IoSiS – A high performance experimental imaging radar for space surveillance

Simon Anger, Matthias Jirousek, Stephan Dill and Markus Peichl
German Aerospace Center (DLR)
Microwaves and Radar Institute
82234 Weßling, Germany
Email: simon.anger@dlr.de

***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), being presently still in the commissioning phase. 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). Such images can allow the analysis of complex satellite structures for detection of possible mechanical damages or irregularities generated by space debris, for example. Furthermore investigations on unknown space objects or satellites can be performed. Based on inverse synthetic aperture radar (ISAR) geometry, a ground-based radar produces high-resolution range profiles along a certain azimuth angle by tracking the space object using a steerable antenna system. Steered tracking of objects during overpass, whose trajectories have to be sufficiently known, allows a very wide range of azimuth observation angle. Thus high azimuth resolution in the order of the range resolution can be achieved, depending on center frequency and bandwidth. The IoSiS range resolution is given by the radar bandwidth of up to 4.4 GHz, being in theory up to few centimeters. This paper outlines the system design of IoSiS. Elementary processing steps from raw data to the final ISAR image of a space object are discussed. Finally, a measurement result of the International Space Station (ISS) is shown as an example.**

Keywords—space surveillance, inverse synthetic aperture radar, ISAR, high-resolution radar, space debris, space system situational awareness

I. Introduction

In the last decade the number of operating satellites orbiting the earth has increased as never before. This evolution is shown in the graph of satellite history depicted in Fig. 1. In parallel the number of satellite launches per year has also strongly increased after a long period of a more or less consistent number of satellite launches. Since the first satellite launch in 1957 a total of approximately 8300 artificial objects have been launched into space. Some of them are decayed or recovered with the result that currently there are about 5000 satellites left still orbiting earth. According to the European Space Agency (ESA), more than half, nearly 3000 are out-of-service besides the almost 2000 operational satellites. Considering the orbital height, most of these operational satellites (≈ 1300) orbiting earth in a low earth orbit (LEO). 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. Considering in addition the potential hazard of damage and destruction by space debris, which is massively present in LEO, ISAR imaging of space objects can provide crucial information to characterize satellites [1]. Therefor research on high-performance radar concepts was initiated and started with IoSiS basic system development [4]. IoSiS is intended as an entrance for basic experimental investigation of high-resolution imaging of space objects based on ISAR techniques as well as new imaging concepts like multi-static ISAR imaging [3]. Due to the highest satellite density in LEO, IoSiS is focusing on that space area. The basic purpose of the instrument is to explore very high-resolution radar imaging for corresponding information extraction, and related impacts on image quality by manifold error sources.

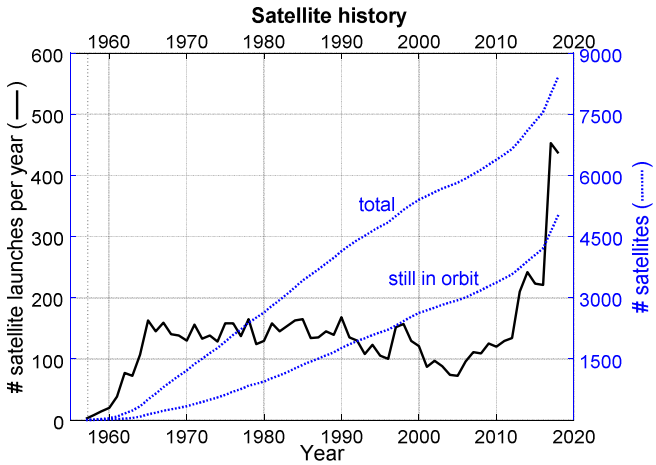

Fig. 1. Timeline of the number of satellites orbiting earth for the last decades and corresponding number of satellite launches per year (Source: UNOOSA)

II. IoSiS System Design

The experimental setup of the IoSiS system is realized at DLR ground station Weilheim, Germany. Here a variety of different antennas are operated to establish communication links with manifold satellites (Fig. 2). In order to save cost, IoSiS uses an existing steerable second backup antenna, initially used for satellite launch procedures. For radar operation, the originally direct fed antenna was rebuilt to a broadband Cassegrain configuration. Fig. 3 shows the antenna system after the modification into a broadband high-power radar antenna. The existing large dish is used as transmit (Tx) antenna, which was completed by two receive (Rx) antennas attached to its sides. Due to the high pulse power and the large signal bandwidth a new feeding system was realized by a high-performance corrugated feed horn and a sub-reflector for Cassegrain operation. The new feeding system illuminates the Tx main reflector by an edge taper of -10 dB at a radius of 4 m. Hence the side and back lobes of the main reflector are sufficiently reduced to avoid

interference with adjacent satellite communication antennas as can be supposed by Fig. 2.

