Imaging of satellites in low earth orbit using IoSiS system – antenna validation and first results

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Abstract

The Microwaves and Radar Institute of DLR is running an experimental radar system called IoSiS (Imaging of Satellites in Space), in order to do basic research on advanced methods for imaging of objects in space and, furthermore, for the purpose of gathering high-resolution radar images of objects in a low earth orbit (LEO). Such images can be an appropriate tool for generally analyzing satellite structures and especially identifying possible mechanical damages caused by space debris, for example. Furthermore the analysis of unknown objects is an eligible interest. Considering the radar imaging process of objects in LEO, based on inverse synthetic aperture radar (ISAR) geometry, several error sources have to be taken into account. Results from first imaging experiments are discussed with respect to such challenges in the imaging process.

1 Introduction

The experimental imaging radar system IoSiS consists of a pulse radar system called GigaRad and a multiple-dish based steerable antenna system [1] [2]. A parabolic transmit (TX) antenna of 9 m diameter is arranged in a Cassegrain configuration, and the receive (RX) antenna is a directly fed parabolic reflector antenna of 1 m diameter. **Figure 1** shows the main components of IoSiS. The physical separation of TX and RX signal path provides sufficiently high isolation taking into account the large intended bandwidth and the required high pulse power. The main parts of radar electronics and computer control are located in a container nearby the antenna system.

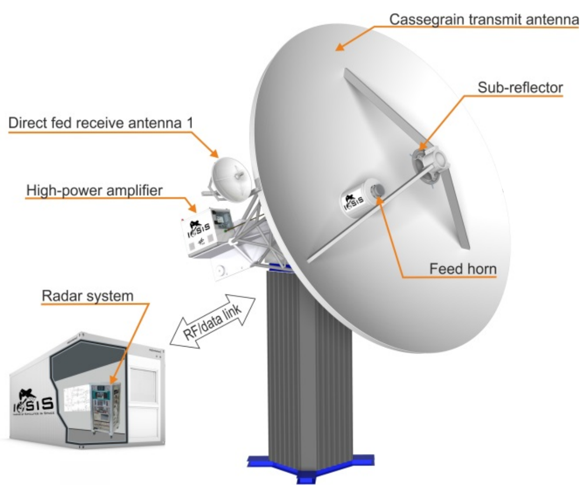

Figure 1: *Sketch of the main components of IoSiS, containing the radar system GigaRad and the two-dish based steerable antenna system.*

From here the system is configured and programmed for observation of a specific object or satellite in LEO. In contrast to existing operational and planned new radar systems, being intended for imaging of satellites [3], 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. During a measurement, the steerable antenna system is following the known orbit of a satellite and the radar system is collecting highly resolved range profiles. Based on a set of range profiles along a certain range of observation angles, a two-dimensional radar image is formed in a subsequent processing procedure. Hence the object position over time has to be known with sufficient precision in order to keep the object within the highly focusing beam of the TX antenna. The next section describes the antenna validation procedure in detail. Afterwards some first measurements are discussed.

2 Validation of antenna system

The 9 m parabolic antenna system was initially used for satellite communications. In order to use it for radar experiments, the originally direct fed antenna was rebuilt to a Cassegrain configuration. **Figure 2** shows the antenna system before and 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. Both requirements are necessary to avoid radio interference with adjacent satellite communication systems. However, the heavily tapered illumination of the main reflector leads to a known loss in antenna gain.

Figure 2: *Comparison between the original satellite communication antenna (left) and the IoSiS radar antenna system, consisting of a Cassegrain configuration for TX and a smaller RX antenna installed at the side (right).*

Despite precise mechanical construction and implementation of the new antenna components, a validation of the whole antenna characteristics was necessary. In doing this a possible squint angle of the main lobe can be identified and the corresponding misalignment to an orbiting satellite can be avoided. Considering an antenna system of many meters in size, it is challenging to determine precisely the antenna characteristics. For calibration purposes of antennas of this size, often a transmitter is used which is located in a few kilometres distance. By measuring the received power over a certain azimuth and elevation angle, the true direction of the main lobe can be identified. The main disadvantage of the latter calibration geometry is the very small elevation angle above ground, which is required to point to the ground-based reference transmitter. Consequently the calibration can be distorted by side-lobe driven multipath scattering, especially during the antenna movement in elevation.

