High Resolution Imaging of Satellites and Objects in Space with IoSiS

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Abstract

Space debris nowadays is one of the main threats for satellite systems especially in low earth orbit (LEO). Following official estimates, more than 700,000 debris objects having potential to destroy or damage a satellite exist. Very often the impacts of a hit cannot be identified directly from ground. However, high-resolution radar images are helpful in detecting such a possible damage. Furthermore, investigations on unknown space objects or satellites can be performed. Therefore, DLR has developed an experimental radar system called IoSiS (Imaging of Satellites in Space)[2, 3], being based on an existing steering antenna structure and a multi-purpose high-performance radar system called GigaRad [1] providing a resolution in propagation direction of better 5 cm.

In cross-range or azimuth direction high spatial and range independent resolution is obtained by using Inverse Synthetic Aperture Radar (ISAR) techniques. This technique is based on coherent observation of the object from different perspectives along the synthetic aperture, requiring precise tracking of the objects during orbit pass. Thereby a wide azimuth observation angle has to be performed for similar resolution in range and azimuth direction. The intended spatial resolution of 5 cm yields to an observation angle of approximately 25° for one ISAR image.

Such a high spatial resolution is not a standard for those radar applications in remote sensing. Present systems for earth observation achieve resolution in the order of several decimeters, being one order of magnitude worse. As a consequence, this improvement requires corresponding higher performance in system and orbit correction. Especially sufficiently accurate calibration of the radar electronics, the antennas' and the feeding frequency responses is essential. In addition, precise orbit determination of the observed objects is mandatory.

This paper outlines the major technical characteristics of the IoSiS radar system. Main error sources and corresponding solutions are addressed. The calibration effort to finally generate radar images at few centimeters of resolution is illustrated.

1. Introduction

Currently there exist more than 6000 operational satellites in a LEO. Main application areas of such satellite systems are communication, remote sensing, and military reconnaissance and surveillance. The high-end solution in complexity of course is given by the International Space Station (ISS). The wide range of applications and the resulting dependence of industrialized nations on such space systems cause the fact, that possible failures can have serious consequences. In order to verify unexplainable changes of the system performance, such as mechanical malfunction of the platform or electronic failures, both being indicators of possible mechanical damage, a regular assessment of the situation should be performed. Furthermore, the cost of typically several hundred million Euros per satellite and the increasing number of space debris demands for preventive protection, which can be supported by a continuous ground-based observation. In order to address some of those gaps DLR developed the experimental system IoSiS. IoSiS is based on broadband X-band radar allowing range resolution of a few centimeters. In combination with a steerable antenna system, wide azimuth angles and thus high azimuth resolution can be achieved. This enables the application of Inverse Synthetic Radar techniques for precise investigation of object details and hence the detection of possible mechanical damages.

2. IoSiS System Concept

2.1 SAR Imaging Principle

Fig 4 shows a sketch of the principal imaging geometry. Fixed ground-based microwave radar and a moving object on a specific orbit together build the requirement for ISAR imaging geometry [4, 8]. The fixed ground-based IoSiS radar system is using a steerable antenna to follow a space object on its orbit path during the pass. In the first place a large azimuth integration angle, i.e. a large synthetic aperture, is desirable in order to get a high azimuth resolution. Secondly, this range of observation angle provides as much as possible backscatter responses from the space object, which will not be available for small angle.

The second dimension, the range or propagation direction, is generated by pulse compression. The transmitted frequency modulated pulse, usually a up- or down-chirp, is reflected by the object and received by the radar. By cross-correlation the digitally sampled received signal with the known transmitted signal a compression of the signal is performed. This leads to a range resolution depending on the signal frequency bandwidth used for the pulse.

