Advanced space surveillance with the imaging radar IoSiS

Simon Anger, Matthias Jirousek, Stephan Dill and Markus Peichl
German Aerospace Center

Abstract

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). The overall goal of that system is research on concepts for advanced acquisition of high-resolution radar images of objects in a low earth orbit (LEO). Compared to existing radar-based space surveillance systems, which has monostatic antenna configurations, in future IoSiS will use not one but more spatial distributed antennas in order to handle the upcoming amount of orbiting satellites and more important to realize bi-static imaging geometries. The latter allows the enhancement of the image information content compared to existing monostatic radar-based images of satellites. The paper outlines first the basic theory of radar-based satellite imaging using an inverse synthetic aperture radar (ISAR). Further a short description of the IoSiS system is addressed. The atmospheric effects on radar images are illustrated based on simulated imaging results and the advantages of a multi-channel system is introduced based on interferometric imaging results providing spatial resolution in three dimensions. A measurement result obtained by the IoSiS system of a real space object with spatial resolution in the centimeter region show the successively implemented error correction strategies.

1. INTRODUCTION

There are more than 6000 operational satellites as well as nearly 3000 out-of-service satellites which are still orbiting earth. From the observed tendency it has to be expected, that the total number of satellites, and especially the rate of increase per year, both will keep increasing. According to the European Space Agency (ESA) there are in addition tens of thousands of particles classified as space debris. And also, the number of debris will increase like the latest measurements with the Haystack Ultrawideband Satellite Imaging Radar (HUSIR) have shown [1]. Considering the potential hazard of damage and destruction by space debris, which is massively present in the low earth orbit (LEO), research on high-performance radar concepts was initiated for the purpose of doing a precise evaluation of the satellite structure based on high resolved radar images. Radar techniques allow the acquisition of very high resolved images of satellites measured from ground and constitutes therefore in cooperation with optical sensors a powerful tool for proper space surveillance.

Therefor 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) [2]. The overall goal of that system is research on concepts for advanced acquisition of high-resolution radar images of objects in a low earth orbit (LEO). Compared to existing radar-based space surveillance systems, which has monostatic antenna configurations [3], in future IoSiS will use not one but more spatial distributed antennas in order to handle the upcoming amount of orbiting satellites and more important to realize bi-static imaging geometries. The latter allows the enhancement of the image information content compared to existing monostatic radar-based images of satellites.

Using the electromagnetic spectrum in the region of longer wavelengths compared to optical systems has actually the main advantage that influences caused by the atmosphere or the weather conditions are smaller or negligible, respectively. Nevertheless, considering the radar-based acquisition of images of satellites with a spatial resolution of 10 cm and even better, influences of the atmosphere like the ionospheric delay as well as tropospheric range delay can’t be neglected any more. Both lead to a massive phase error and hence to severe distortion in the processed radar image. Hereby the frequency dependent ionospheric range delay is caused by free electrons in the atmosphere whereas the tropospheric range delay depends on the refractive index of this part of the atmosphere.

Besides the experimental measurements of IoSiS a software tool was implemented for performance estimations. Using that tool the hardware setup was optimized in parallel during development and construction. Further on the software tool allows the visualization of the mentioned and expected influences of the atmospheric distortions on a radar image.

2. INVERSE SYNTHETIC APERTURE RADAR (ISAR)

A fixed ground-based microwave radar and a moving object on a specific orbit together build the requirement for the ISAR imaging geometry according to Figure 1. The proper motion of the objects generates the required synthetic aperture of length L_{SA}. R_B is the range at the beginning and R_E at the end of the imaging process. Therefore, the satellite path has to be known very precisely in order to have a proper antenna alignment during the pass, because up to now IoSiS don't have an auto-tracking capability. A steerable antenna system provides capability of wide azimuth scanning required for high azimuth resolution. In parallel the integration time of observation is extended resulting in an enhancement of the Signal-to-Noise Ratio (SNR) in the radar image. The basic requirement of an ISAR imaging method is the change in the viewing angle seen from the satellite. Easily spoken the satellite has to be seen from different perspectives to form the ISAR image. Further on the radar pulses along the synthetic aperture have to be acquired coherently, because the phase information is crucial to process the ISAR image. That means the radar transmitter and receiver operates with the same reference phase. If the transmitter and receiver are closely together in a quasi-monostatic arrangement the coherence of both can achieved rather easy. Are both, transmitter and receiver, widely separated to achieve bi-static imaging geometries, the achievement of coherence is one of the most difficult challenges.