In order to avoid such multipath propagation one of the geostationary ASTRA satellites was used for antenna calibration, transmitting in the same frequency range like IoSiS. The ASTRA satellite is located at 19.2° East providing TV services. It can be located at an elevation angle of approximately 34.4° based on the observer position on ground in South Germany. Despite the geostationary location a slightly varying satellite position over time has to be considered. **Figure 3** shows the observation geometry. The ASTRA satellite was considered as a fixed point source and the IoSiS TX antenna was temporarily used in RX mode. In this way a total-power measurement across a certain elevation and azimuth angle was performed and thus the antenna pattern determined with sufficient accuracy. Because precise TX power and shape of the antenna pattern of the ASTRA satellite wasn't known, only a relative power calibration could be realized. Using the identical configuration the alignment of the separated RX antenna could be established and adjusted for identical pointing compared to the TX antenna.

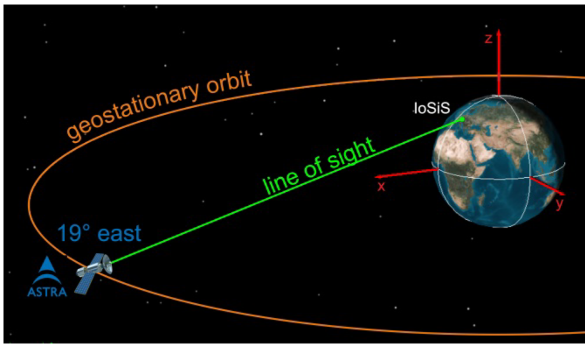

Figure 3*: Antenna pattern validation geometry using the geostationary satellite ASTRA.*

The measurements of the TX antenna have shown that a squint angle of 0.4° in elevation is present, to be compensated during later ISAR measurements. In addition a slightly broadened elevation pattern was identified leading to a gain loss of about 5 dB. Unfortunately also the purchased RX antenna showed some major deviations from ideality. Despite these irregularities, which lead altogether to a loss in antenna gain product of 10-12 dB, first measurements could be carried out successfully.

3 Measurement results

3.1 Range profiles

The first object in LEO to be imaged by IoSiS was the International Space Station (ISS). Having an altitude of 420 km and a size of approximately 100x80 m^2 a very large radar cross section (RCS) can be expected. **Figure 4** shows one single range profile of the ISS within the RX window of IoSiS. In that illustration the reflected signal can be clearly identified showing a signal-to-noise ratio (SNR) of almost 20 dB. Atmospheric effects like tropospheric and ionospheric delay, non-ideal amplitude and frequency transfer function of the radar electronics, and the transfer function of the antenna system are already compensated. The length of the RX window was set to 20 km being visible as length of the constant noise floor. The measurement was performed at reduced signal bandwidth of 2.85 GHz.

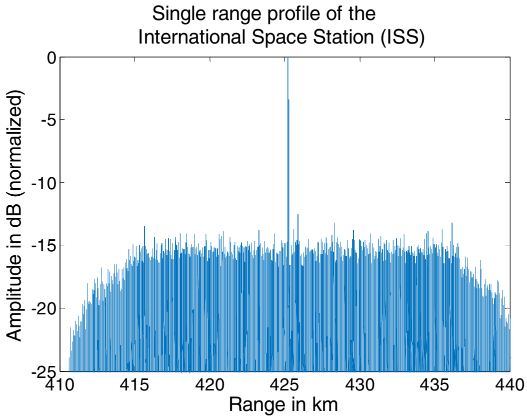

Figure 4: *Range profile of the first ISS measurement. More detail is not visible here due to size of range gate.*