Fig. 2. Photograph of DLR ground station Weilheim, Germany, showing a varity of communication antennas and the location of the experimental IoSiS radar system.

The design using two separately mounted Rx antennas allows a two-channel operation for different polarization settings, and especially provides a high isolation between Tx and Rx paths. The two Rx antennas have a size of 1 m and 1.8 m diameter. 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 initialized for a measurement of a passing space object.

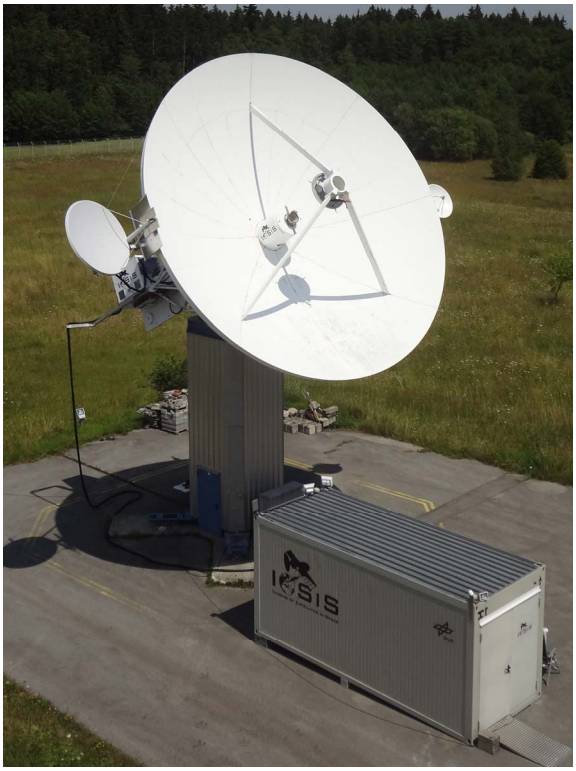

Fig. 3. Steearable multi-dish antenna system of IoSiS, using a 9 m Cassegrain antenna for Tx, and a 1 m and a 1.8 m direct fed antenna for Rx. The container is housing of relevant radar and control electronics and provides room for the operators.

Fig 4 shows a sketch of the principal imaging geometry. 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 ranges. As related burden, the satellite path has to be known very precisely for a large angle range in order to provide proper antenna alignment during the whole intended record of the pass. This requirement turns out to be a huge challenge if no auto-tracking is available. Due to finite accuracy in required orbit prediction, a deviation of the real position has to be expected in all three spatial directions, and especially in time of being on a certain position. The largest observed deviation appears in that time estimate, i.e. in flight direction. Later in that paper it is shown, how the, by wrong time prediction, produced position error in flight direction can be determined and corrected, based on an additional radar measurement.

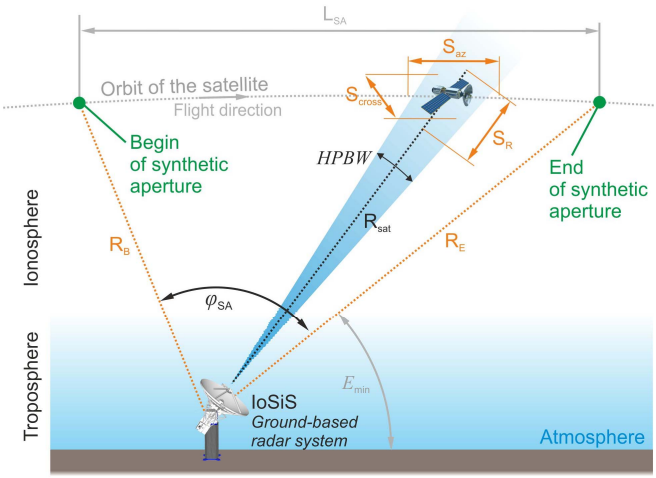

Fig. 4. Satellite imaging geometry with a ground-based pulse radar system and a steerable antenna following the satellite on its orbit path in order to acquire high resolved range profiles over a large azimuth integration angle.

In present implementation of the IoSiS system the DLR multi-purpose advanced X band radar system GigaRad is used. 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 [2]. The Rx antennas are connected via low-noise amplification and coaxial cabling to both Rx channels of GigaRad. Fig. 5 shows basic system parameters of IoSiS radar as used for ISAR imaging operation. Here the bandwidth is the maximum possible instantaneous bandwidth allowing range resolutions up to 3.4 cm.

IoSiS basic parameters	
Type	Pulse radar
Frequency band	X band
Center frequency	10.2 GHz
Bandwidth	≤ 4.4 GHz
Tx signal	Chirp
Pulse length	≤ 50 µs
Pulse repetition frequency	≤ 200 Hz

Fig. 5. Basic parameters of the IoSiS radar system for ISAR imaging of space objects.

