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GUEST EDITORIAL

Guest Editorial: Radar systems and processing methods for space situational awareness

Satellites and the services they provide are indispensable to our society: Communication, Navigation, Remote Sensing, Surveillance, and Reconnaissance—all of these applications benefit significantly from the support of an ever-growing network of ubiquitous sub-systems in orbit. Although space seems almost infinite and the population comparatively small, increasingly frequent orbital overlaps, conjunctions and sometimes even collisions clearly show us how vulnerable this environment is. Due to the increasing number of satellites and the associated increase in space debris (e.g. man-made remnants of rocket launches, defective payloads, or their fragments) and the growing threat of attacks in military conflicts, protecting this critical infrastructure is becoming an increasingly important task.

Space situational awareness (SSA) is the ability to monitor activities, objects, and events in outer space. It involves detecting, imaging, tracking, and analysing the positions, trajectories, and characteristics of satellites, space debris, and other objects in space. Due to the laws of physics, the precise assessment and cataloguing of such data also allows for a look into the future and can predict the position of objects over an extended period. Thus, one main purpose of SSA is to enhance the safety, security, and sustainability of space activities by providing essential information, for example, on potential collisions and on the purpose of satellites.

Among the various sensors used for SSA, radar sensors hold a particularly important position. The primary advantages of radars in this context are that they do not need an external source of illumination, can detect the smallest debris over long ranges, accurately track objects even against the bright daylight sky and actively measure the distance as well as target motion. Imaging radars using inverse synthetic aperture radar (ISAR) techniques can provide a high-resolution image of an object and reconstruct a three-dimensional representation of its shape and features using either a bistatic, multistatic or radargrammetric system configuration.

In this first Special Issue of *IET Radar, Sonar and Navigation* on 'Radar Systems and Processing Methods for SSA', we are presenting eight articles covering the following topics.

1 | TOPIC A—GROUND-BASED AND SPACE-BASED RADAR FOR SSA

The paper, 'High-resolution ISAR imaging of satellites in space' by S. Anger, M. Jirousek, et al., comprehensively illustrates the technological steps for the construction and successful operation of advanced radar-based space surveillance. Besides the basic description of the experimental system design based on pulse radar technology, this paper outlines a useful theory for ISAR imaging of objects in space, together with relevant imaging parameters, calibration and error correction. All relevant processing steps, necessary for very high-resolution imaging of satellites in practice, are introduced and verified by simulation as well as measurement results.

An important aspect of SSA is to estimate the intent of objects in space. The paper, 'Recognition of Objects in Orbit and their Intentions with Space-Borne sub-THz ISAR' by M. Cherniakov, E. G. Hoare, et al., discusses how discriminating features can be obtained from ISAR images of such objects and how these discriminators can be used to recognise the objects or to estimate their intent. The focus is on imagery obtained in the subterahertz band because of the greater imaging capability given by the diffuse scattering which is observed at these frequencies. The paper also discusses the importance of using images obtained by electromagnetic simulation to be able to train the sub-system, which recognises features of the objects and describes a practical scheme for creating these simulations for large objects at these very short wavelengths.

2 | TOPIC B—MULTISTATIC RADAR NETWORKS FOR SSA

The paper, 'GLRT-based Compressive Subspace Detectors in Single-Frequency Multistatic Passive Radar Systems' by J. Ma, J. Zhao, et al., studies the problem of compressive target detection in a single-frequency network (SFN)-based multistatic passive radar system consisting of multiple illuminators of opportunity and one receiver. A generalised likelihood ratio test SFN-based compressive subspace detector is derived by exploiting the sparsity of the target echoes for the case of known noise variance. The theoretical analysis and efficacy of the proposed method is validated via numerical simulations, and the performance of the proposed detector is illustrated relative to several benchmark detectors.

While several radar systems have been designed to detect space objects, only a few of them have dealt with long baseline distributed bistatic pairs. The paper, 'Performance analysis of ground-based long baseline radar distributed systems for SSA' by S. Diaz Riofrio, S. Da Graca Marto, et al., focuses on the feasibility of long baseline bistatic radars (LBBRs), which can be extended for the multistatic case. The performance of a multistatic system is evaluated for a target at different altitudes assuming one transmitter over three different scenarios: a cluster of receivers, receivers spatially distributed throughout the world and the combination of the two previous cases.

The paper, 'LBBR Imaging of Tumbling Space Objects for Enhancing Space Domain Awareness' by A. Serrano, A. Kobsa, et al., describes long baseline bistatic measurements using radar transmitters and receivers in several countries and experiments conducted in the scope of a Research Task Group formed by the NATO Science and Technology Organisation. Novel bistatic and monostatic radar imaging experiments with real on-orbit tumbling rocket bodies are performed at near-GEO orbits, highlighting successful demonstrations of advanced bistatic Doppler characterisation across diverse imaging geometries.

The article, 'Characterisation of resident space objects using multistatic interferometric ISAR imaging' by M. T. Rudrappa, M. Albrecht, et al., describes the mathematical model of multistatic three-dimensional interferometric reconstruction and rotation rate estimation irrespective of the baseline sensor system geometry. A database of interferometric point clouds at varying aspect angles is constructed, and novel rotation-invariant shape-based features are derived for classification purposes. Different classification methods are applied, and comparative analysis results are presented.

3 | TOPIC C—COGNITIVE RADAR AND DEEP-LEARNING METHODS FOR SSA

While SSA is typically addressed by an ensemble of radar and radio-telescopes that detect and track space objects, a large proportion of space debris is composed of very small objects which are very difficult to detect. In the paper, 'Deep Learning-based Space Debris Detection for SSA: a feasibility study applied to the radar processing' by F. Massimi, P. Ferrara, et al., the benefits of using deep learning architectures for small space object detection by radar observations are investigated. Range-Doppler maps generated from radar simulations are used as inputs for object detection based on the *You-Only-Look-Once* (YOLO) framework. Analysis results demonstrate that object detection using YOLO algorithms outperform conventional target detection approaches, thus highlighting the potential benefits of using deep learning techniques for space surveillance applications.