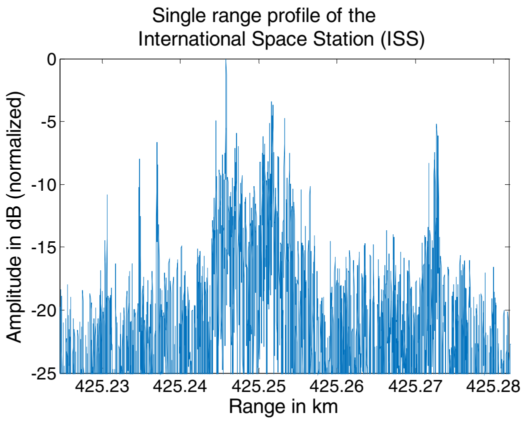

Figure 5 *Detail of ISS range profile having a range resolution of about 5 cm.*

A closer look of the range profile depicts **Figure 5**. Here the SNR of about 20 dB can be better observed. Furthermore detailed range dependent reflections from the rather complex structure of the ISS are visible. The shown range profile was acquired at high elevation pass at an angle of about 80°. Such high elevation angle provides a rather perpendicular incidence angle with respect to the plane of main truss segments of the ISS. As a result the range profile shows an extent of only about 40 m compared to the 80 m or 100 m of maximum size, respectively.

3.2 Range profile history

During the ISS pass-by range profiles were acquired at a pulse repetition frequency of 190 Hz. **Figure 6** shows a sample of 50 range profiles for a range area of 14 m. The signal bandwidth in that case was 400 MHz resulting in a range resolution of 40 cm. Due to the large variation of the object distance during the pass, the range position of the RX window has to be successively adjusted. In the shown range history this range migration is already compensated based on the theoretically predicted orbit path. **Figure 7** shows the identical section of range history for a range resolution of about 5 cm and a corresponding bandwidth of 2.85 GHz, respectively. The improvement of spatial resolution and thus signature quality compared to lower bandwidth is obvious. Much more finer structural details can be identified. In a next step range profiles are processed to an ISAR image.

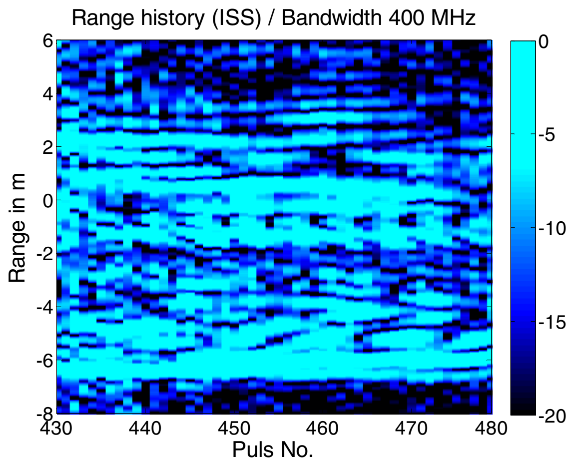

Figure 6: *Segment of the range history from ISS measurements. Range resolution is about 40 cm.*

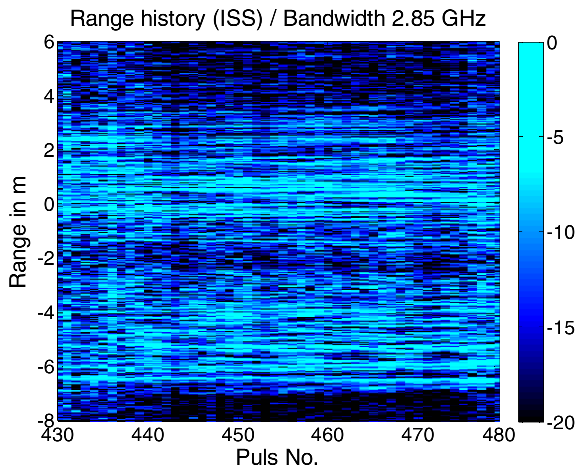

Figure 7: *Segment of the range history from ISS measurements. Range resolution is about 5 cm.*

3.3 ISAR Image of the International Space Station (ISS)

The ISAR image of the ISS, processed based on 400 range profiles of 400 MHz bandwidth and using a simple Range-Doppler algorithm [4], is illustrated in **Figure 8**. Considering an angular velocity of nearly 1°/s in azimuth direction, the PRF in conjunction with the number of processed pulses results in an azimuth integration angle of approximately 2° (being the synthetic aperture width), which corresponds to an azimuth resolution of about 40 cm based on X-band frequency.

