Foreword to the Special Issue on Multichannel Space-Based SAR

WITH the advent of active electronically steerable phased-array synthetic aperture radar (SAR) antennas equipped with more than one receive channel (i.e., analog-/digital converter) on the most recent generation of commercial/civilian spacecraft, such as RADARSAT-2, TerraSAR-X & TanDEM-X, PAZ, and ALOS-2, relatively mature single-channel SAR imaging is now rapidly evolving into advanced, multiaperture SAR concepts. The spatial diversity of multiple parallel receive channels can, for instance, be used to discriminate moving objects from the stationary background, to determine the underlying topography of the backscattering terrain, or to measure the large-scale surface motion using single-pass interferometry. The flexible programmability of this newest generation of SAR satellites offers quasi-seamless antenna beamsteering at a rate equivalent to the pulse repetition frequency and, in conjunction with sophisticated array signal processing algorithms, opens up novel radar concepts and capabilities that were not previously possible.

Although virtually all investigations of multichannel SAR in the recent past were motivated by ground moving target indication (GMTI) [1], recent studies, however, include a much broader range of applications. As a matter of fact, due to the linearity of a multichannel measurement, it is always, without any loss, possible to recreate what would have been measured by a single antenna of equivalent length. Thus, there is no loss in capability or performance. The main tradeoffs to consider are the increased cost of the RF-switching hardware, typically negligible compared to the overall mission costs, and the increased data volume and subsequent downlink demands. In contrast, this incremental cost offers improved strategic wide-area surveillance coupled with an accurate motion estimation capability. As an example, high-resolution wide swath (HRWS) imaging techniques overcome the inherent physical coverage-versus-resolution limitations of conventional single-channel SAR systems.

Although still rather rudimentary, even two parallel apertures offer such palpable advantages compared to classical SAR that specialized modes have been designed and implemented on present on-orbit systems after launch. Convincing examples are the Maritime Satellite Surveillance Radar (MSSR) modes on RADARSAT-2 which are nowadays used operationally [2].

It is expected that innovative future space radar concepts with many parallel channels and waveform diversity will open up new areas of research and applications, such as fully adaptive digital beamforming in azimuth and elevation to dramatically increase SNR and hence coverage, to enhance resilience against electronic interferences stemming from other competing radar sensors or deliberate jamming, or to resolve individual scatterers within a resolution cell. Many of these methods have been proven using ground-based and airborne systems, but are only recently being considered on space-based platforms due to cost and resource limitations.

Owing to the demonstrable benefits, there is no doubt that spacecraft with more than two parallel receive paths will materialize in future generations of space-based SAR. Consequently, R&D on this topic has gained considerable steam over the last few years as witnessed by many publications in renowned journals and presentations at international conferences. To offer the SAR community, a first dedicated venue to present their recent advances and the latest direction of their R&D activities has been the motivation and driver for this Special Issue (SI) of the IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING (JSTARS).

Although the research presented in this SI represents only a limited snapshot of the present state-of-the art of multichannel space-based SAR science and technology, a review of this work reveals some interesting trends. The main work topics can loosely be grouped into four different areas that are not mutually exclusive.

1) *HRWS:* In two papers, practical problems in the realization of HRWS SAR systems are tackled. del Castillo *et al.* [4] present an L-band demonstrator based on a reconfigurable multichannel SAR prototype concept, while Zhao *et al.* [3] introduce an efficient algorithm that considerably reduces the computational complexity of HRWS signal processing. Furthermore, Baumgartner and Krieger [5] propose a new technique for HRWS in conjunction with GMTI, while Yang *et al.* [6] report on a method to reduce the data volume in a multiple elevation beam system.
2) *GMTI:* As multiple receive channels in the flight direction are a prerequisite of SAR in conjunction with GMTI, one-half of the papers in this SI deal with this application. Baumgartner and Krieger [5] introduce a matched reconstruction filter bank that enables HRWS and GMTI to be performed simultaneously, while Wang [7] explores improvements gained by the MIMO principle with waveform diversity. Makhoul *et al.* [8] compare SAR-GMTI performance of airborne and space-based sensors on the basis of experimental acquisitions. Rousseau *et al.* [9], meanwhile, report on the first experimental results of a two-channel ScanSAR mode implemented on RADARSAT-2, thereby demonstrating wide-area GMTI. Finally, Lombardo *et al.* [10] study GMTI using MIMO SAR systems.

