Multi-channel imaging of space objects

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Abstract

The heavily increasing number of satellites within the New Space era necessitates much more efficient and considerably improved space surveillance. Imaging radar systems make significant contributions towards providing updated knowledge of the situation in space. Based on the IoSiS (Imaging of Satellites in Space) system, DLR is researching new concepts for radar-based imaging of space objects. Following the basic intention of IoSiS, the objective has been to build up a multi-channel imaging radar that can facilitate the exploration of novel imaging concepts for highest-performance space target imaging purposes. This paper presents the current experimental findings based on a dual-channel image of the International Space Station (ISS). The investigation of image quality parameters demonstrates the technical capability of an intended forthcoming multi-channel imaging radar system. This system will have the potential to produce high-resolution images of spatial targets with completely new functionality.

1 Introduction

The enormous number of new satellites in orbit and the future trend towards mega-constellations with thousands of satellites have led to massive efforts in the field of high-performance space surveillance [1] [2]. On one hand that is developing or improving powerful tracking radars or, on the other hand researching radar systems that can take high-resolution images of space targets. Tracking radars are a well-known instrument for precisely determining the orbit of objects or detecting still unknown space debris. Imaging radars are capable of resolving the target in an image using a large bandwidth together with the technique of inverse synthetic aperture radar (ISAR). In addition to several thousands of satellites, there exist millions of fragments of varying sizes that orbit the Earth, which are commonly known as space debris. Such debris can range from decommissioned satellites, burnt-out upper stages of rockets, lost parts, chipped paint, to debris resulting from upper stages or satellites exploding. With the increasing number of new and decommissioned satellites and the vast quantity of space debris, it is likely that collisions will significantly increase in the future. As a consequence, satellites cannot only be partially damaged by space debris, but also completely destroyed. Here, high-resolution imaging radar can help to accurately assess the satellite from the ground.

The Microwaves and Radar Institute of the German Aerospace Center (DLR) is conducting research on advanced concepts using the experimental satellite imaging radar IoSiS in order to improve considerably the future imaging capabilities of space targets [3]. The primary objective of this system is to explore approaches for acquiring high-resolution radar images of objects in a low Earth orbit (LEO). In contrast to current radar-based space target imaging systems that have monostatic antenna configurations, IoSiS will employ multiple spatially distributed antennas in the future to improve further considerably the quality and information content of radar images, simplifying the status assessment of space objects and improving its reliability. Additionally, this approach will facilitate bistatic and three-dimensional imaging geometries, thereby improving above mentioned information content of radar-based satellite images compared to existing monostatic images.

Having these future multi-static capabilities in mind, IoSiS was already designed as a multi-channel system using one transmit and two receive channels. Multi-static imaging based on synthetic aperture radar (SAR) technology is already used or at least explored in various application areas such as satellite-based Earth observation or drone-based near-range measurements [4][5]. However, IoSiS is the first instrument to apply this concept in the field of space target imaging. Consequently, the presented work is discussing a dual-channel measurement of a real space target. This allows the investigation of different image quality parameters and processing steps such as channel coherence or coregistration procedures, both being important in multi-channel measurements.

2 The multi-channel system IoSiS

The fundamental objective of IoSiS has been to produce a multi-channel imaging radar that can facilitate the exploration of novel imaging concepts for novel high-performance space target imaging purposes. In addition to conducting fundamental investigations into multi-channel measurements over very long range, the experimental setup will facilitate exploration of areas of research such as bistatic or interferometric imaging in the near future. To date, practical implementation of multi-channel imaging for space targets has not been realized. However, as is typical with other applications utilizing multi-channel or bistatic imaging, the advantages are evidently apparent.

Bistatic radars have the ability to detect scattering that a monostatic configuration cannot do. Using a limited number of transmitters (at least one) and a vast number of receivers, the collective images captured create a more comprehensive and complete representation of the target of interest. Furthermore, increasing the quantity of receivers will decrease the cost for an individual receiver module, advancing system performance versus cost per module. Furthermore, from a military point of view, the receivers are passive components and therefore cannot be detected by radio reconnaissance Finally, these systems possess a counter stealth ability due to the fact, that reshaping targets to minimize their monostatic radar cross section (RCS) typically has little effect on their bistatic or multi-static RCS.