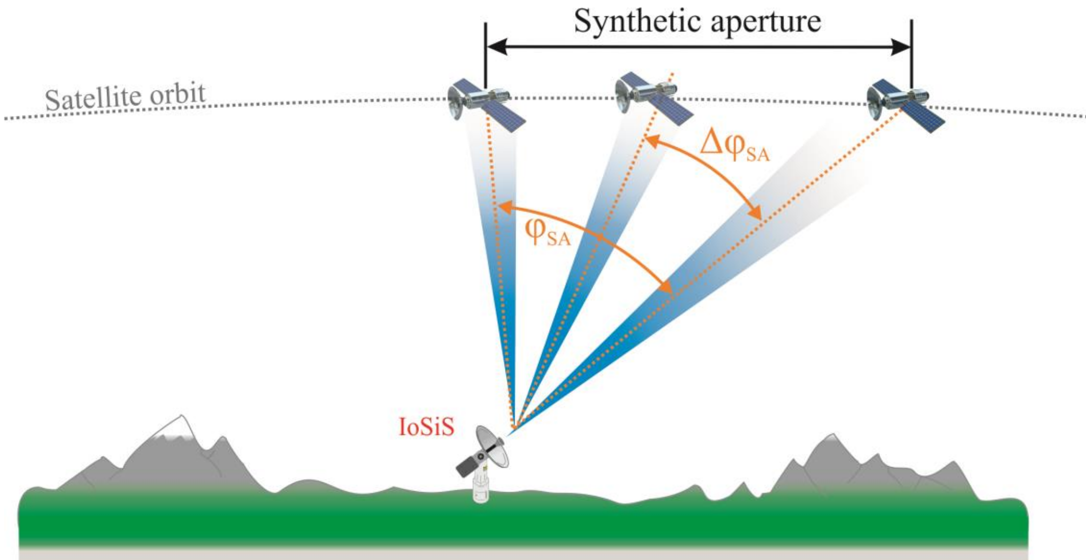

Fig. 1. IoSiS satellite imaging geometry with a steerable antenna following the satellite on its orbit path in order to acquire range profiles over a large synthetic aperture path for ISAR processing

2.2 IoSiS System Design

The experimental system IoSiS is setup at the DLR ground station in Weilheim [6], close to Munich, were the commanding of a variety of satellites is performed with several antennas (Fig. 2). To save cost and bureaucratic obstacle IoSiS uses an existing steerable communication antenna which was used as a backup for S band commanding. The 50 years old antenna was redesigned to a Cassegrain broadband X-band antenna with a high-power feeding in the back shown in Fig. 3. The main dish is used as transmit antenna TX.

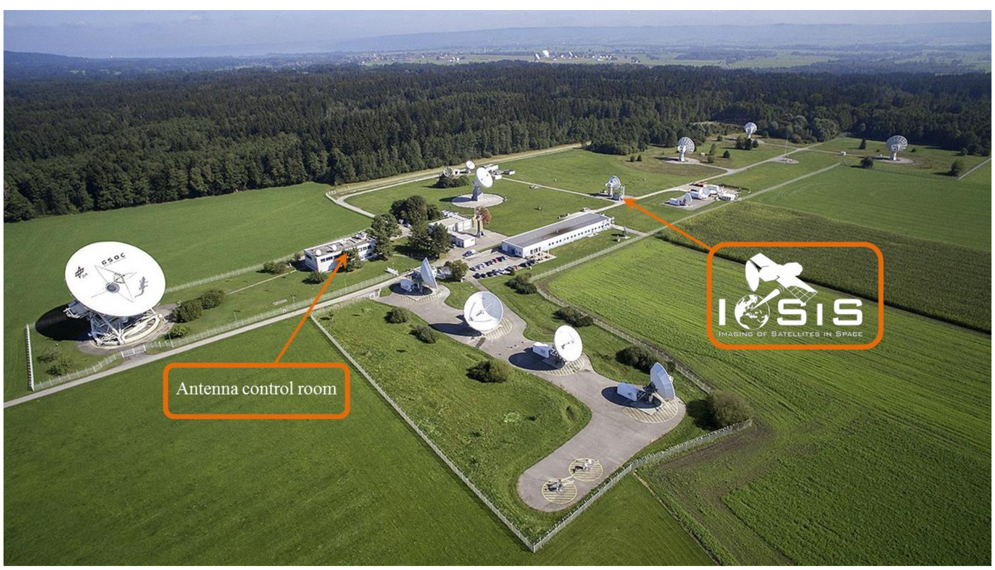

Fig. 2. Aerial image of IoSiS location at the DLR ground station in Weilheim with the antenna control room.