Digital Object Identifier 10.1109/JSTARS.2015.2507878

3) *Maritime applications:* The wide coverage of space-based sensors, particularly using an HRWS capability with the addition of motion sensitivity, is a natural fit for maritime domain monitoring applications. While [8] analyzes and compares sensor performance for this challenging environment at X-band, in [9] vessel detection is improved by employing clutter suppression together with ScanSAR in C-band. Meanwhile, Suchandt and Runge [11] address ocean surface current estimation using a constellation of two back-to-back flying satellites that increase sensitivity to relatively slow, distributed scatterer movements.
4) *New concepts:* Refs. [7] and [10] address the innovative MIMO concept applied together with several different waveforms as a means to significantly improve the GMTI performance of future multichannel space-based SARs. Sikaneta and Gierull [12], in contrast, propose to improve the conventional stripmap mode through toggling of the azimuth beam in a "wiper" fashion together with multiple receive channels. By increasing the dwell time on the individual scatterers, the spatial resolution increases and, compared to the classical beam spoiling approach, the SNR also improves considerably.

From our perspectives, it is not surprising that the bulk of current R&D involves the exploitation of multiple apertures to drastically increase the surveyed area while maintaining or even improving the spatial resolution (i.e., HRWS). Within the operational community, this is considered the "holy grail of SAR" as the resulting imagery satisfies the somewhat conflicting requirements of various user groups, i.e., surveillance of ocean-scale areas with a simultaneous zoom-in capability for recognition and identification. These advanced systems will be so effective that a relatively small number are sufficient to cover vast areas with short revisit times, especially if placed on orbits with different inclinations. Since multiple phase centers, in principle, also permit suppression of the stationary background, these systems will also provide an improved, tactically relevant capability through high-resolution high-sensitivity imagery, including GMTI, in challenging environments over land, ice-infested waters, or in high sea states.

A world-wide, quasi-persistent Intelligence, Surveillance, and Reconnaissance (ISR) capability is thereby becoming more and more technologically feasible and affordable, offering the potential to significantly improve the safety and security of the public, putting today's dream for the first time into the realm of possibility.

It is likely that some of the presented investigations in this SI will become the building blocks of future operational systems. Of course, much work is still required to overcome theoretical, conceptual, and practical problems prior to finally placing these advanced multichannel space-based SAR systems into orbit. This exciting research should be closely followed and will, no doubt, warrant an updated SI in the future.

CHRISTOPH H. GIERULL, *Guest Editor*
Defence Research and Development Canada—Ottawa Research Center
Ottawa, ON K1A 0Z4, Canada

PARIS W. VACHON, *Guest Editor*
Defence Research and Development Canada—Ottawa Research Center
Ottawa, ON K1A 0Z4, Canada

ACKNOWLEDGMENT

We thank Prof. J. Chanussot, the Editor-in-Chief of JSTARS, for his support and assistance, and all the authors and reviewers for their outstanding contributions that made this SI happen.

REFERENCES

[1] C. H. Gierull, I. C. Sikaneta, and D. Cerutti-Maori, "Space-based SAR ground moving target indication," in *Novel Radar Techniques and Applications*, R. Klemm, U. Nickel, C. Gierull, H. Griffiths, P. Lombardo, and W. Koch, Eds. London, U.K.: IET Publishers, ch. II.7, 2016.

[2] P. W. Vachon, C. Kabatoff, and R. Quinn, "Operational ship detection in Canada using RADARSAT," in *Proc. IEEE Int. Geosci. Remote Sens. Symp. (IGARSS)*, Quebec City, QC, Canada, 2014, pp. 998–1001.

[3] S. Zhao, Y. Deng, R. Wang, L. Guo, W. Wang, and N. Li, "Modifications on multi-channel reconstruction algorithm for SAR processing based on periodic non-uniform sampling theory and non-uniform fast Fourier transform," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 4998–5006, Nov. 2015.

[4] J. del Castillo, S. Sánchez, R. Porras, A. Pedreira, and J. R. Larrañaga, "L-band digital array radar demonstrator for next generation multichannel SAR systems," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 5007–5014, Nov. 2015.

[5] S. V. Baumgartner and G. Krieger, "Simultaneous high-resolution wide-swath SAR imaging and ground moving target indication: Processing approaches and system concepts," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 5015–5029, Nov. 2015.

[6] T. Yang, X. Lv, Y. Wang, and J. Qian, "Study on a novel multiple elevation beam technique for HRWS SAR system," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 5030–5039, Nov. 2015.

[7] W.-Q. Wang, "Multichannel SAR using waveform diversity and distinct carrier frequency for ground moving target indication," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 5040–5051, Nov. 2015.

[8] E. Makhoul, S. Baumgartner, M. Jäger, and A. Broquetas, "Multichannel SAR-GMTI in maritime scenarios with F-SAR and TerraSAR-X sensors," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 5052–5067, Nov. 2015.