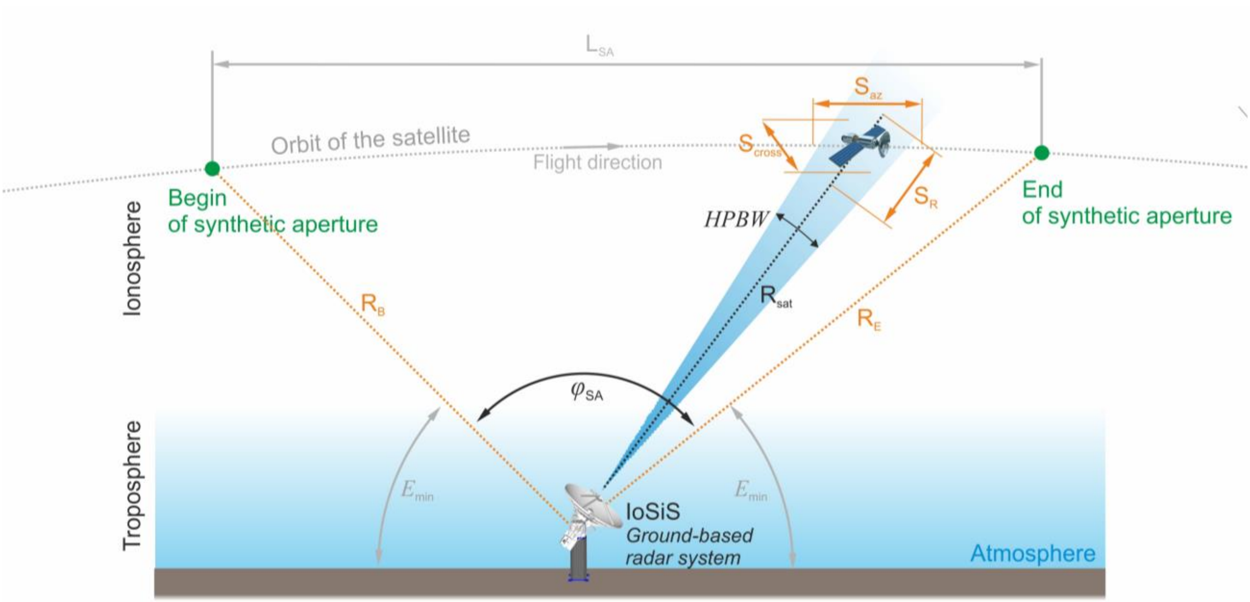

Fig. 1. Imaging geometry of a ground-based inverse synthetic aperture radar (ISAR). The tracking antenna illuminates a satellite along its orbit path and collects coherently radar echos. Afterwards the image is processed based on the acquired radar echos.

The range resolution of the latter ISAR image can be calculated with:

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

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:

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

Here f_c is the radar center frequency and φ_{SA} the azimuth integration angle corresponding to Figure 1. Considering a fixed radar transmit frequency, large integration angles are mandatory for a high spatial resolution in azimuth direction. φ_{SA} is limited by the minimum elevation angle E_{min}. Considering the large transmit power the minimum elevation angle is limited to E_{min} due to security reasons.