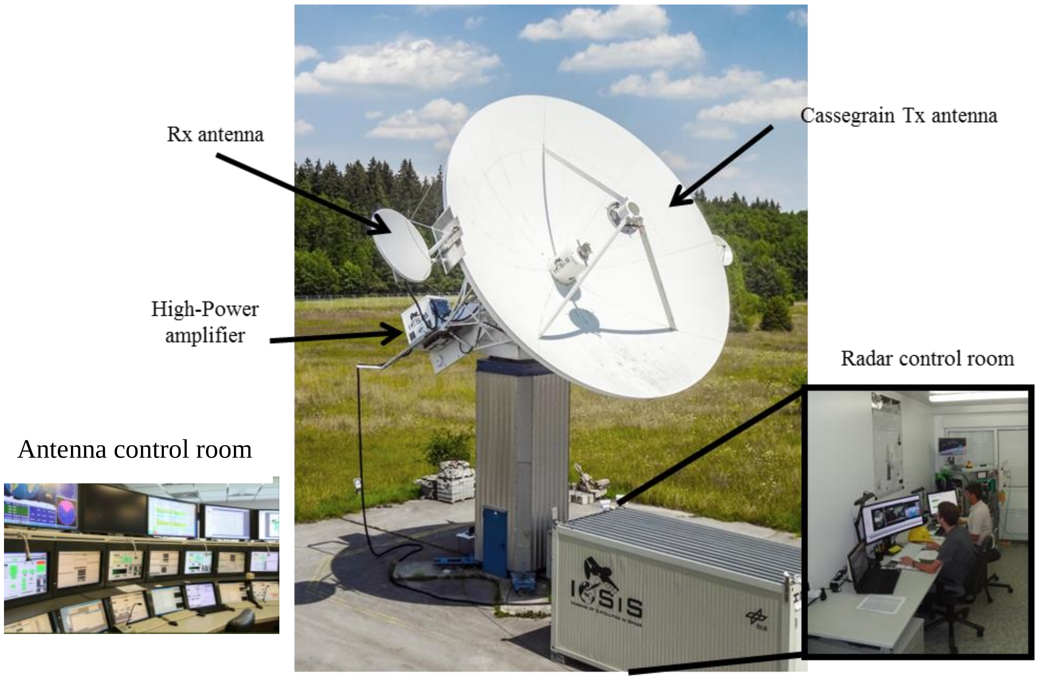

Fig. 3. IoSiS System setup. Two small RX antennas are mounted on the steerable TX antenna. The high power amplifier and distribution electric is located in the back of the antenna. A nearby container showing the radar control room. The antenna positioner is controlled by the DLR operational room shown on lower left.

Two 1.8 m receive (RX) antennas are flanged beside the existing 9 m antenna on both sides to allow a two channel receive operation for future imaging modes, like polarimetric or interferometric measurements. The high-power amplifier (HPA) with 10 kW peak power is located as close as possible in the back of the antenna. The main radar electronic and control is housed in a container nearby the positioner base. Here the whole instrument configuration and programming as well as the image acquisition are conducted. The radar instrument called GigaRad used for this purpose is shown in Fig. 4.

The single units of the radar sytem are arranged in a 19” rack. The high-power and low-noise amplification sections are excluded to allow a bi-static and high-power operation via optical transmission [3]. Due to the large complexity of the system, the different filter constellations, the error correction, and the required timing accuracy, an Erasable Programmable Logic Device (EPLD) and a micro controller are used to control the whole instrument via appropriate clocks. The original signal is generated in the Arbitary Waveform Genarator (AWG), followed by frequency conversion, and conditioning in the TX section. Then the signals are routed via an optical link to the extension modules shown here in the lower part of the rack. Also, the time sensitive control signals for duty cycle modulation of the HPA, and the receive gate switches are connected via a high-speed real-time bus. This extension modules and the connection are the basis for an upcoming IoSiS NG application were a significant separation of the antennas, or between the radar electronics and the antennas, is necessary.

On the receive RX side the functional concept is similar, except the digitization, using the highspeed Digital-to-Analogue converter providing a sampling rate of 8 GS/s. Hence, in order to fulfill the Nyquist criterion with some safety margins, the maximum analogue IF bandwidth is 3 GHz resulting in a maximum RF bandwidth of 6 GHz using IQ modulation and demodulation at a center frequency of 11GHz. For the IoSiS application the bandwidth is reduced to 2.8 GHz because of interferences, resulting in a single sideband solution.

Fig. 4. Photograph of the basic radar hardware setup of GigaRad including the extension modules, all being installed in a mobile 19’’ rack.

