Editorial
Introduction to the Special Issue on Recent Advances in Wideband Signal Processing for Classical and Quantum Synthetic Apertures

A KEY aphorism pertaining to the nature of instrumentation comes from (although the attribution is sometimes disputed) the Italian scientist Galileo Galilei: "*Measure what can be measured, and make measurable what cannot be measured*." Clearly, making things measurable is akin to choosing appropriate methods to measure them. From the perspective of signal processing, such techniques involve designing efficient signal acquisition systems and processing the acquired signals to extract relevant information.

In this context, it is instructive to recall a phrase coined by the Austrian-American educator Peter Drucker: "*You can't improve what you don't measure*". There are plenty of signals of interest – complex, hidden, weak, and distant – that are difficult to measure or acquire. For instance, an airborne radar's swath is limited while using a conventional phased array antenna. Similarly, it is tedious to image a three-dimensional (3-D) object using a single sensor. In optics, in the absence of advanced phase retrieval techniques, the complex signal cannot be accurately estimated from magnitude-only diffraction patterns.

Once the signal is acquired, retrieving useful information from it entails developing an additional set of algorithms to sample, process, and enhance it. It is against this background that synthetic aperture (SA) systems, which provide improved signal acquisition and information extraction than is inherently possible via a single sensor, have gained salience in various signal processing applications. The SA concepts have been leveraged in a variety of applications to improve environmental imaging and sensing performance beyond the spatial or temporal resolution limits of conventional antennas and sensors. In general, synthetic apertures are generated by moving an antenna, sensor, or probe to different spatial locations such that it records phase coherent measurement samples over an extended spatial volume.

The most prominent example of SA application is, of course, in radar remote sensing. In the case of synthetic aperture radar (SAR), the antenna is mounted on an airplane and constant velocity motion along the flight path creates an angle-dependent Doppler shift that is used to image a ground scene with cross-range resolution proportional to the length of the aircraft's path along the coherent processing interval. Airborne SAR was developed in the 1950 s. The successful launch of the SEASAT satellite in 1978 heralded the era of satellite-borne SAR systems [1].

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In channel sounding applications where the propagation characteristics of a static wireless environment must be determined, the SA is created by using a robot or other mechanical positioner to move the antenna and collect phase-coherent samples from different spatial locations. The complex samples are then combined coherently in post-processing to yield high-resolution angle estimates of signal sources and scatterers.

In long-range optical imaging applications, the resolution of the image is limited by the diffraction of light at the limited aperture of the imaging system [2]. To overcome this limitation, the coherently- illuminated scene is captured using a large SA created by a holographic camera that collects complex field information and is moved to different locations arranged on a square grid. Each camera location generates diffraction-limited low-resolution images that are then combined to yield a high-resolution image. Alternatively, for incoherent objects one collects interferometric data between two separated apertures, instantaneously measuring a small patch of Fourier space, and moves the apertures around to make additional measurements and fill in Fourier space to create the high-resolution image. Additional examples demonstrating the utility of SAs are now found in sonar (for which the earliest SA studies were conducted in the 1970s), radiometry, and medical imaging applications.

Furthermore, quantum information processing offers techniques that substantially enhance performance without using prohibitively complex quantum hardware. For example, state-of-the-art Rydberg sensors [3] have recently been developed for sensing electric fields and rely on the use of atomic vapors. Since the quantum states of atoms are fundamental constants of nature that are not subject to calibration errors, manufacturing defects, or degraded performance due to aging, atomic vapors are well-suited for making precise electric field measurements. These atomic sensors could conceivably replace antenna probes in several SA applications [4].

The rising importance of SAs in signal processing was recently recognized by the IEEE Signal Processing Society (SPS) when it formally approved the creation of the Synthetic Aperture Technical Working Group (SA-TWG) in April 2020 under the auspices of the Sensor Array and Multichannel (SAM) Technical Committee (TC). This subsequently led to the establishment of the first SPS standards activity in the form of the IEEE Synthetic Aperture Standards Committee (SASC) in 2021. This special issue on Recent Advances in Wideband Signal Processing for Classical and Quantum Synthetic Apertures was motivated by and arose from discussions within the SA-TWG. In particular, this issue seeks to identify new wideband processing techniques that leverage large signal bandwidths in SAs to estimate delay, as well as new processing techniques that compensate for the lack of available signal bandwidth and yet still manage to achieve practical delay estimation performance. Generating and processing wide bandwidths for delay estimation performance in SAs is a challenging problem and an ongoing area of research. Also, of particular interest to this issue are theoretical and mathematical treatments that address the performance bounds of classical and quantum SAs.