3. SYSTEM DESIGN DESCRIPTION

The experimental setup of IoSiS is realized at the DLR ground station Weilheim. Here a variety of different antennas are operated to establish communication links with satellites during its pass. For the IoSiS experiment an antenna, initially provide a S-band communication link after a satellite launch, is used. For the radar experiments, the originally direct fed antenna was rebuilt to a X-band Cassegrain configuration. Figure 2 shows the antenna system after the modification into a broadband high-power radar antenna. Due to the high pulse power in conjunction with the large signal bandwidth compared to the communication system, the development of a completely new feeding system was essential. Therefor a broadband high-performance corrugated feed horn together with a sub-reflector was developed. The new feeding system illuminates the RX main reflector with an edge taper of 10 dB at a radius of 4 m. By that way the side lobes of the main beam as well as the radiation in the back of the main reflector are sufficiently reduced. Knowing that the heavily tapered illumination of the main reflector leads to a loss in antenna gain, both requirements are necessary to avoid radio interference with adjacent satellite communication antennas.

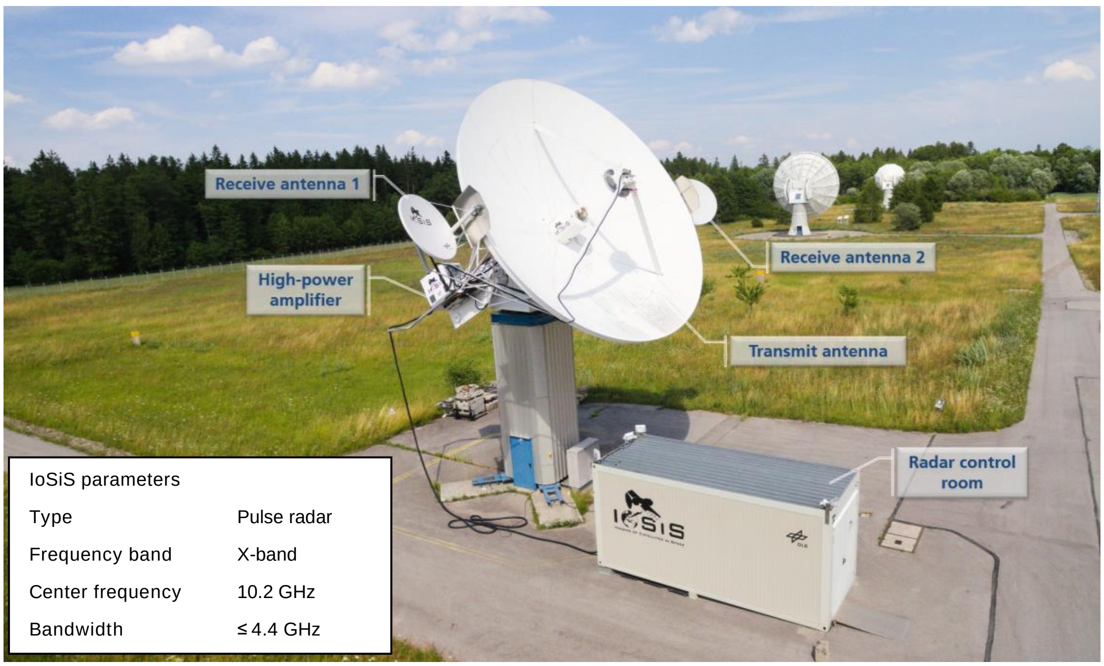

Fig. 2. Experimental setup of the satellite imaging radar IoSiS with a 9 m transmit antenna and two 1.8 m receive antennas.

Two separately mounted receive antennas allow a two-channel operation mode and further on a high isolation between the transmit path and receive path. Two in-house developed offset parabolic reflector antenna of 1.8 m diameter were used for receive. The main parts of radar electronics and computer control are located in a container nearby the antenna system. From here the system is configured and programmed for the measurement of the passing satellite. In contrast to existing operational and planned new radar systems, being intended for imaging of satellites, the basic long-term concept of IoSiS is focused on the use of considerably smaller reflector antennas. For the basic startup system, a TX and a RX antenna of 3 m diameter each, was considered. Now, due to the availability of the 9 m TX antenna the RX antenna can be designed much smaller in order to keep the product of the effective antenna area of both TX and RX antennas constant. Two receive antennas allow the simultaneous acquisition of two radar images. Either you take two images with different polarization, i.e. co- and cross-polarization, or you take two images with the same polarization, then superimpose them to get an improvement in the signal-to-noise ratio (SNR) as shown in the later measurement results.