2.3 RF error correction and absolute calibration

The complexity of the radar system and the challenging application requires a precise characterization of the radar instrument and a proper error correction. The two main correction and calibration steps are shown in Fig. 5 in a simplified block diagram. The IQ sections, necessary for full band operation of the GigaRad instrument, are not required for the IoSiS application with 2.8 GHz. The main correction is performed in two steps indicated in the two colors. The inner correction and an absolute calibration.

The frequency response in the TX and RX chains is measured with respect to phase, group delay and amplitude (orange path) using the internal calibration path. A signal, similar to the used radar signal, is generated by the AWG and upconverted in the X-Band. The signal is filtered in the desired sideband (8 – 10.8 GHz), amplified, and routed to the receive chain through the calibration path with a proper attenuation. Also including the coupler right before the TX antenna and the switch following the RX antenna. The power reduced signal is than amplified filtered and down-converted. The signal is digitalized and compared to the transmitted one resulting in the inner transfer function.

To link the received signal of a measurement of a target to a physical property (Radar Cross-Section RCS value), an external calibration is necessary. In this second step the signal is transmitted and reflected by a known reference target in a known distance. As for the inner correction the received and sampled signal is compared by a cross-correlation to the transmitted one resulting in a second transfer function. In this step especially the response of the antennas, the waveguides and the antenna feed systems are characterized. The external calibration is performed using a trihedral corner reflector. The latter is mounted on a crane in a known distance to the antennas providing therefor the known free-space transfer function. This setup is shown in Fig. 6.

The combination of the inner and external calibration determines the overall frequency response of the system and ensures the focusing and resolution capability in range direction.

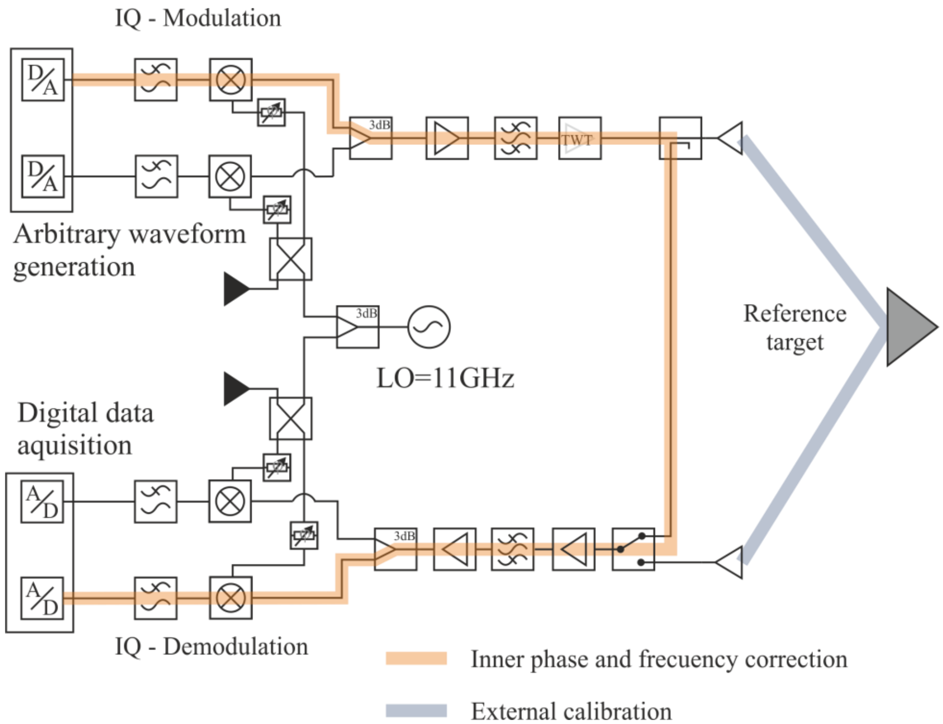

Fig. 5. Block diagram explaining the system correction strategy: amplitude and phase correction of the RX and TX units, amplitude and phase correction of the overall signal path including the antennas and waveguides to the antenna.

Fig. 6. Photograph showing the setup for external calibration and frequency dependent error correction including antennas, feed systems and waveguides. A trihedral corner reflector in elevated position is used as well-known external radar target.