Figure 1 depicts IoSiS's experimental radar configuration. A reflector antenna of 9 m diameter is used for transmission, along with two offset parabolic reflectors of 1.8 m diameter for receive, all together mounted on a single pedestal. The pointing alignment among all three antennas is achieved through the use of geostationary satellites that broadcast a television signal in X band. Operating all three antennas in receive mode allows precise alignment by aligning the pedestal to the intended orbital position of the television satellite and finetuning the pointing for maximum receive power level. As multiple geostationary satellites transmit in the X band, antenna alignment can be verified under mobile conditions by moving the antenna along the azimuth and elevation profile corresponding to the geostationary orbit. Based on the fixed positions of such satellites, this measurement yields a receive power profile for all three antennas over time. It should be mentioned again that in this verification measurement the large antenna is operated in receive mode. By superimposing the received power profiles, one can ascertain whether the antennas are properly aligned.

Further challenges must be addressed in realizing a multichannel and subsequently a bistatic imaging system. Accurate synchronization between the transmitter and all receivers is crucial. Both, phase synchronization and precise time synchronization for accurately timing of pulse transmission and reception are critical. In the current experiment, IoSiS implements one transmitting channel and two receiving channels in a quasi-monostatic antenna configuration on the pedestal. As the transmitting and receiving electronics are located together in a nearby container, synchronization of the system is easily attained through a single local oscillator and a further GPS-controlled oscillator that provides digital interlock signals.

The illustration in **Figure 2** depicts a simplified block diagram of the IoSiS radar system architecture with fully digital signal generation and acquisition. The digital signal generation is realized by an Arbitrary Waveform Generator (AWG) with a sample rate of 10 GS/s. The receive signal digitizers are realized by two high-speed digital-to-analog converters allowing a maximum sampling rate of up to 10 GS/s. Both the transmit and receive signals are realized in full bandwidth in the time domain in this way. More recently, extensive theoretical and experimental research has begun on various synchronization methods for

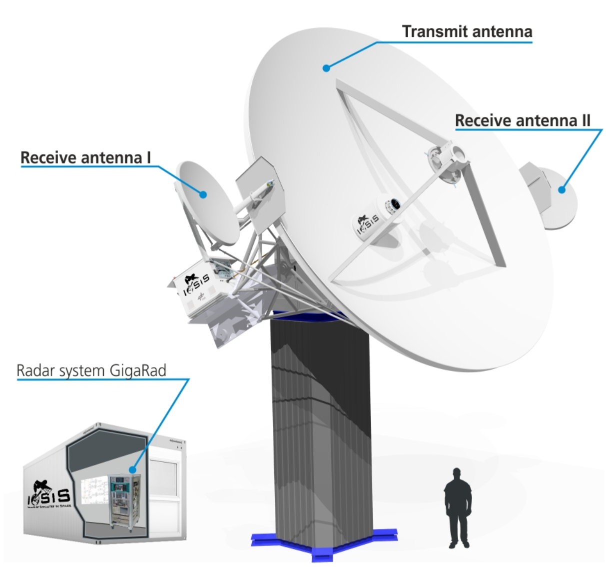


Figure 1 Experimental setup of the satellite imaging radar IoSiS with a 9 m transmit antenna and two 1.8 m receive antennas.

