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Editorial

Radar for Space Observation: Systems, Methods and Applications

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1. Context and Motivation

In today's world, where near-Earth space constitutes an increasingly congested and contested theater of economic, political, and military activities for the growing number of space-faring nations, the significance of actionable situational awareness cannot be overstated. The proliferation of objects in orbit results in an increased risk of collisions, requiring robust methods of debris detection and surveillance for the timely resolution of conjunctions. Radar systems, renowned for their versatility and precision, have emerged as indispensable tools for addressing these challenges. From tracking the trajectories of satellites and space debris to protect critical infrastructure, to imaging celestial bodies, they provide crucial data that underpin space domain awareness (SDA), space safety, and planetary defense. This Special Issue, titled "Radar for Space Observation: Systems, Methods and Applications", was established to serve as a platform for disseminating innovative research and fostering collaboration within this vital field, underscoring how cutting-edge radar technology contributes to safer, more effective operations in increasingly crowded orbits.

2. Overview of Contributions

Contributions to this Special Issue are divided into two thematic areas: Existing and Upcoming Radar Systems for Space Observation (Section 2.1) and Advanced Signal Processing, Models and Simulations (Section 2.2). In the following paragraphs, a brief overview of the contributions is given.

2.1. Existing and Upcoming Radar Systems for Space Observation

Very-high-frequency (VHF) wind profiling radars are a sensor class capable of observing resident space objects (RSOs) in low-Earth orbit. Holdsworth et al. [1] detail the use of the Buckland Park VHF radar for space surveillance. Their study, "Space Domain Awareness Observations Using the Buckland Park VHF Radar", presents a new beam scheduling and signal processing functionality of the radar system. The results reveal a three-fold increase in the detection rate over previous single-beam direction observations and the capability to detect objects in medium-Earth orbit. It is also shown that it is possible to investigate the rotational behavior of satellites and to monitor ionospheric plasma waves and instabilities.

In their contribution, "The Future of Radar Space Observation in Europe—Major Upgrade of the Tracking and Imaging Radar (TIRA)", Klare et al. [2] present the modernization effort centered around the TIRA system, a cornerstone of European space observation. This major upgrade will equip TIRA with advanced capabilities for detecting, tracking, and imaging objects in orbit. This work highlights the improvement of TIRA's tracking precision, its increased imaging resolution for monitoring the status and integrity of RSOs,

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and its enhanced data processing to address the challenges arising from the ever-growing space traffic. The article delves into the project's technical innovations and their critical role in supporting Europe's space sustainability initiatives.

Pandeirada et al. [3] present the recent progress of the ATLAS tracking radar, which is part of Portugal's contribution to EU SST (EU Space Surveillance and Tracking) and a promising test bed for space surveillance technologies. Their paper, titled "ATLAS: Latest Advancements and First, Observations", focuses on the activities of calibration of the pointing system and initial observations of RSOs. ATLAS aims to not only be a standalone radar system but rather a full-featured space surveillance and tracking ground station with the capacity to predict the orbit of RSOs, generate observing schedules, and maintain an internal objects' catalog.

Space-based radars for SDA have also been proposed and are the subject of ongoing research efforts by various space actors. In "Joint Power and Bandwidth Allocation with RCS Fluctuation Characteristic for Space Target Tracking", Yang et al. [4] present a method for optimal allocation of resources for a space-based radar aimed at tracking targets in orbit. The method takes into account the variability of the target's radar cross-section. This way, the power and the bandwidth required for an observation can be adjusted for optimal tracking accuracy.

This section is concluded with a fascinating review article, titled "Overview of High-Power and Wideband Radar Technology Development at MIT Lincoln Laboratory". Here, MacDonald et al. [5] present over 60 years of radar history and groundbreaking technology development at the MIT Lincoln Laboratory. This captivating review focuses on space observations from early research on satellite tracking and planetary radar to present capabilities for centimeter-resolution imaging of RSOs and future plans to extend this to the geosynchronous orbit domain.