As guest editors of this special issue, our objective is to showcase the enormous and fascinating diversity of SA research problems. We are pleased to report that our call for papers attracted many submissions across the globe. After peer review, 14 manuscripts, or 48%, have been accepted for publication. The contributions capture SA applications beyond the standard radar domain. For example, "An Overview of Advances in Signal Processing Techniques for Classical and Quantum Wideband Synthetic Apertures" by Vouras et al. [A1] provides a comprehensive overview of the extent of recent wideband SA signal processing techniques. While SAR and synthetic aperture sonar (SAS) are widely prevalent, SAs are evidently inspiring creative and new system designs and gaining momentum across other fields such as channel sounding, radiometry, interferometry, polarimetry, coded apertures, Rydberg sensing, and medical imaging. The paper provides an in-depth overview of wideband signal processing techniques for each one of these applications. This is a ready reference of SA techniques that interested researchers may dwell upon for interesting problems.

In the context of SA radars, "Aperture Synthesis with Digital Arrays and Covariant Change of Wavenumber Variables" by Barnes et al. [A2] proposes a creative Solopulse approach that employs digital array radars to enhance wideband frequency-wavenumber (omega-k) methods for imaging from stationary arrays using a single pulse. This technique is then extended to multiple-pulse inverse aperture synthesis for moving targets. The paper suggests various modifications to conventional omega-k algorithms to accommodate different array parameters. This may also be viewed as a form of multi-channel SAR, wherein coherent fusion is implemented with pixel domain additions.

The SAs need not always employ a positioner to move an antenna through space. In some cases, SA imaging is carried out by deploying a distributed network of sensors. Here, "Widely Distributed Radar Imaging: Unmediated ADMM Based Approach" by Murtada et al. [A3] proposes reconstructing the observed scene via widely distributed radar sensors. It poses the problem as a constrained optimization with sparsity priors and solves it iteratively through consensus and sharing alternating direction method of multipliers (ADMM) using the Civilian Vehicles Dome dataset.

In some cases, systems synthesize wide bandwidths from discrete narrowband signals. This concept is tackled in "Radar Band Fusion using Frame-Based Compressed Sensing" by Guha et al. [A4], which addresses the application of compressed sensing (CS) to gapped-radar systems. A gap in the frequency band results in high coherence CS sensing matrix. The paper proposes a fusion of signals recovered from the subdivision of the sensing matrix and shows an improved performance in the presence of spectral gaps.

In the context of the conventional wideband SAR, "Joint Design of SAR Waveform and Imaging Filters Based on Target Information Maximization" by Zhang et al. [A5] studies wideband SAR waveform design by optimizing the target mutual information while also optimizing the imaging filters. This approach yields more effective information acquisition, better image quality, and target detection performance than the conventional SAR.

A recent application of SAR is automotive imaging for autonomous driving. Here, "Fusion of Inverse Synthetic Aperture Radar and Camera Images for Automotive Target Tracking" by S. S. Ram [A6] proposes the formation of inverse SAR (ISAR) images by leveraging the available vision data from a high-resolution camera with the automotive radar observations. These ISAR images have the potential to facilitate complete 3-D visualizations of the target. Accurate object detection by the camera is useful for eliminating clutter and multipath propagation.

Continuing the innovations in automotive SAR, a high-resolution multiple-input multiple-output (MIMO) SAR imaging with Doppler-division multiplexing (DDM) is proposed in "Multi-channel Back-Projection Algorithm for mmWave Automotive MIMO SAR Imaging with Doppler-Division Multiplexing" by Zhang et al. [A7] Here, wide viewing angle imaging and high SNR gain are achieved through a combination of the transmit DDM code and Doppler filtering at the receivers. The use of Doppler degrees of freedom for pulse coding reduces system complexity, improves image quality, and extends the range swath.

In sonar, SAs are nowadays a matured technology. However, several challenges remain to enhance SAS performance. In particular, "SINR: Deconvolving Circular SAS Images Using Implicit Neural Representations" by Reed et al. [A8] explores the classic problem of deconvolution for a circular SAS collection geometry that enables improved resolution and reduced speckle noise. This work uses an implicit neural representation to deconvolve SAS images by exploiting the knowledge of the SAS point spread function to optimize a network with a suitable cost function. This has the potential for improved target recognition and underwater visualization which generally suffer from poor resolution.