2.4 Correction of Two-Line-Element Data

As mentioned previously IoSiS uses a steerable antenna to follow the path of an object necessary for a proper azimuth focusing by the ISAR principle. The time dependent pointing of the antenna is calculated from public available Two-Line-Element (TLE) data sets. This TLE data are accurate enough for orbit determination in cross track dimension for most of the observed objects for the antenna half power beamwidth of 0.2° and a receive window of 5 km in the propagation direction. As well known, the along track part of the orbit determination is charged with a position error in flight direction often present due to inaccurate time-of-arrival prediction, corresponding with the time component. To overcome this problem a tracking instrument like the DLR's satellite laser ranging (SLR) station at the local astronomical observatory (Stuttgart, Germany) [9] measuring the precise orbit time would provide online corrected orbit data. Since the positioning controller of the IoSiS antenna does not support online correction or even a more advanced method, the on the fly based time corrected slave mode, a straight forward method is used for the experiment IoSiS system.

This method is applicable for a target in LEO with several contacts per day. For the ISS, with two subsequent orbital passes as illustrated in Fig. 7 a time correction is possible. The first pass is used to determine the time offset using a fixed aligned antenna, and the next pass (after one orbit) is used to perform the ISAR measurement by steering the antenna according to the time-offset corrected prediction.

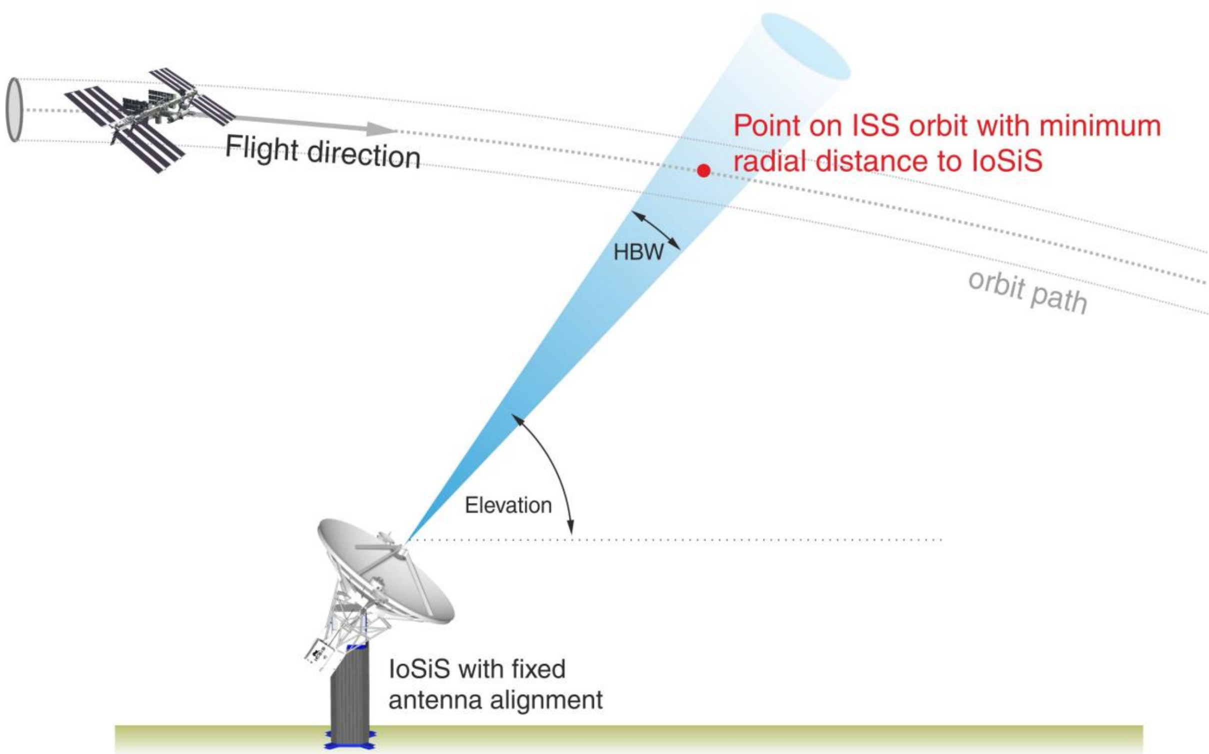

Fig.7. Measurement geometry for a fixed antenna alignment as used for the determination of the precise time of arrival in case of the ISS as target of interest.