In the study, 'Few-shot Learning for Satellite Characterisation from Synthetic ISAR Images' by F. G. Heslinga, F. Uysal, et al., a framework addressing the scarcity of representative ISAR data through synthetic learning is presented. The approach utilises a few-shot domain adaptation technique, leveraging thousands of rapidly simulated low-fidelity ISAR images, and a small set of ISAR images from the target domain. The results are validated by simulating a real-case scenario, fine-tuning a deep learning-based segmentation model, and demonstrating the effectiveness of the proposed framework.

4 | SUMMARY/CONCLUSION

The editors are pleased to be able to provide the radar community with an extensive overview of current developments in the field of 'Radar Systems and Processing Methods for SSA' with this first Special Issue. We hope you enjoy reading!

KEYWORDS
multistatic radar, radar detection, radar imaging, space debris, spaceborne radar

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DATA AVAILABILITY STATEMENT

There is no relevant data included in the editorial.

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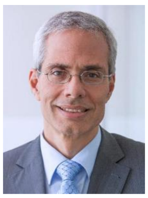
Prof. Dr. Peter Knott has received the Diploma and Ph.D. degree from RWTH Aachen University, Germany, in 1994 and 2003, respectively. In 1994, he joined the Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR (formerly FGAN e.V.) in Wachtberg, Germany. From 2005 until 2016, he was head of the Department of Antenna Technology and Electromagnetic Modelling (AEM), where the focus of his work was the design and development of antenna arrays and active antenna front-ends as well as electromagnetic modelling and beamforming methods for conformal antenna arrays. Since 2016, he is the Executive Director of the institute Fraunhofer FHR. He is currently holding a professorship of Radar Systems Engineering at RWTH Aachen University and a lecturer at different other organisations. He was Co-Chair of the 14th European Radar Conference (EuRAD) in Nuremberg in 2017 and Chair of the International Radar Symposium (IRS) from 2018 to 2023. From 2014 to 2019, he was also Chairman of the Executive Committee of the IEEE MTT/AP Joint Chapter, Chairman of the VDE/ITG Technical Committee HF4 'Localisation' and a member of the Scientific Advisory Board of the German Society for Localisation and Navigation (DGON) e.V. As part of his scientific activities, Prof. Knott has published numerous papers in scientific journals and at conferences, including several patents. He is also currently an expert for AESA Radar on the Sensors and Electronics Technology (SET) Panels of the NATO Science and Technology Organisation (STO) and a member of the Brussels Advisory Board of the German Defence Technology Society (DWT).



Prof. Alberto Moreira is the Director of the Microwaves and Radar Institute at the German Aerospace Centre (DLR) and a Full Professor with the Karlsruhe Institute of Technology (KIT), Germany, in the field of microwave remote sensing. He has been contributing to the advancement of Synthetic Aperture Radar (SAR) systems with innovative concepts, technologies and associated signal processing for more than 35 years. Today, his DLR Institute contributes to several scientific programmes and projects for spaceborne SAR missions such as TerraSAR-X, TanDEM-X, SAR-Lupe and SARah, Sentinel-1, BIOMASS, ROSE-L, Harmony, Sentinel-1NG, Kompsat-6, PAZ, EnVision and VERITAS. The TanDEM-X mission, led by his Institute, is the first bistatic spaceborne SAR system consisting of two satellites flying in close formation and has generated a global, high-resolution digital elevation model of the Earth with unprecedented accuracy. Prof. Moreira is the initiator and Principal Investigator (PI) of this mission. He has authored or co-authored more than 500 publications in international conferences and journals, 8 book chapters and holds more than 45 patents. He is an IEEE Fellow and has served as President of the IEEE Geoscience and Remote Sensing Society (GRSS) in 2010. Prof. Moreira is the recipient of several international awards including the IEEE AESS Fred Nathanson Award (1999), the IEEE Kiyo Tomiyasu Technical Field Award (2007), the IEEE W. R.G. Baker Award from the IEEE Board of Directors (2012), the IEEE GRSS Distinguished Achievement Award (2014) and the IEEE Dennis J. Picard Medal for Radar Technologies and Applications (2023). His professional interests and research areas encompass end-to-end spaceborne radar system design, microwave techniques and system concepts, signal processing, and remote sensing applications.

Dr. Braham Himed received the Engineer Degree in Electrical Engineering from Ecole Nationale Polytechnique of Algiers, Algeria in 1984, and his M.S. and Ph.D. degrees both in Electrical Engineering, from Syracuse University, Syracuse, NY, in 1987 and 1990, respectively. Dr. Himed is a Division Research Fellow with the Air Force Research Laboratory, Sensors Directorate, Multi-Spectral Sensing and Detection Division, Distributed RF Sensing Branch, in Dayton Ohio, where he is involved with several aspects of radar developments. His research includes detection and estimation, multichannel adaptive signal processing, array processing, adaptive processing, waveform diversity and design, distributed active/passive MIMO radar, and over the horizon radar. Dr. Himed is the recipient of the 2001 IEEE region I award for his work on bistatic radar systems, algorithm development, and phenomenology. He is a Fellow of IEEE (Class of 2007), a past-Chair of the IEEE AESS Radar Systems Panel, and a current AESS Board of Governors member, serving as VP of Conferences. He is the recipient of the 2012 IEEE Warren White award for excellence in radar engineering. Dr. Himed is also a Fellow of AFRL (Class of 2013).