Nowadays, the reconfigurable intelligent surface (RIS) has emerged as a low-cost, compact, and low-power technology to realize SAs in the next-generation wireless systems, wherein higher spectral and energy efficiencies are the defining characteristics. In this setting, "Index-Modulated Metasurface Transceiver Design using Reconfigurable Intelligent Surfaces for 6G Wireless Networks" by Hodge et al. [A9] studies RIS-aided index modulation (IM) techniques, which transmit information through permutations of indices of spatial, frequency, or temporal resources. The paper, which will appear in a future issue of JSTSP, proposes novel electromagnetics-compliant RIS designs for realizing IM in future wireless transceivers. It shows that these implementations have better bit-error-rates than traditional wireless communications.

In recent years, quantum SAs are increasingly investigated through quantum estimation theory to obtain fundamental performance limits. In "Quantum-Enhanced Transmittance Sensing" by Gong et al. [A10], the problem of estimating the unknown transmittance of a target embedded in thermal background light is studied using the lossy thermal-noise bosonic channel model. It derives guarantees to asymptotically achieve the minimal Cramér–Rao Lower Bound using two-mode squeezed vacuum states. This is useful for trade-offs between the complexity and performance of practical systems.

In "Quantum-Inspired Multi-Parameter Adaptive Bayesian Estimation for Sensing and Imaging" by Lee et al. [A11], the authors expand upon some classical quantum results to construct a Bayesian greedy measurement for multiparameter estimation in SA fluorescence microscopy and astronomy. This approach leads to a multi-spatial-mode transformation prior to a photon-detection array, wherein the receiver outperforms the conventional quantum-noise-limited focal-plane direct imaging.

The optical SA systems do not have any inherent bandwidth and may estimate delay or distance using machine learning techniques that determine depth in 2-D images. The paper "D^2UF: Deep Coded Aperture Design and Unrolling Algorithm for Compressive Spectral Image Fusion" by Jacome et al. [A12] tackles compressive spectral imaging (CSI) that employs synthetic apertures for both spatial and spectral domains while sensing only 2-D projections of a 3-D spectral image. The paper presents the fusion of the compressive measurements of two sensors which are low-spatial, high-spectral and high-spatial, low-spectral resolution, respectively. It employs an unrolling-based deep network that follows the ADMM optimization.

Similar to a distributed SA, "Multi-Sensor Image Feature Fusion via Subspace-based approach using ℓ_1-Gradient Regularization" by Vargas et al. [A13] proposes image fusion to estimate features with high-spatial-resolution and appropriate spectral content by combining data from a multi-sensor hyperspectral imaging system. It extracts spatial features using morphological profiles. The resulting joint optimization problem for fusion is then solved by an ADMM-based algorithm by penalizing the ℓ_1-norm of the spatial gradient magnitudes.

The last contribution "Efficient Superoscillation Measurement for Incoherent Optical Imaging" by M. Tsang [A14] attempts to address the long-standing problem of improving the resolution of an optical imaging system beyond the diffraction limit in problems such as astronomy, remote sensing, fluorescence microscopy, and spectroscopy. It leverages upon the fact that the Fourier coefficients of an object intensity function, expressed with a basis of superoscillatory functions, are constructed from the object moments. The technique yields better performance than direct imaging and is efficient in terms of photon collection.

In summary, this special issue highlights some pioneering leaps in a very wide spectrum of SA technologies. These innovations are equipped with characteristics such as super-resolution measurements, sensor fusion, high data rates, and state-of-the-art hardware designs. The plethora of SA algorithms, their possible variants, and relative benefits make it difficult to conclude which SA technique will always be the best. The only foregone conclusion is that the SA community will continue to complement the strengths of each technique and extend them to other domains. We hope that this special issue on Recent Advances in Wideband Signal Processing for Classical and Quantum Synthetic Apertures helped demonstrate this rapidly evolving signal processing technology.

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APPENDIX: RELATED ARTICLES

[A1] P. Vouras et al., "An overview of advances in signal processing techniques for classical and quantum wideband synthetic apertures," *IEEE J. Sel. Topics Signal Process.*, vol. 17, no. 2, pp. 317–369, Mar. 2023, doi: 10.1109/JSTSP.2023.3262443.

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