In a first implementation the IoSiS system includes our multi-purpose advanced X-band radar system GigaRad in conjunction with a high-power amplifier (HPA) placed on the rear side (white box) of the antenna system [4]. The table in Figure 2 shows the typical IoSiS radar system parameters which are used for the imaging measurements.

4. SIMULATION RESULTS

4.1 IoSiS system simulation result

Besides the experimental measurements a software tool was implemented for performance estimations. Using that tool the hardware setup was optimized in parallel during development and construction. The theoretical sensor data is obtained by consideration of the specific orbital data, the sensor parameters as well as the reflectivity map of the target satellite. The latter is calculated based on an in-house developed hybrid ray tracing algorithm together with a 3-dimensional model of the satellite [5].

A simulation result of a satellite, using the IoSiS system parameters is shown in Figure 3 [6]. As target one of the Iridium communication satellites has been used and the signature was computed based on the sensor parameters of IoSiS. Here the maximum bandwidth of 4.4 GHz together with an azimuth integration angle of 24° results in a quadratic resolution cell of approximately 3.5 x 3.5 cm. For instance, all three aluminum antennas and the edges of the solar panels can be clearly identified. In this ideal simulation no error sources where considered.

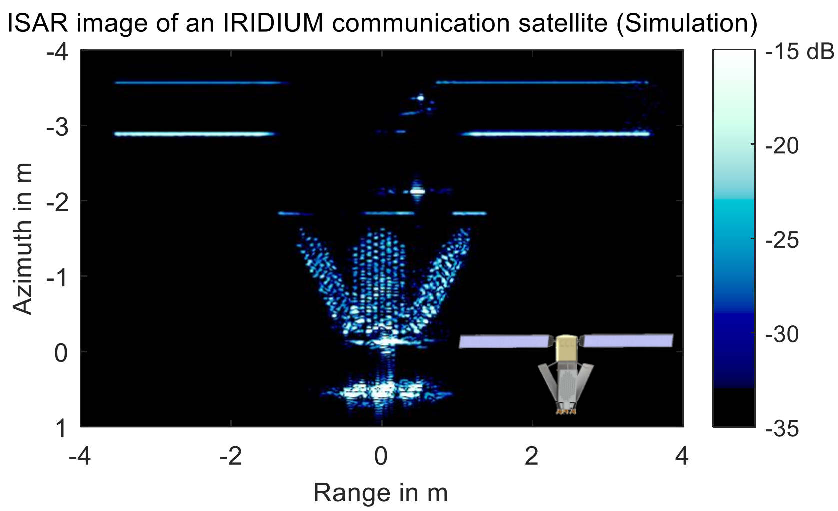

Fig. 3. Simulation result of an ISAR image of an IRIDIUM communication satellite using the IoSiS radar system parameters.

4.2 Atmospheric effect

Although the propagation of microwaves is nearly independent from weather conditions, the atmospheric effects have to be considered very well to achieve very high resolved ISAR images of space objects using a ground-based radar.

The impact of these atmospheric distortions on high-resolution ISAR images shows Figure 4 using the example of a simulated ISAR image of the IRIDIUM communications satellite. The satellite simulation is again based on a reflectivity map gathered from a three-dimensional object model. The maps include triple, double, and edge reflections. Those are computed at the center frequency of the system in order to minimize computational load. For the rest the simulation parameters are based on the IoSiS system. Herby only the influence of the troposphere and ionosphere are considered and no further error effects are present, in order to demonstrate only the distorting effect of the atmosphere. For the comparison, Figure 3 shows the simulation result without any error effects. One can observe a severe distortion in azimuth direction which is mainly caused by the troposphere. Herby the frequency independent tropospheric delay leads to an imperfect assumed imaging geometry with the result of an incoherent integration which avoids a proper focusing. The ionospheric effect, causing mainly a slightly distortion in range direction, is only marginal. This shows that the tropospheric properties should be known very well in order to mitigate sufficiently the distorting effect, or a proper empirical or auto-focusing algorithm has to be applied.

