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RESEARCH ARTICLE

OVERVIEW OF THIRD GENERATION SPACEBORNE X-BAND SYNTHETIC APERTURE RADAR (SAR)

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Abstract

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The deployment of advanced spaceborne Synthetic Aperture Radar (SAR)systems plays a crucial role in modern Intelligence, Surveillance, and Reconnaissance (ISR) operations, supporting military decision-making across strategic, operational, and tactical levels. This paper investigates engineering solutions for next generation high performance e X-band SAR instruments aimed at overcoming current limitations in resolution and swath width trade-offs.The proposed approach integrates innovative acquisition techniques, including Scan On Receive (SCORE), Multiple Azimuth Processing (MAP), and Digital Beam forming (DBF), enabling simultaneous improvement of geometric resolution and coverage area. The presented system concept targets a resolution of up to 1 m with a swath width of 50 km in Stripmap mode, significantly exceeding the capabilities of existing SAR missions.Performance analysis demonstrates achievable Noise Equivalent Sigma Zero (NESZ) values around -20 dB and Distributed Target Ambiguity Ratio (2D-DTAR)up to -18 dB over a wide range of incidence angles,highlighting enhanced image quality and reliability. The paper also outlines a modular instrument architecture composed of SAR Electronic and Antenna subsystems, designed to support advanced processing and multi-channel calibration.Although not exhaustive, the proposed solutions illustrate the potential impact of next-generation SAR technologies in improving Imagery Intelligence (IMINT) capabilities and expanding operational applications for national defence and security.

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Introduction:-

Spaceborne Synthetic Aperture Radar (SAR) systems represent a fundamental asset for military applications, particularly in the surveillance of border regions, the management of complex logistical operations in critical theatres, and the acquisition of intelligence related to national security. Contemporary defence frameworks rely heavily on the Intelligence, Surveillance and Reconnaissance (ISR) function, which is considered one of the core capabilities for building a comprehensive and accurate understanding of the operational environment. This function enables the collection and processing of relevant information, supporting decision-making processes at strategic, operational, and tactical levels. Within this context, SAR satellites play a crucial role, as they provide reliable and

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timely data that significantly enhance ISR effectiveness, ultimately contributing to the protection of military personnel, infrastructure, and assets deployed in operational scenarios.In this framework, the overall quality and usefulness of the information delivered to end users are strictly dependent on the performance of the SAR system, and in particular on the capabilities of its central component, namely the radar instrument itself. For this reason, ongoing research is increasingly focused on the development of next-generation SAR instruments capable of exceeding the current state of the art. This paper proposes several engineering solutions that can be considered in the design of such advanced systems, with the aim of improving imaging performance, enhancing the quality of intelligence and reconnaissance products, and expanding their range of operational applications in support of defence and security needs.

A key objective addressed in this work concerns the possibility of overcoming the existing limitations related to the trade-off between spatial resolution and swath width, which remains one of the main constraints in conventional SAR systems. In this regard, the paper presents an example of an X-band SAR configuration designed to achieve high-resolution imaging over extended coverage areas. The corresponding performance in terms of image quality is discussed to illustrate the potential benefits of the proposed approach. Although the presented solution is not intended to be exhaustive, it provides a meaningful indication of the significant impact that the proposed architectural innovations could have on future developments in Imagery Intelligence (IMINT) applications.

Instrument Design:-

Current spaceborne X-band SAR systems are capable of generating microwave imagery characterized by moderate geometric resolution, typically on the order of 3 meters, and a swath width of about 30 kilometers when operating in Stripmap mode. In addition to this standard acquisition configuration, such instruments provide alternative modes designed to enhance specific performance aspects: Spotlight modes allow for higher spatial resolution, while ScanSAR modes enable wider area coverage. However, these operational configurations are inherently subject to a trade-off, meaning that any improvement in resolution is generally achieved at the expense of swath width, and vice versa.In contrast, the requirements of modern remote sensing applications are becoming increasingly demanding, calling for a simultaneous enhancement of both spatial resolution and coverage area. Moreover, it is essential to complement these improvements with high radiometric and ambiguity performance, typically quantified through parameters such as Noise Equivalent Sigma Zero (NESZ) and Distributed Target Ambiguity Ratio (2D-DTAR). These metrics are crucial for ensuring high-quality and reliable SAR imagery, especially in complex observation scenarios.