III. DATA PROCESSING

The range profiles are recorded in time domain for full bandwidth. Now, in order to get a well-focused ISAR image, a couple of subsequent signal processing steps have to be carried out as indicated in Fig. 6. Due to the large range migration of a passing satellite, the receive window of length 5 km has to be shifted successively to the actual distance to the satellite. In this way, a large range area can be covered with a small receive window leading to considerably reduced amount of sampled data. During a regular satellite pass roughly 130 receive windows are required considering an overlap of 1.5 km for two adjacent windows. Hence the first processing steps are the allocation of the pulses to its receive window and a basic range correction. Based on meteorological parameters the influence of the troposphere, leading to a frequency independent range error, and the ionosphere, leading to a frequency dependent range error, are approximatively compensated. Considering nearly circular orbits (Eccentricity≈0) at orbital altitudes between 400 km and 1500 km above the earth surface, the corresponding orbital velocities are between about 7.67 km/s and 7.15 km/s [6]. These high orbital speeds result in a considerable Doppler shift and hence produce a significant range cell migration, resulting in defocusing of the range profiles in high-resolution radar if not compensated. However, by mitigating the known Doppler shift this degrading effect is compensated. Considering that the Doppler shift is frequency dependent the Doppler shift has to be computed and considered for each single frequency in the signal spectrum of IoSiS.

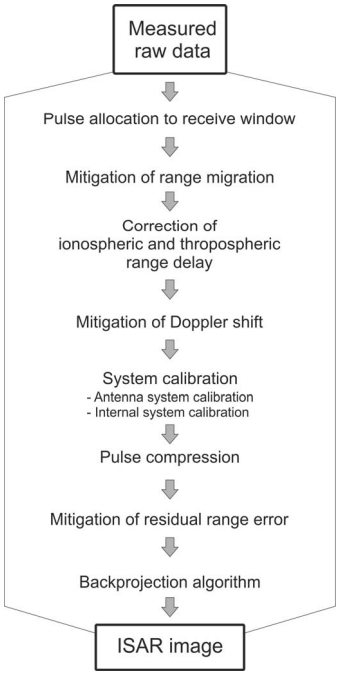

Fig. 6. Signal processing steps for the IoSiS basic ISAR processor.

Next the non-ideal frequency transfer function of the whole radar system is compensated in two steps. First this is done for Tx and Rx antennas by using calibration measurements of a reference target like a trihedral reflector of well-known response. Then the transfer function of the radar electronics itself is corrected using a special calibration procedure. This procedure is carried out shortly before and after each ISAR measurement using a well-known line segment as calibration path. Since for the Tx signal usually a linearly frequency-modulated pulse (LFM chirp) is used, the next processing step is a pulse compression, focusing the range profiles in range direction.

However, at the end of previous processing procedure still a range migration can be identified. This range error mainly is caused by residual errors of orbit prediction and still can be in the order of several hundred meters. Up to now IoSiS do not have the possibility of auto track a space object, with the result that the knowledge of the satellite paths is crucial to obtain the trajectory information required for the ISAR processing. Presently the necessary orbit predictions are performed using publicly available Two-Line-Element (TLE) data, which only allow predictions within a specific accuracy. In addition, small part of the residual range error can also be caused by limited compensation of atmospheric range delay. As a consequence an additional mitigation of the residual range error has to be accomplished. This is done by extracting now a robust point target in the focused range profiles, which can be extracted over a sufficiently wide range of azimuth angles. Now a first linear range correction is carried out and afterwards, if necessary, in addition a quadratic correction is applied. It is foreseen that this residual range error will be mitigated by a dedicated autofocus algorithm. Finally for ISAR processing a backprojection algorithm [5] is applied.

As mentioned earlier, a position error in flight direction is often present due to inaccurate time-of-arrival prediction, when TLE datasets have to be used. Hence, prior to the imaging measurement, the position error or the equivalent time offset in flight direction have to be determined. In case of the ISS as the target, this can be done using two subsequent orbital passes as illustrated in Fig. 7. The first pass now 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.

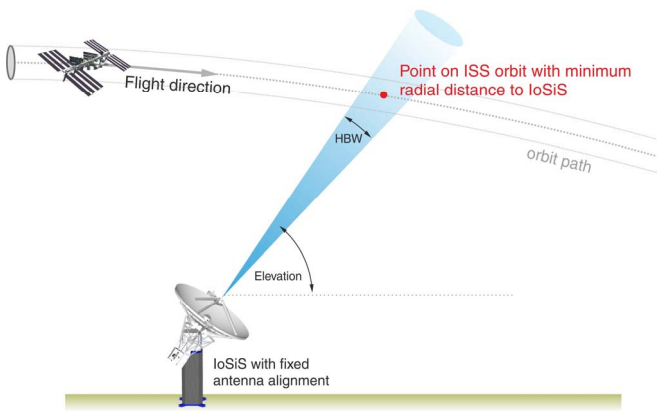

Fig. 7. Measurement geometry for a fixed antenna alignment as used for the determination of the precise time of arrival in case of the ISS as target of interest.