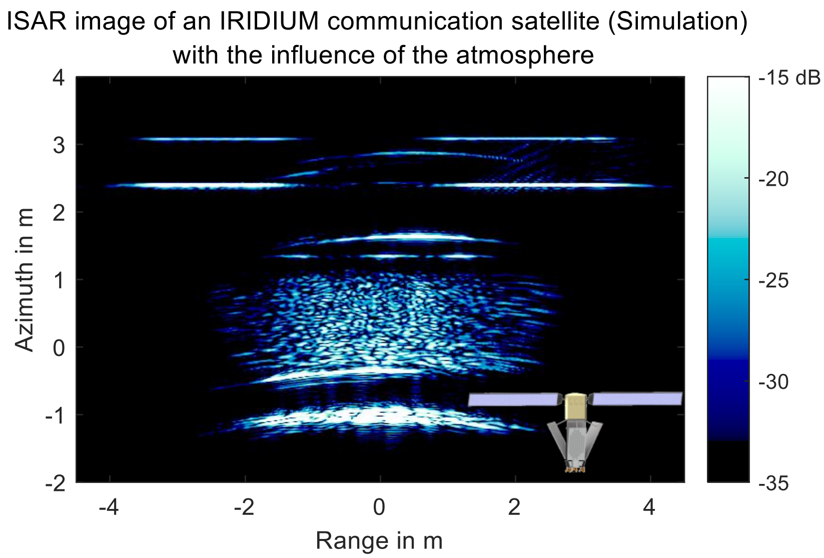

Fig. 4. Simulation result of the influence of the atmosphere on an ISAR image of an IRIDIUM communication satellite.

4.3 Interferometric satellite imaging

The previous shown simulation results show a two-dimensional image of the satellite. A possibility to acquire also the height information in the third spatial direction is radar interferometry. Interferometric imaging is based on the exploitation of the phase difference (interferometric phase) of at least two radar images available in a complex-valued form [8]. Therefore, for instance, the images have to be acquired using different incidence angles in respect to the target scene. In earth remote sensing interferometry is an often-used method to measure geophysical parameters, like topography or glacier flows. Considering interferometric satellite imaging the additional information obtained from these interferometric data sets can be used to reconstruct the elevation profile of the satellite comparable to a 3-dimensional image for instance. In earth remote sensing it is distinguished between a single-pass interferometry, where two radar images are acquired from two sensors simultaneously, and the repeat-pass interferometry, where one sensor acquires the images at a different time from slightly different orbits for instance.

In the following we are considering the first case, where two ground-based sensors acquire simultaneously two ISAR images from slightly different positions.

Figure 5 shows the height of ambiguity depending on the effective baseline for typical distances for satellites in LEO.

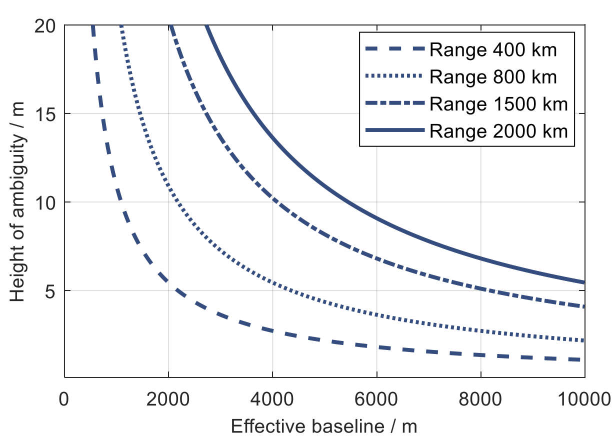

Fig. 5. Interferometric height of ambiguity as function of the effective baseline (distance of the two radar receivers) for different ranges of the target object.