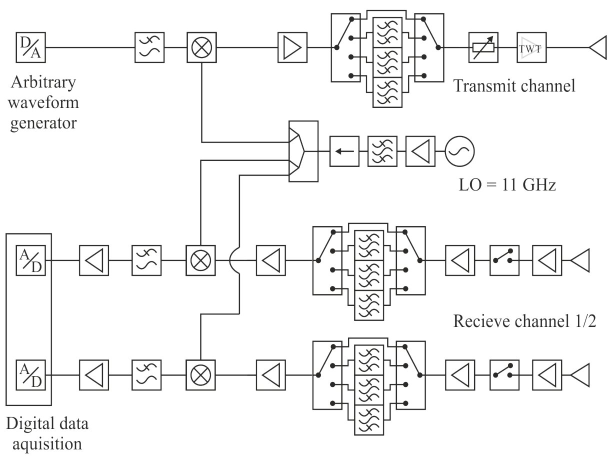
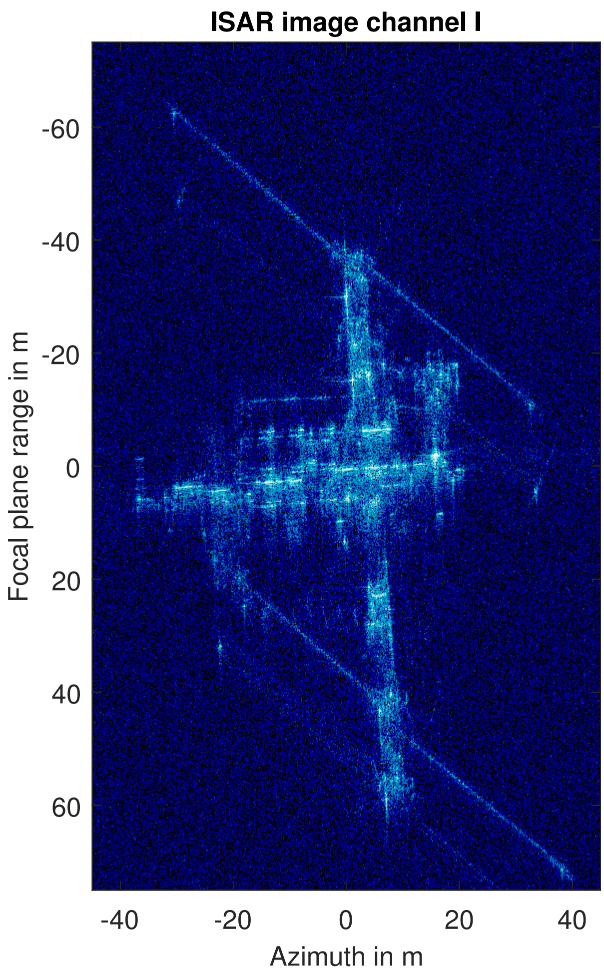


Figure 2 Simplified block diagram of the IoSiS radar system architecture with one transmit and two receive channels.

Table 1 Image parameters for single channel measurement and the incoherent and coherent summation of both channels.

	Polarisation	Entropy	Noise level [dBc]
Channel I	HH	6.45	-52.18
Channel II	HH	6.45	-52.76
Coherent $\sum$	-	6.39	-55.42
Incoherent $\sum$	-	6.47	-52.46

long baseline measurements using the IoSiS system. These methods encompass baselines ranging from several hundred meters up to several kilometers.