Figure 1 illustrates the relationship between azimuth resolution and swath width for current SAR instruments, such as Cosmo-SkyMed Second Generation and TerraSAR-X, compared to the target performance envisioned for future third-generation systems. This comparison highlights the existing limitations of current technologies and underscores the need for innovative solutions capable of overcoming these constraints.

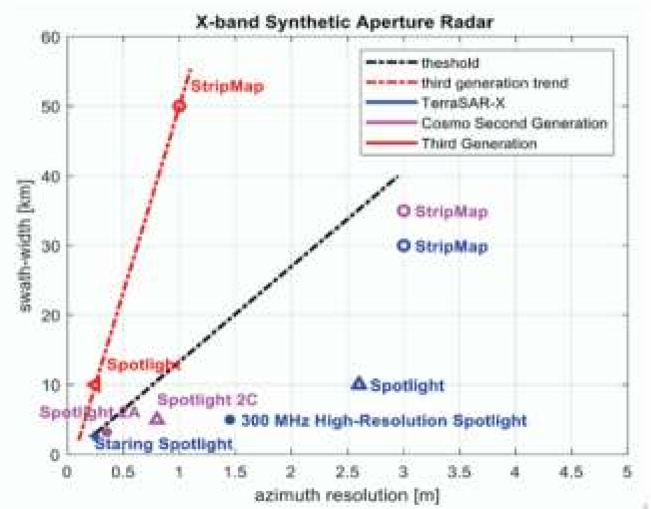

Figure 1 - X-band SAR Instrument swath-width vs. azimuth resolution: comparison between present and third generation

Achieving high geometric resolution over extended observation areas is possible through the adoption of advanced radar acquisition strategies, such as Scan-On-Receive (SCORE) and Multiple Azimuth Processing (MAP). These techniques, introduced in recent years, have been specifically developed to overcome the fundamental trade-offs that traditionally limit SAR systems, where improvements in spatial resolution typically result in a reduction of swath width. By moving beyond the constraints of conventional acquisition modes, these innovative approaches enable a more efficient use of the radar system’s capabilities.For instance, the implementation of SCORE and MAP allows the design of SAR instruments capable of simultaneously delivering fine spatial resolution and wide-area coverage. In practical terms, this can translate into system performance targets on the order of 1 meter resolution with a swath width of approximately 50 km in Stripmap mode, and around 10 km in Spotlight mode. Such capabilities represent a significant advancement compared to current-generation systems, effectively paving the way for a new class of high-performance SAR instruments that can exceed existing operational limitations.

Performance:-

The SAR instrument under consideration is assumed to be based on a planar active phased array antenna, a solution that enables flexible beam control and advanced signal management capabilities. In addition to this hardware configuration, the proposed system integrates a set of innovative acquisition techniques aimed at significantly enhancing overall performance.In particular, Digital Beamforming (DBF) is employed to enable the implementation of Digital SCORE functionalities, with the primary objective of maximizing the receive antenna gain. This approach contributes to a substantial improvement in key performance indicators such as Noise Equivalent Sigma Zero (NESZ) and range Distributed Target Ambiguity Ratio (DTAR). Furthermore, Azimuth Processing (AP) is implemented at the digital level within the SAR Electronic Sub-system (SES), allowing for a more effective mitigation of azimuth ambiguities and consequently improving azimuth DTAR performance.