Assumed was an X-band radar system with a center frequency of 10 GHz comparable to the current IoSiS configuration. The height of ambiguity must not be smaller than the extension of the imaged satellite, otherwise an unwrapping of the interferometric phase can hardly be done. Hence a proper distance of the two sensors has to be chosen. When we consider large solar panels, the typical satellite dimension is 10 to 20 meters. Further on, the trend is going to rather small satellites, with the result that we can assume these dimensions as an upper boundary. For high phase sensitivity the height of ambiguity should approximately match to these dimensions. Figure 5 shows, that this requirement cannot fulfilled with one single baseline length if we consider the typical distances to the imaged satellites. Thus, for proper phase sensitivity multiple baselines are needed.
For the generation of a height profile of the satellite on the basis of an interferogram a second image was simulated using a bi-static imaging geometry, i.e. the transmitter and the receiver are separated by a specific baseline. This effective baseline was assumed with 2000 m and the satellite distance amounted to 780 km according to the orbital height of the Iridium satellites. This results in a height sensitivity of 2.8 cm/degree resulting in a height of ambiguity of about 10 m. The reconstructed elevation profile of the satellite, determined based on the interferometric phase can be seen in Figure 6. By the analysis of the colors we can now identify for instance, that the distance of the upper edge of the solar panel to the focusing plan is 35 cm and of the lower edge -60 cm. This allows further on the precise determination of the solar panel area as well as the alignment of the panels during the ISAR measurement. Also, the alignment of the three communication antennas can be determined more precisely compared to the image in Figure 3 showing only the backscattered amplitude [6].

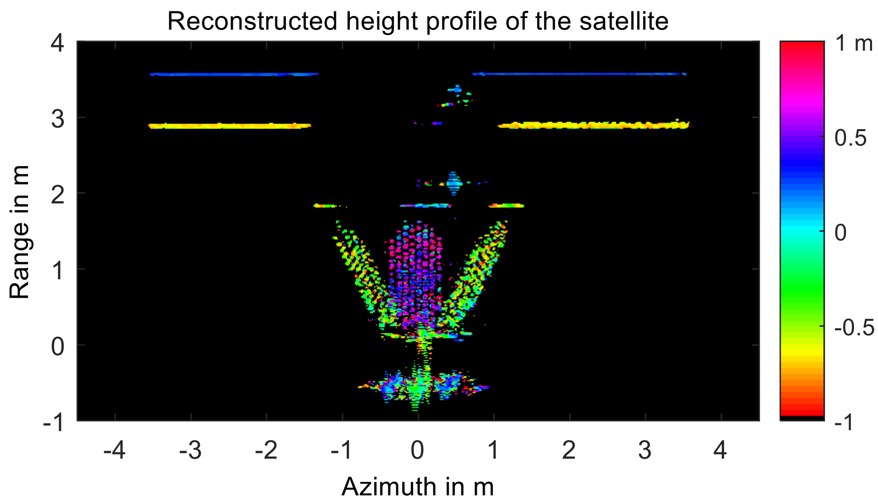

Fig. 6. Simulation result of a reconstructed height profile of a satellite using an interferometer with one transmit and two receive antennas separated by a baseline of 2 km.

5. MEASUREMENT RESULTS

Figure 7 shows the measurement results of both IoSiS receive channels of the International Space Station (ISS). Both images are acquired with a horizontal polarization (HH), a radar system bandwidth of 2.8 GHz and an azimuth integration angle of 10°. The corresponding spatial resolution is approximately 6 cm in range direction and 8 cm in azimuth direction. As transmit signal a linear frequency modulated chirp was used with a pulse length of 45 µs and a pulse repetition frequency of 190 Hz. The images show the large backscattering behavior of the ISS along the main truss segment as well as in the center area where the various modules are installed. Also, the grid structure holding the large solar panels are clearly visible. The solar panels itself cannot be seen, because they were not perpendicular aligned towards the radar system during the measurement. Both channels exhibit a very similar behavior with a noise signal level of -52.2 dB in channel I and -52.8 dB in channel II. The small difference could be explained by a slightly different system noise temperature of the two receive channels which is mainly determined by the low noise amplifier right after the receive antennas.
Figure 7 shows in addition the superimposition of both images. On the lower right side, the result of an incoherent superimposition is depicted. In this image the absolute amplitude values (non-complex) of both upper images are summed up. It can be seen that the noise level does not decrease compared to the single channel images. With a value of -52.5 dB the noise level is the average value of the single images of both channels. The incoherent superimposition