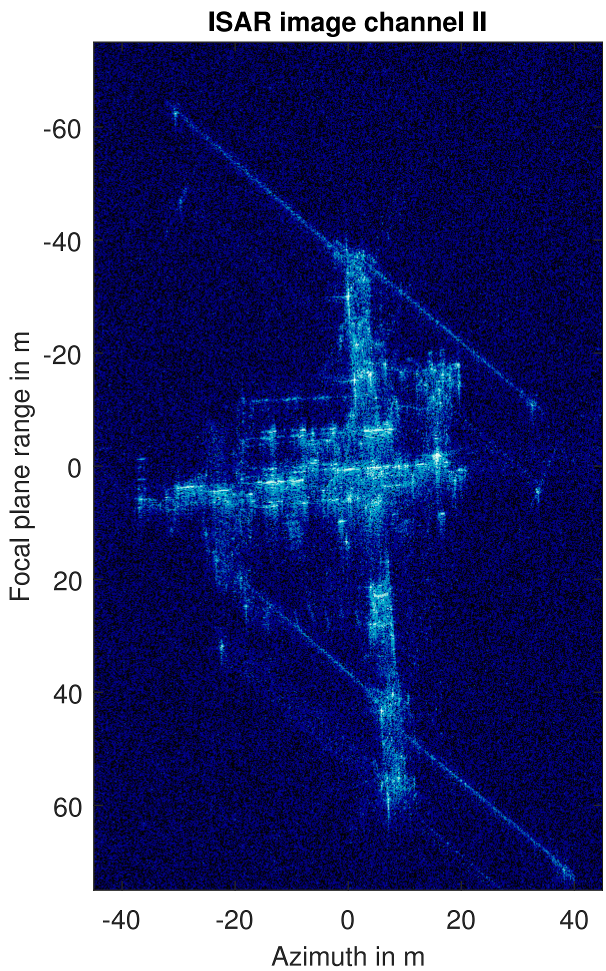


Figure 3 ISAR image of the ISS taken with channel I of the IoSiS instrument.

Figure 4 ISAR image of the ISS taken with channel II of the IoSiS instrument.

3 Experimental measurement results

In order to basically demonstrate the multi-channel measurement capability, results of a real space object using one transmit and two receive channels are presented in this paper. **Figure 3** and **Figure 4** show the ISAR images of the ISS for channel I and channel II, respectively. All images are normalized to their respective maximum and displayed with a dynamic range of 50 dB . Both images have been recorded with horizontal polarization (HH), a radar system bandwidth of 2.8 GHz and an azimuth integration angle of 10° for the synthetic aperture. The corresponding spatial resolution is approximately 6 cm in range direction and 8 cm in azimuth direction. A linearly frequency modulated chirp of pulse length 45 µs and a pulse repetition frequency of 190 Hz were used for the transmit signal. The radar images show the expected extensive and quite complex backscatter features of the ISS, extending across the truss segment and the central area where various attached modules are located. Because of the very high resolution, the grid structure supporting the large solar panels is clearly visible . The panels themselves cannot be seen because they were not oriented at right angles with respect to the line of sight during the assessment. **Table 1** shows some image quality parameters for more quantitative assessment. Both channels exhibit a very similar behavior, with a noise power level of -52.2 dB in channel I and -52.8 dB in channel II . The slight variation may be attributed to a marginally distinct system noise temperature of the two receiving channels and other slight differences in receiver hardware. The noise temperature is largely determined by the low-noise amplifier situated immediately after the antennas.

Figure 5 and **Figure 6** depict a superposition of both channels. For the incoherent superposition on the left, the absolute power amplitude values (non-complex) of both channels are just added pixel-by-pixel. It is evident that the absolute noise power level does not decrease in comparison to the single channel images. See **Table 1**. The noise level is the average value of the noise levels of the single images, hence resulting in -52.5 dB. As expected, the incoherent superposition does not produce any improvement of the signal-to-noise ratio (SNR). However, the expected increase in SNR is obtained with coherent superposition. Now, the complex amplitude values, which contain the phase information for each pixel, are summed up. Theoretically, an improvement of a factor of two is ex-