[9] L.-P. Rousseau, C. H. Gierull, and J.-Y. Chouinard, "First results from an experimental ScanSAR-GMTI mode on RADARSAT-2," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 5068–5080, Nov. 2015.

[10] P. Lombardo, D. Pastina, and F. Turin, "Ground moving target detection based on MIMO SAR systems," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 5081–5095, Nov. 2015.

[11] S. Suchandt and H. Runge, "Ocean surface observations using the TanDEM-X satellite formation," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 5096–5105, Nov. 2015.

[12] I. C. Sikaneta and C. H. Gierull, "Phased-array beam-diversity with multiple channels for improved SAR imaging," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 8, no. 11, pp. 5106–5115, Nov. 2015.

Christoph H. Gierull (S'94–M'95–SM'02) received the Dr.-Ing. degree in electrical engineering from the Ruhr-University Bochum, Bochum, Germany, in 1995.

Since 2011, he has been an Adjunct Professor with Laval University, Quebec City, QC, Canada. From 1991 to 1994, he was a Scientist with the Research Establishment for Applied Science (FGAN), Wachtberg, Germany. In 1994, he joined the German Aerospace Center (DLR), Oberpfaffenhofen, Germany, where he headed the SAR Simulation Group, Microwaves and Radar Institute. Since 2000, he has been a Senior Defence Scientist with the Radar Sensing and Exploitation Section, Defence Research and Development Canada—Ottawa Research Center, Ottawa, ON, Canada. During NASA's Space-Shuttle Radar Topography Mission (SRTM) in 2000, he was responsible for the X-band-SAR performance at Mission Control, Johnson Space Center Houston during Endeavor's 11 days in orbit. From 2006 to 2009, he was on assignment to the Fraunhofer Institute FHR, Wachtberg, Germany, collaborating on aerospace ground moving target indication (GMTI). Since returning to Canada, he is assuming the duties of Group Leader, Space-Based Radar. He has been a Technical Advisor to the Canadian and the European Space Agencies on several of their current and future space-based SAR missions including RADARSAT-2, RCM, RADARSAT Next Generation, and Sentinel-1. He has authored or coauthored numerous journal publications and scientific reports. He has filed a CAN/U.S. patent application on a novel vessel detection algorithm in space-based SAR imagery. He is Co-Editor of a scientific textbook on *Novel Radar Techniques and Applications* (IET, 2016), and is the author of a chapter on GMTI for RADARSAT-2 in *Application of Space–Time Adaptive Processing* (IEE, 2004). His research interests include various aspects of radar (array) signal processing, including adaptive jammer suppression, space–time adaptive processing, super-resolution, aerospace multichannel SAR in combination with MTI and HRWS, and bistatic and passive SAR.

Dr. Gierull served as Associate Editor for a Special Issue in EURASIP's Signal Processing in 2004 and for the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING from 2010 to 2013. He was the recipient of the Best Annual Paper Prize Award of the Association of German Electrical Engineers in 1998 and jointly the Best Paper Awards at the International Radar 2004 and the 6th EUSAR 2006 Conferences, and the DRDC's S&T Performance Excellence Award 2013.

Paris W. Vachon (M'89–SM'96–F'07) received the B.Ap.Sc. (Hons.) degree in engineering physics and the Ph.D. degree in physical oceanography from the University of British Columbia, Vancouver, BC, Canada, in 1983 and 1987, respectively.

From 1987 to 1988, he was a Visiting Fellow at the Canadian Government Laboratory, Canada Centre for Remote Sensing (CCRS), RADARSAT Project Office, Ottawa, ON, Canada. In 1988, he joined CCRS as a Research Scientist. From 1993 to 1994, he was a Visiting Scientist at the Nansen Environmental and Remote Sensing Center, Bergen, Norway. In 2002, he became the Head of CCRS's Harsh Environment Applications Section. In 2003, he joined the Defence Research and Development Canada–Ottawa Research Center, Ottawa, ON, Canada, where he led the Intelligence, Surveillance, and Reconnaissance (ISR) Data Exploitation Group. He was an S&T Advisor to the Polar Epsilon project, which implemented near-real time ship detection using RADARSAT-2 and the dual-receive Maritime Satellite Surveillance Radar modes for RADARSAT-2. His research interests include many aspects of SAR signal and image processing, and SAR ocean imaging including ship detection, ocean wind and wave retrieval, and storms such as polar lows and hurricanes.

Dr. Vachon was the Editor-in-Chief of the *Canadian Journal of Remote Sensing* and an Associate Editor for IEEE GEOSCIENCE AND REMOTE SENSING LETTERS. He was the recipient of the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING Best Paper Award twice and the Canadian Remote Sensing Society 2013 Larry Morley Gold Medal Award "for significant contributions to SAR remote sensing of oceans and their operational implementation."