therefore brings no improvement in the SNR. On the lower left side, the result of a coherent superimposition is depicted. Here the complex amplitude values, containing the phase information for every image pixel, are summed up. In theory an improvement by a factor of two is expected which corresponds to 3 dB in the logarithmic scale. It can be seen that the noise-level decreases by 3 dB compared to the average value of the single images. It is clearly visible that the background becomes darker and hence the noise in the image is lower.
Up to now IoSiS uses the two receive channels for the improvement of the SNR by superimposition both images. In future one of the receive antennas can be spatially separated to achieve bi-static imaging geometries and perform experimental interferometric measurements, for instance.

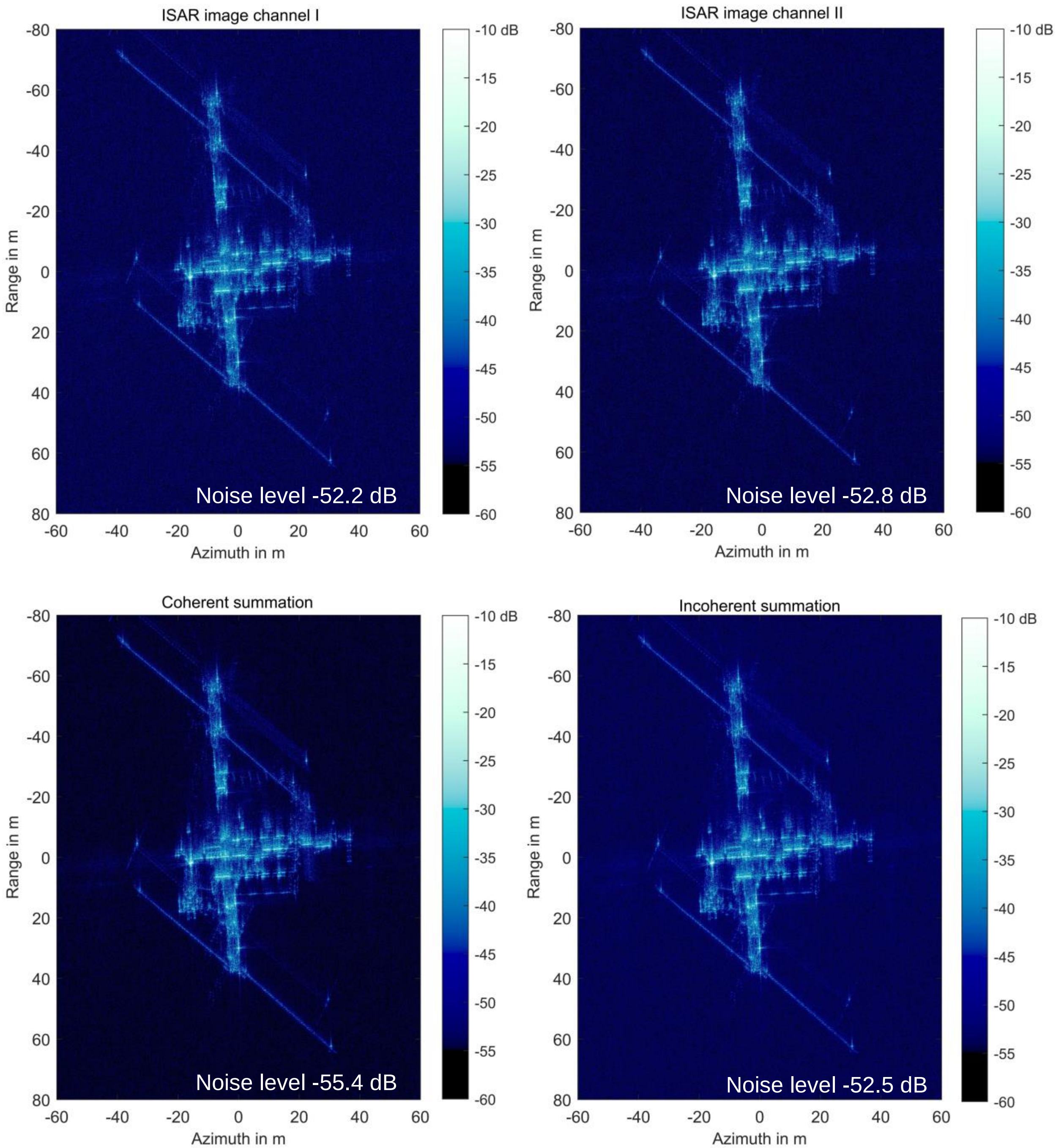

Fig. 7. Measurement results of the ISS imaged with IoSiS using both receive channels. In addition, the coherent and incoherent summation of both channels is depicted.

A further measurement result is depicted in Figure 7 showing the range profiles of a rocket body. These are the range profiles before they are processed to an ISAR image. In this case an ISAR imaging was not possible because the rocket body was heavily rotating or tumbling, respectively. Due to this tumbling the sample rate in azimuth direction was not sufficient to process an ISAR image. Due to the very high range resolution, however, information about the rotation period can be determined from the range profiles. The periodic structure in the range profiles shows that the