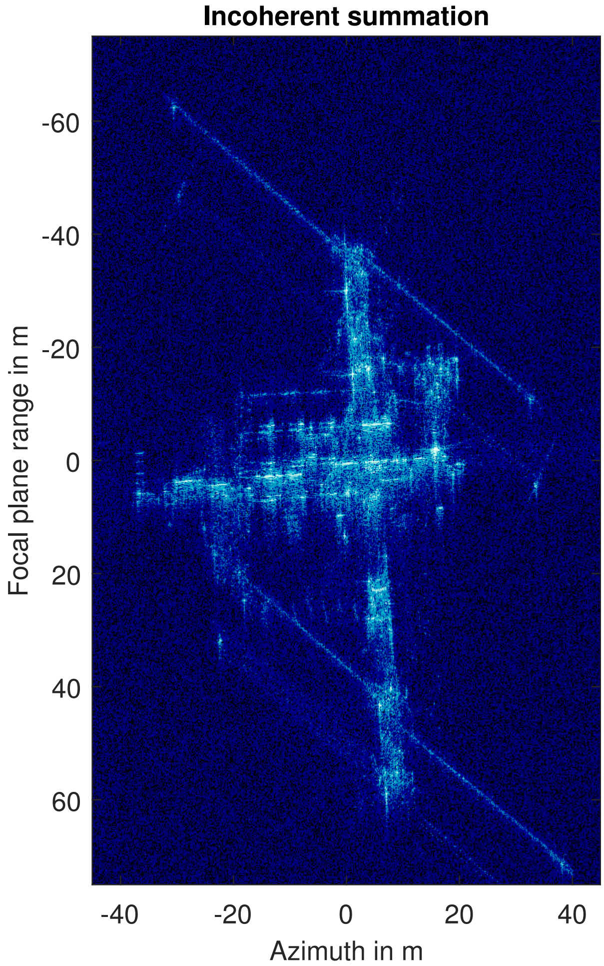


Figure 5 Incoherent superposition of the single channel images.

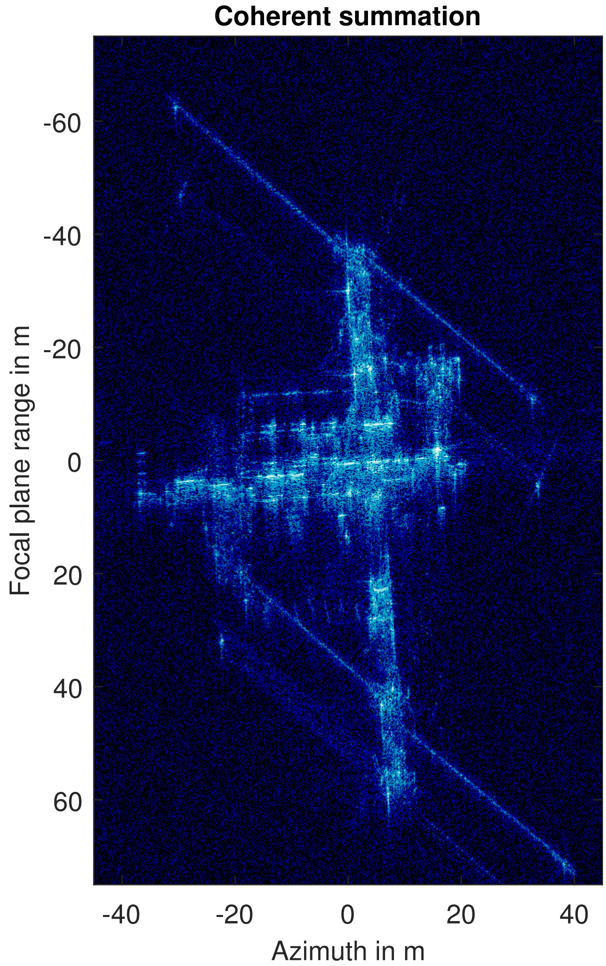


Figure 6 Coherent superposition of the single channel images.

pected, which is equivalent to about 3 dB on the logarithmic scale. **Table 1** shows that the noise level is reduced by about 2.7 dB compared to the average of the individual images. Now, the reduction in image noise causes a noticeable darkening of the background by increasing the dynamic range. Also, the reduction in entropy, as a measure for disorder, resulting from coherent summation demonstrates the improvement in image quality.

Up to this point, IoSiS has employed both receive channels to enhance SNR through coherent merging of both images. These results also confirm that sufficient coherence between the two channels is realized and hence demonstrate the technical feasibility of a future multi-channel imaging system capable of producing a series of independent but coherent very high-resolution images of space objects for much more advanced processing. In bi-static configurations can be achieved by spatially separating one of the receiving antennas from the pedestal, thus enabling interferometric measurements, provided that long-distance synchronization as mentioned above is achieved.

4 Conclusion

This paper presents for the first time the results of experimental multi-channel measurements of a space target. The measurements were carried out using IoSiS, an experimental radar system of DLR. The findings demonstrate the coherent operation of one transmitting and two receiving channels, as shown by the coherent superposition of two corresponding independent ISAR images, indicating an SNR increase being almost equivalent to the theoretical value of 3 dB. This demonstrates the technical feasibility of a forthcoming imaging system, that can generate high-quality images of space objects with multiple receiver channels. However, proper synchronization of all subsystems is mandatory.

5 Literature

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