The effectiveness of these techniques is illustrated through the performance results reported in Figures 2 and 3. Specifically, Figure 2 presents an example of achievable NESZ values in Stripmap mode when the aforementioned methods are applied, while Figure 3 shows the corresponding 2D-DTAR trends. The analysis refers to an observation scenario characterized by an incidence angle range between 20° and 60°. The results indicate that, across this access region, it is possible to achieve worst-case NESZ values on the order of -20 dB and 2D-DTAR values up to approximately -18 dB. These performance estimates are derived assuming an orbital altitude of 619 km, confirming the effectiveness of the proposed solutions in enhancing SAR imaging quality.

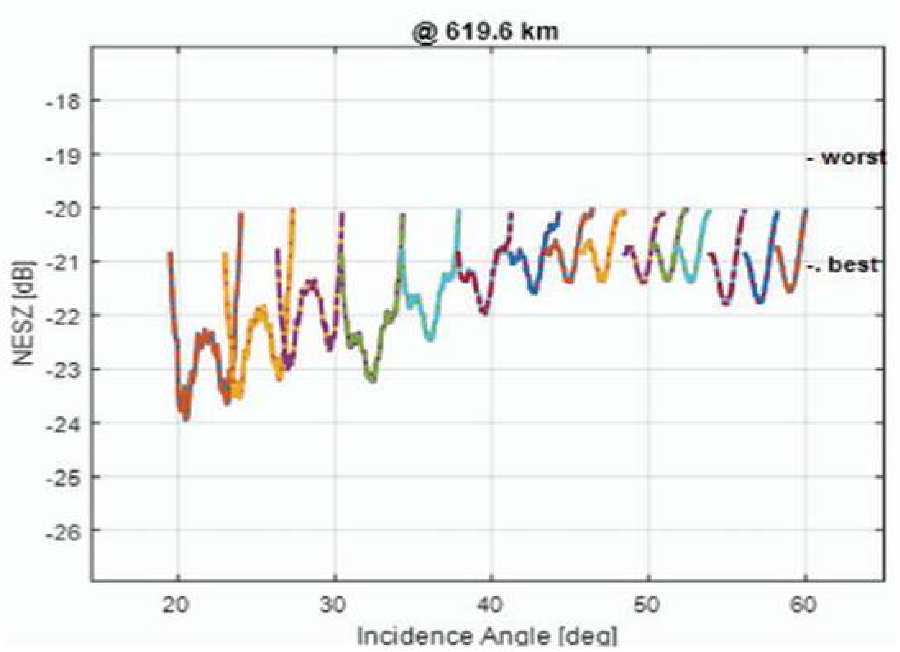

Figure 2: SAR Stripmap NESZ performance

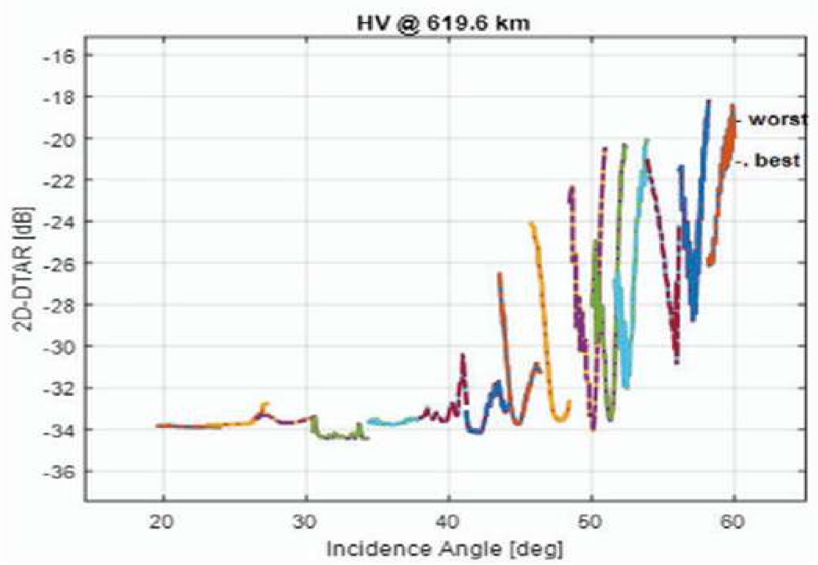

Figure 3: SAR Stripmap 2D-DTAR performance

Instrument Architecture

The functional architecture of the proposed SAR instrument, illustrated in Figure 4, is structured around two primary subsystems: the SAR Electronic Sub-system (SES) and the SAR Antenna Sub-system (SAS). This division reflects a common design approach aimed at separating signal processing functionalities from radiating and transmission components.Within the SES, the Digital Unit (DGU) is designed as a modular and scalable element, capable of handling a large number of receiving channels required to support advanced acquisition techniques such as SCORE and MAP. Following a well-established architectural paradigm, the DGU can be organized into two distinct stages of echo processing. The First Stage Processor (FSP) is responsible for initial signal processing tasks, including sampling, filtering, decimation, compensation, and the implementation of digital beamforming. Subsequently, the Second Stage Processor (SSP) completes the signal processing chain by refining the outputs of the FSP and executing multi-channel calibration algorithms necessary to support DBF operations. In addition, the SSP manages data compression functions, such as the Automatic Block Adaptive Quantization (BAQ) algorithm.