2.2. Advanced Signal Processing, Models and Simulations

In "Inverse Synthetic Aperture Radar Imaging of Space Targets Using Wideband Pseudo-Noise Signals with Low Peak-to-Average Power Ratio", Anger et al. [6] investigate the application of pseudo-noise signals for imaging in the context of inverse synthetic aperture radar (ISAR) imaging of RSOs. The use of pseudo-noise signals provides several advantages, including a reduction in RF interference with other radar and communication systems operating within the same frequency band. Additionally, these signals facilitate the concurrent use of multiple channels and exhibit a low probability of intercept, thereby decreasing vulnerability to electronic support measures (ESM), electronic intelligence (ELINT) systems, and jamming. The paper details the implementation of pseudo-noise signals within the IoSiS radar system, developed by the Microwaves and Radar Institute of DLR.

The paper "The Radar Signal Processor of the First, Romanian Space Surveillance Radar" by Bîră et al. [7] focuses on the signal processing chain of the Cheia space surveillance radar. It offers an in-depth look at the signal processor's architecture, alongside a comprehensive review of state-of-the-art signal processing techniques for space radars. The study also includes a comparison between the signal processor's outputs and the results produced by benchmarking processing algorithms. This work represents a significant contribution to the field, providing valuable insights into the core radar processing functions of the Cheia radar, a highly capable space surveillance asset with substantial potential.

In their contribution "Micro-Doppler Signature Analysis for Space Domain Awareness Using VHF Radar", Heading et al. [8] characterize defunct satellites by analyzing their micro-Doppler signatures, which are linked to their rotational motion. They conducted this study using the Buckland Park Stratosphere–Troposphere VHF radar in South Australia.

Computational electromagnetic simulations were used to provide a basis for comparison with the observed radar data, helping to characterize three RSOs. By comparing the simulated and measured micro-Doppler signatures, they were able to estimate key parameters, such as spin axis, attitude, number of solar panels, rotation rate, and approximate size.

In "Range-Doppler-Time Tensor Processing for Deep-Space Satellite Characterization Using Narrowband Radar", Serrano et al. [9] address the challenge of characterizing satellites in geostationary orbit (geosynchronous equatorial orbit, GEO), a domain where existing wideband radars, typically used for low-Earth Orbit satellites, lack the sensitivity required for the long ranges involved (approximately 36,000 km or greater). The authors propose a novel range–Doppler–time (RDT) tensor processing technique tailored for GEO satellite characterization using a narrowband radar. This method generates fully-resolved two-dimensional images of rotating GEO satellites under low-bandwidth observational conditions. In scenarios where the change in the aspect angle is limited, the technique provides enhanced Doppler information, improving the monitoring of a satellite's status. The efficacy of the technique is evaluated using simulated radar data and radar data collected in a compact range on a scaled satellite model.

In the context of space-based SDA, Zheng et al. [10] explore a novel algorithm for tracking objects in orbit, from orbit. In their article, titled "Space Target Tracking with the HRRP Characteristic-Aided Filter via Space-Based Radar", they utilize high-resolution range profiles to improve the radar system's tracking performance. This approach is also put to the test, and its performance is evaluated.

Radars play a significant role in the observation of planetary bodies and asteroids. The contribution by Anne Virkki [11], "Numerical Evaluation of Planetary Radar Backscatter Models for Self-Affine Fractal Surfaces", presents a valuable collection of open source Python codes for generating self-affine fractal surfaces and evaluating radar scattering laws, thus offering a versatile tool for researchers in remote sensing, electromagnetic simulations, and material sciences. The synthetic surfaces successfully reproduce measured rms slopes for natural terrains, reinforcing the model's validity. Key findings include the confirmation of the Gaussian law as an optimal scattering model for surfaces with rms slope angles up to 40°, along with insights into the role of roll-off length in surface roughness characteristics. Additionally, the article highlights the impact of multiple scattering on backscattered power and identifies key challenges in modeling wavelength-scale interactions on complex surfaces. By providing a computational framework for analyzing radar scattering, this work paves the way for future advancements in planetary and terrestrial surface characterization.