For the time offset determination, the antenna is aligned to that orbit point where the object has the nearest distance to the IoSiS system. A corresponding measurement result is illustrated in Fig.8. The range evolution of the signature shows a parabolic shape. In that illustration, already the abscissa shows the time offset with respect to prediction. It can be observed, that in fact the ISS reaches the nearest approach slightly shifted in time by little less than 0.1 s. Considering the high orbital speed, the corresponding flight path of the ISS is about 760 m. Since the by the antenna beam illuminated area at a distance of 400 km is about 1500 m, it is quite clear that already a small-time offset can cause wrong beam pointing during the pass, corresponding to a massive reduction in receive power due to the antenna beam shape. However, the range offset is always small, considering the used 5 km length of the receive window.

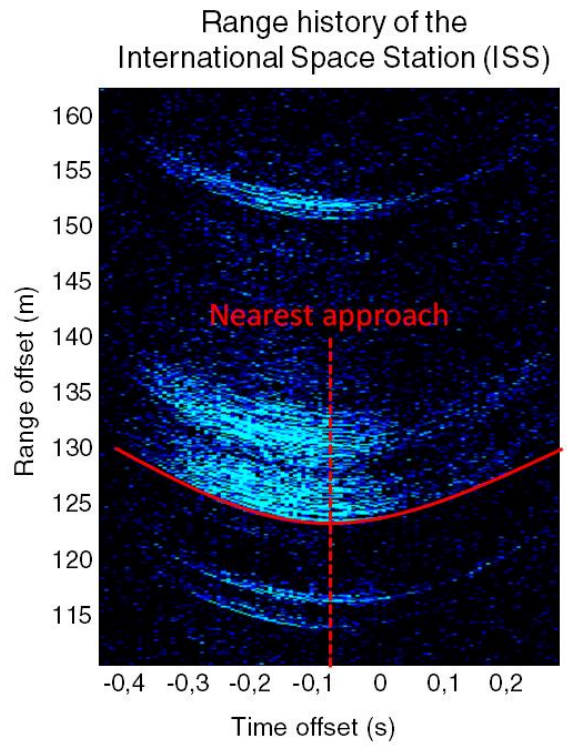

Fig. 8. Measured evolution of subsequent range profiles of the ISS using a fixed antenna alignment as depicted in Fig. 7.

3. Measurement result

The ISAR image in Fig. 9 of the ISS is processed from 2500 range profiles for which a measurement time of about 13 seconds at a pulse repetition frequency of 190 Hz is required. The pulse used for range compression was a linear frequency modulated pulse with a bandwidth of 2.8 GHz and a theoretical resolution of 6 cm. As azimuth processing method the back-projection algorithm was chosen. The number of range profiles corresponds to a width in azimuth angle of about 25 degrees, leading to the spatial azimuth resolution of about 6 cm at X band [10].

The ISAR image impressively shows the whole structure including the main truss segment, the various modules as well as the solar panels. Note that the size of the ISS in length direction is around 110 m, corresponding to about 1833 resolution cells.

The radar image shows a quite detailed representation of the whole ISS structure. More precisely, the solar panels or rather the mounting between those, being composed of a wire frame, are clearly visible (①). The flat panels themselves can't be seen by that measurement configuration due to their tilted alignment with respect to the radar during the flyover. At the end of all eight solar panels the structure provides suitable radar reflectors by pot-like resonators, resulting in strong point targets in the image. In the center region of the ISS, providing the most complex structure, even some single modules can be identified and associated.

The robotic arm of the ISS (②), which is mounted on the main truss segment, can be clearly identified in shape and orientation. Also, the exposed facility of the KIBO module together with its experimental canisters can be identified in structure (③). Furthermore, the heat radiators show significant reflections (④). In summary, many details of the radar image can be interpreted directly and associated with of CAD illustration or optical closeup views.