The SAS is managed by a dedicated Antenna Controller and Processor (ACP), which not only supervises antenna operations but also coordinates the functioning of internal instrument units and ensures communication with the spacecraft platform (P/F). Within the SES, the Radio Frequency Unit (RFU) plays a key role in signal conditioning, enabling proper adaptation between transmitted and received signals exchanged between the DGU and the antenna subsystem. An intermediate unit, referred to as the Signal Conditioning and Switching Unit (SCSU), is responsible for signal routing functions, including splitting, combining, switching, and the management of redundancy paths to enhance system reliability.For each receiving channel, the RFU performs several essential operations, such as impedance matching, filtering, amplification, gain control, and adaptive down-conversion, which are tailored according to the specific observation mode of the instrument. The internal architecture of the SAS can be further decomposed into five main assemblies: Radio Frequency, Power, Command and Control, Mechanical, and Thermal subsystems. The electrical functionalities associated with the first three assemblies are typically implemented through a set of specialized units characteristic of active phased array antennas, including the Tile Control Unit (TCU), Tile Power Supply Unit (TPSU), Electronic Front-End (EFE), True-Time Delay Line (TDL), Radiating Board (RB), Beam Forming Network (BFN), and DC Harness.

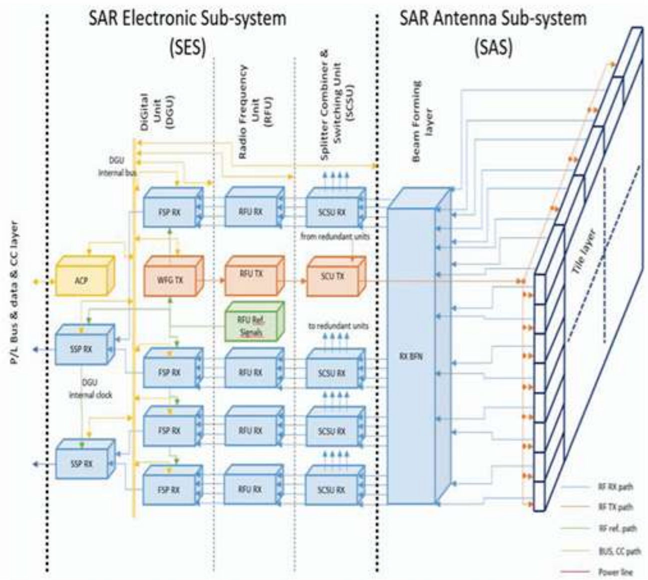

Figure 4: Example of SAR instrument functional architecture comprising two main subsystems: SES and SAS.

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