3. Knowledge Gaps and Future Research Directions

Recent advances in radar technology for space observation have focused on broader coverage, improved tracking performance, higher-resolution imaging, and rudimentary integration with AI-driven data analysis. Nonetheless, challenges persist, notably in the areas of real-time data fusion, autonomous tracking of RSOs, and radar-assisted space debris removal. Although this Special Issue has addressed several key topics, open questions remain. Among other directions, future research should explore the following:

- **AI-enhanced radar techniques:** Leveraging the full potential of AI to improve automation, increase efficiency, and enhance the characterization of RSOs.
- **Distributed sensor networks:** Strengthening international cooperation in space surveillance to achieve comprehensive coverage and multisensor data fusion.
- **Radar-driven investigation of critical size regimes:** Developing systems that can peer into the critical size regime of $\leqslant$10 cm, where cubesats and space debris proliferate and will continue to do so.

- **Radars as enablers of efficient space traffic management (STM):** Advancing the use of ground- and space-based radar technology and methods towards efficient, operational STM.
- **Radar-assisted space sustainability:** Investigating debris mitigation strategies and active removal technologies supported by radar monitoring.

4. Concluding Remarks

Surveillance of the near-Earth space environment is undergoing a profound transformation, driven by the increasing importance of monitoring space assets and debris in orbit. This Special Issue demonstrates the remarkable progress in radar technology applied to space observations and the vital role radar systems play in ensuring the sustainable and safe use of space. I am confident that the insights and innovations presented here will inspire further research and collaboration, driving the field forward towards meeting current and future challenges.

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References

1. Holdsworth, D.A.; Spargo, A.J.; Reid, I.M.; Adami, C.L. Space Domain Awareness Observations Using the Buckland Park VHF Radar. *Remote Sens.* **2024**, *16*, 1252. [CrossRef]
2. Klare, J.; Behner, F.; Carloni, C.; Cerutti-Maori, D.; Fuhrmann, L.; Hoppenau, C.; Karamanavis, V.; Laubach, M.; Marek, A.; Perkuhn, R.; et al. The Future of Radar Space Observation in Europe—Major Upgrade of the Tracking and Imaging Radar (TIRA). *Remote Sens.* **2024**, *16*, 4197. [CrossRef]
3. Pandeirada, J.; Bergano, M.; Marques, P.; Coelho, B.; Barbosa, D.; Figueiredo, M. ATLAS: Latest Advancements and First Observations. *Remote Sens.* **2024**, *16*, 704. [CrossRef]
4. Yang, Q.; Jiang, L.; Zheng, S.; Zhao, Y.; Wang, Z. Joint Power and Bandwidth Allocation with RCS Fluctuation Characteristic for Space Target Tracking. *Remote Sens.* **2023**, *15*, 3971. [CrossRef]
5. MacDonald, M.; Abouzahra, M.; Stambaugh, J. Overview of High-Power and Wideband Radar Technology Development at MIT Lincoln Laboratory. *Remote Sens.* **2024**, *16*, 1530. [CrossRef]
6. Anger, S.; Jirousek, M.; Dill, S.; Peichl, M. Inverse Synthetic Aperture Radar Imaging of Space Targets Using Wideband Pseudo-Noise Signals with Low Peak-to-Average Power Ratio. *Remote Sens.* **2024**, *16*, 1809. [CrossRef]
7. Bîră, C.; Ionescu, L.; Rusu-Casandra, A. The Radar Signal Processor of the First Romanian Space Surveillance Radar. *Remote Sens.* **2023**, *15*, 3630. [CrossRef]
8. Heading, E.; Nguyen, S.T.; Holdsworth, D.; Reid, I.M. Micro-Doppler Signature Analysis for Space Domain Awareness Using VHF Radar. *Remote Sens.* **2024**, *16*, 1354. [CrossRef]
9. Serrano, A.; Capper, J.; Morrison, R.L.; Abouzahra, M.D. Range-Doppler-Time Tensor Processing for Deep-Space Satellite Characterization Using Narrowband Radar. *Remote Sens.* **2024**, *16*, 1374. [CrossRef]
10. Zheng, S.; Jiang, L.; Yang, Q.; Zhao, Y.; Wang, Z. Space Target Tracking with the HRRP Characteristic-Aided Filter via Space-Based Radar. *Remote Sens.* **2023**, *15*, 4808. [CrossRef]
11. Virkki, A. Numerical Evaluation of Planetary Radar Backscatter Models for Self-Affine Fractal Surfaces. *Remote Sens.* **2024**, *16*, 890. [CrossRef]

Short Biography of Author



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