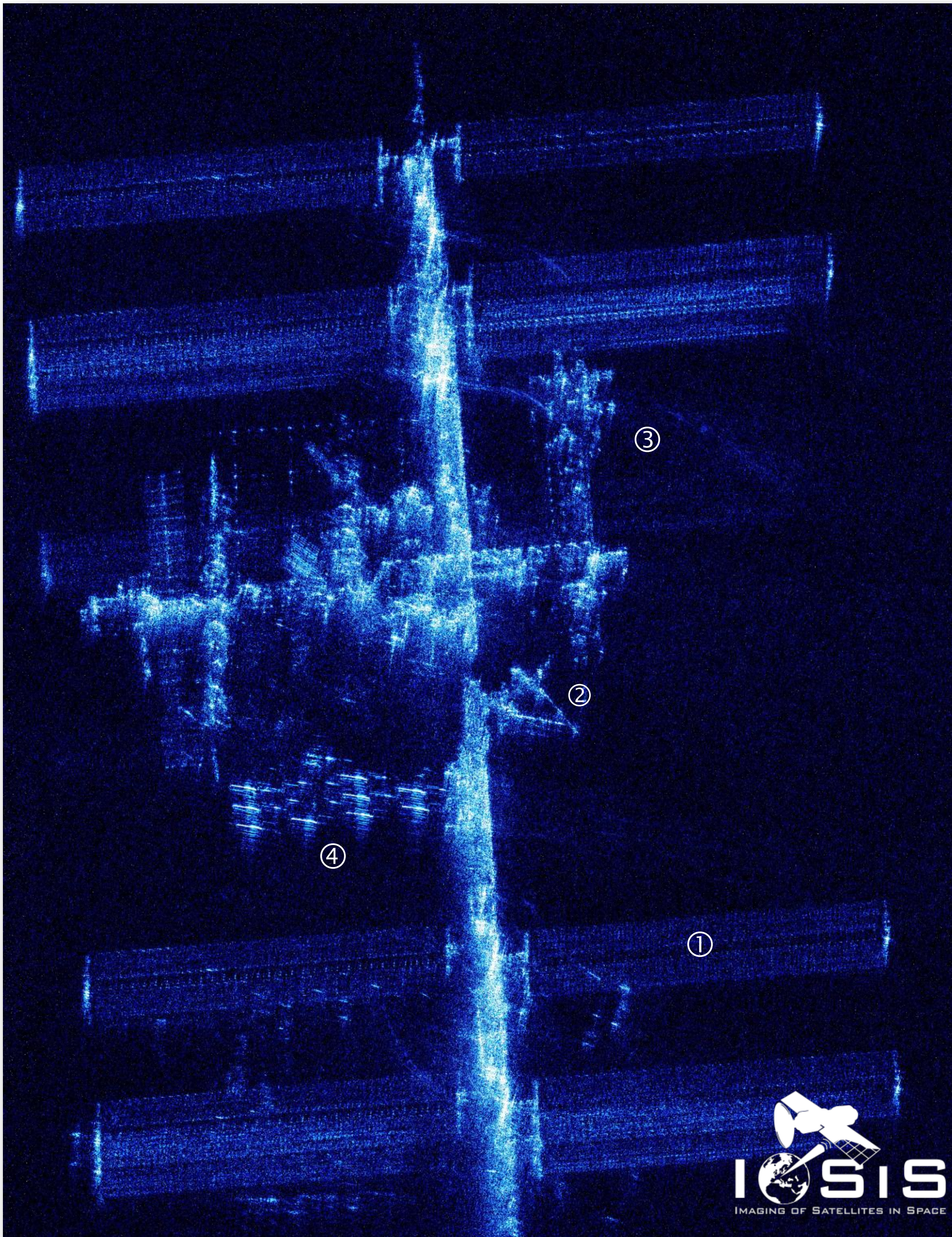

Fig. 9. ISAR image of the ISS acquired with IoSiS at a spatial resolution of about 6 cm x 6 cm [11]

4. Conclusion

In this paper the challenges in very high-resolution imaging of satellites and objects in space was presented based on the experiences of the IoSiS system. The instrument was established by DLR for future high-performance space surveillance radar system, investigating advanced radar concepts for future issues, being not adequately addressable by today's classic imaging approaches. The challenges to generate an image of an object in the LEO with centimeter resolution are enormous. Only if considering all parts of a system including instrument design, proper error correction and calibration, antenna steering unit, and an adapted ISAR processor a focused image is achievable. With the knowledge of the solution of all mentioned challenges, very high resolution ISAR radar imaging with less than 6 cm resolution of objects is possible. The image of the ISS recorded with IoSiS shows a remarkable granularity enabling a profound interpretation and analyses of the object of interest.

5. References

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