rocket body rotates with a period of about ten seconds. This example makes it clear that radar systems can not only obtain very high-resolution images of space objects, but can also determine precise information about the orientation or the tumbling behavior of objects in space. The rocket body belonged to a Long March 2F rocket from People's Republic of China and decayed 2021.

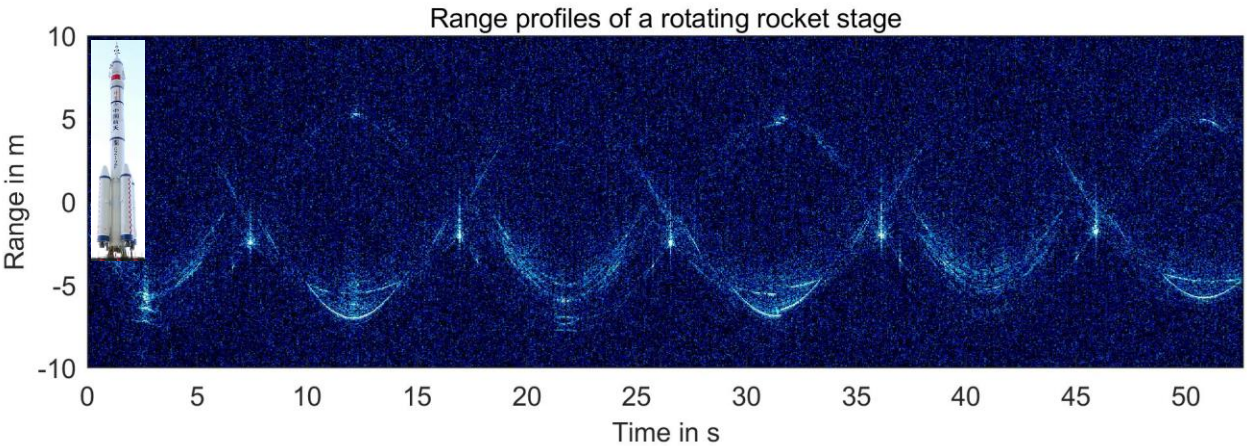

Fig. 8. Range profiles of a rotating rocket stage showing a rotation period of approximately 10 seconds. The rocket body belonged to a Long March 2F rocket from People's Republic of China and decayed 2021.

6. CONCLUSION

Nowadays due to heavily increasing numbers of satellite and space debris a powerful space surveillance gets more and more important. In order to establish a future high-performance radar system for comprehensive weather and daytime independent space surveillance, the Microwaves and Radar Institute of German Aerospace Center (DLR) is investigating advanced radar concepts for future challenges, being not adequately addressable by today's classic imaging approaches. As an entrance in such technology the experimental radar system IoSiS was developed and constructed, being presently still in the commissioning phase. Multi-channel measurements were performed and show ISAR images with a spatial resolution in the centimeter range. When fully operational the system will be used for data collection and modifications to explore suitable modern radar concepts like multi-channel and multi-static approaches.

7. REFERENCES

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