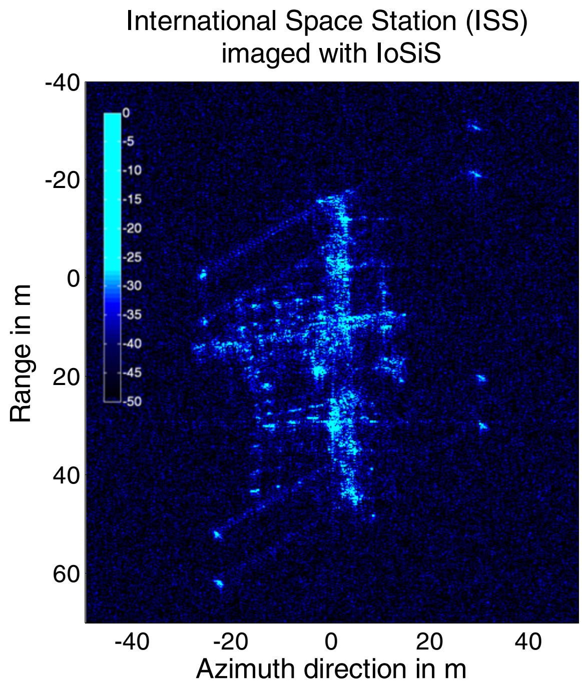

Figure 8: *ISAR image of the ISS at a spatial resolution of 40x40 cm²*.

The image shows a 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 visible. The panels themselves can't be seen due to the flat and smooth shape in conjunction with their alignment during the pass. At the end of all eight solar panels the structure provides suitable radar reflectors by pot-like resonators, resulting in clearly visible point targets in the image. In the center region of the ISS, providing the most complex structure, some single modules can be identified, especially when the image is compared to an optical counterpart. Due to the incidence angle with respect to the orientation of the ISS, and the application of a simple Range-Doppler algorithm for image generation, the image is slightly squeezed together in range direction. Although the shown result provides already high quality and much detail of this complex structure, a much higher resolution is desirable and essential, especially when considering smaller and less structured objects.

Fully coherent processing of the range profiles for proper ISAR imaging can only be performed, if the range migration can be correctly applied over sufficiently wide azimuth angle, defining the synthetic aperture. Therefore the orbital path of the object to be imaged has to be known with sufficient precision, when no in-situ tracking of the object is available. Due to orbital perturbations the sufficiently correct computation of the orbit path for prediction, based on orbital elements, depends on multiple error sources. Especially for the case of the ISS, it pointed out to be very difficult to determine the precise magnitude of such errors. For example, due to the large size and the very low altitude of the ISS, a severe influence of the residual atmosphere is given, changing constantly the orbit trajectory. Consequently, in order to achieve much higher spatial resolution, requiring much longer synthetic apertures and thus ranges of observation angles, the predicted orbit trajectory has to be determined much more precisely, or sufficiently accurate in-situ tracking data has to be provided, respectively.

4 Conclusions

The IoSiS system of DLR is a high-performance experimental radar system for imaging of space objects in LEO. Following the development and construction phase of last few years, some initial operations have been carried out. In this context the implemented Cassegrain antenna system was validated using the geostationary television satellite ASTRA, in order to guarantee proper alignment of the antenna beams during steered tracking of objects in LEO. The first experimental measurements were performed on the ISS as object of interest, and high-resolution range profiles could be acquired over certain azimuth angle. First ISAR images of the ISS at reduced spatial resolution were successfully processed from IoSiS raw data.

References

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