For the time offset determination the antenna is aligned to that orbit point where the ISS has the nearest distance to the IoSiS system. A corresponding measurement result is illustrated in Fig.8. Since the range migration is not compensated here, 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. However, the corresponding range offset is always small, considering the used 5 km length of the receive window.

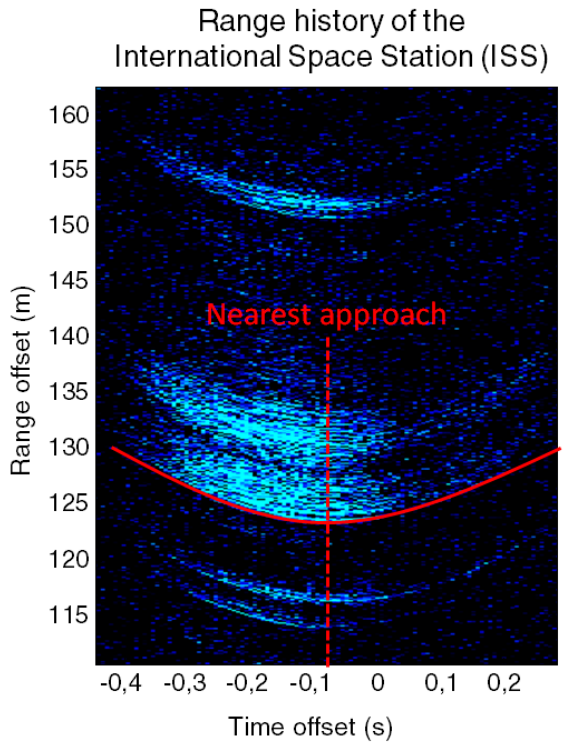

Fig. 8. Measured evolution of subsequent range profiles of the ISS using a fixed antenna alignment as depicted in Fig. 7.

IV. ISAR Measurement Result

In the commissioning phase first ISAR images with a reduced resolution have been gathered. The ISAR image of the ISS by processing 900 range profiles of 400 MHz bandwidth and using the backprojection algorithm is shown in Fig. 9. Here the 1.8 m receive antenna was used. The number of range profiles corresponds to a width in azimuth angle of about 4 degrees, leading to the spatial azimuth resolution of about 20 cm at X band. 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. 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, especially when the image is compared to an optical counterpart.

V. Conclusion

The number of operating satellites orbiting the earth today is already quite high and will increase at increasing rate in near future. 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. 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.

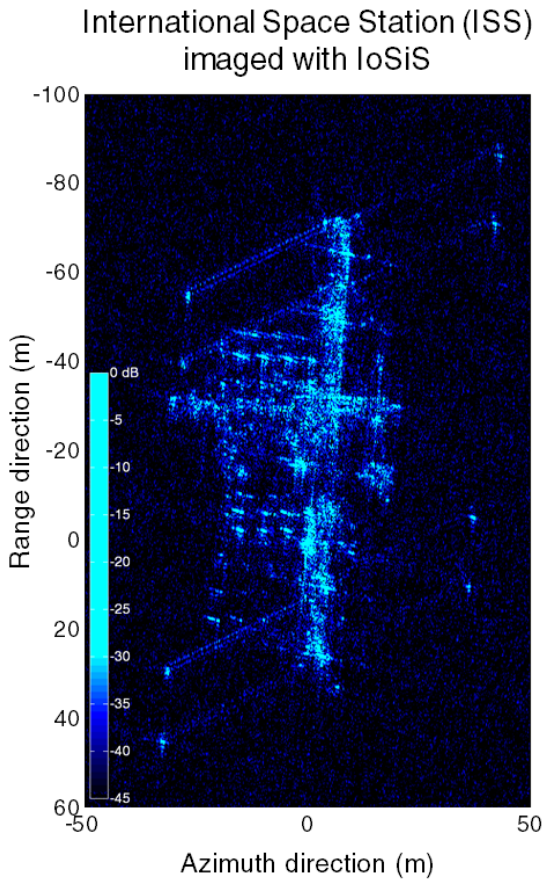

Fig. 9. ISAR image of the ISS measured by the IoSiS system. The spatial resolution is about 40 cm in range direction and about 20 cm in azimuth direction.

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