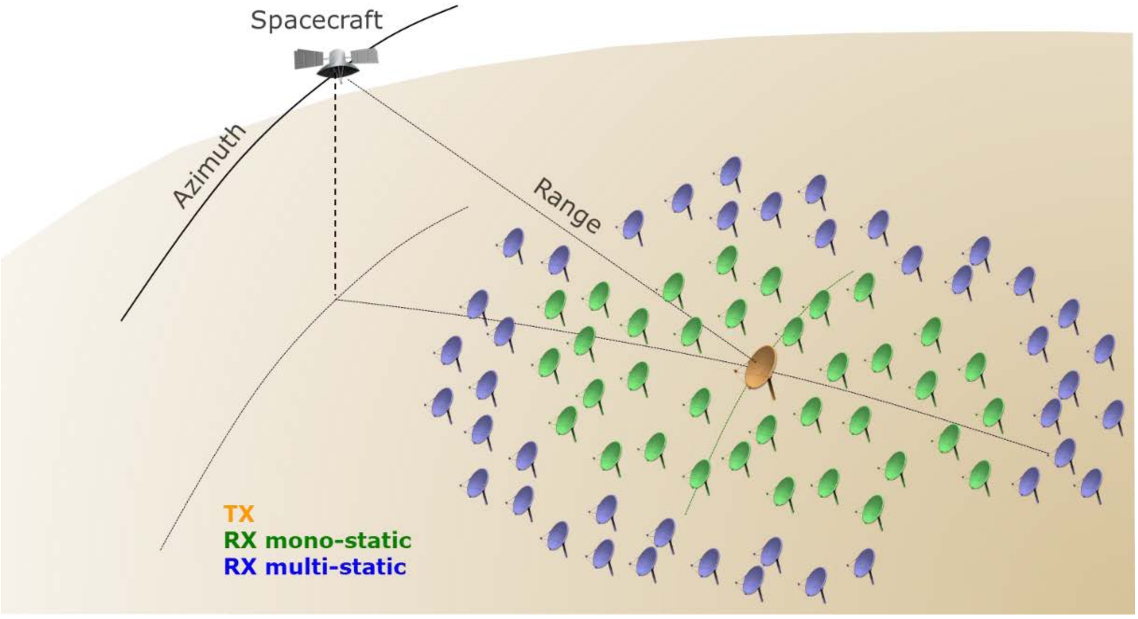

Figure 5: Sketch of the new concept for radar-based spacecraft imaging using distributed antenna apertures (TX – transmit, RX – receive).

In this case the required large antenna gain for proper SNR is realised by a multitude of small antennas. In principle, one transmitter is sufficient, and the receivers are distributed on a large area around it, as shown schematically for an arbitrary distribution pattern in Figure 5. If the bi-static angle between TX and single RX antennas is sufficiently small, a mono-static observation can be performed. If it is larger, multi-static imaging is possible. Even in the mono-static case, a third imaging dimension is spanned additionally in the elevation direction, enabling true three-dimensional radar imaging. By further extending the area of the distributed RX apertures, more and more multi-static information is acquired. If, additionally, the frequency range of the radar is shifted to higher millimetre-waves, e.g., W-band, the single apertures can be kept very small. The study has shown that such a concept is feasible and can deliver outstanding, and to date unmatched, information for even very complex and large spacecraft.

Figure 6 shows the result for the simulation of this kind of distributed apertures radar system working in W band at 92 – 100 GHz. Here one transmitter and 71 receivers have been assumed distributed linearly at equal distances (~ 429 m) along a 30 km distance, this array being oriented orthogonal and centred with respect to the orbit. The target was assumed to be a small cube satellite with a boom, represented by 13,000 ideal point scatterers along its outer edges and the boom. The orbit was assumed to be circular at an altitude of 780 km. The processed spatial resolution is about 7 cm. Now all imaged scattering centres appear on their correct geometrical position, and the 3D signature enables an image interpreter to observe it from any perspective. Hence, target analysis, recognition and identification, and the interpretation of the spacecraft's intended operation are considerably improved. More information on simulation results and ideas about the receive array are given in Ref. [9]. An experimental investigation of the concept using a tower-turntable arrangement and movable receivers is illustrated in Ref. [10].

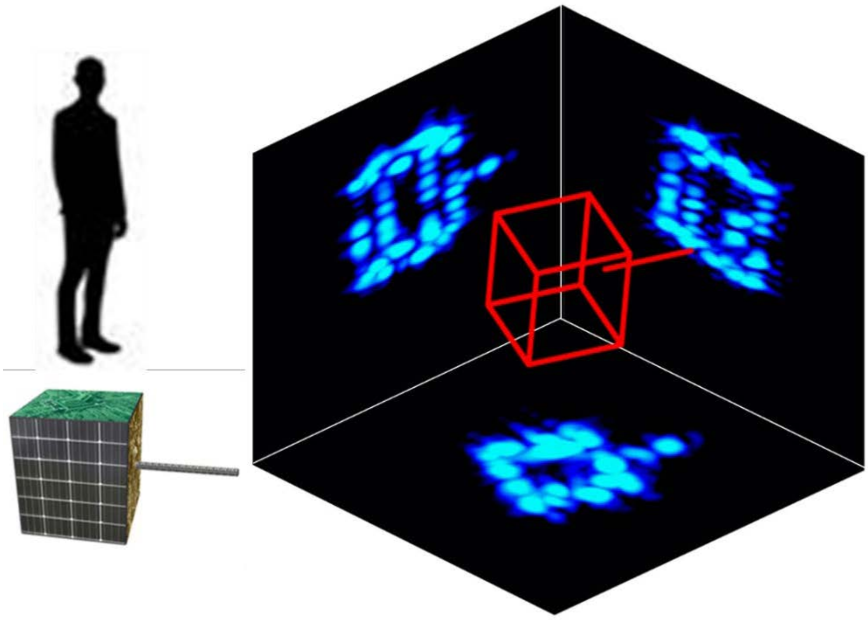

Figure 6: Result for simulated true three-dimensional (3D) radar imaging based on the concept of distributed apertures. The 3D signature is projected on the three image planes for better illustration. The red lines only show the contours of the reconstructed 3D signature. The target is a small cube-shaped satellite with a boom length of 65 cm and an edge length of 70 cm, shown in size comparison to a person.

5.0 CONCLUSIONS

Future SSA will require more powerful tools for detailed and robust LEO space observation. The DLR IoSiS radar system is a high-performance experimental device for research on new radar imaging concepts. Imaging examples showing resolution of a few centimetres demonstrate IoSiS's impressive capabilities and the information content of such data, especially for large and complex structures like the ISS. However, the future occupation of LEO by an ultra-high number of spacecraft of many types requires more detailed and robust information on the nature of those spacecraft, calling for true 3D radar and multi-static imaging. The concept of distributed antenna apertures can deliver such information. However, various technical and technological questions still have to be addressed by simulation, experiment, and corresponding development.

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