Foreword to the Special Issue on Cyclone Global Navigation Satellite System (CYGNSS) Early on Orbit Performance

THE Cyclone Global Navigation Satellite System (CYGNSS) constellation of eight satellites was successfully launched on December 15, 2016 into low earth orbit. Each satellite carries a four-channel bistatic radar receiver that measures GPS signals scattered by the earth surface. Global Navigation Satellite System Reflectometry (GNSS-R) techniques are used to retrieve near surface wind speed over ocean and soil moisture over land. The measurements are unique in several respects, most notably in their ability to penetrate through high levels of precipitation, made possible by the low frequency at which GPS operates, and in the frequent revisit time and complete sampling of the diurnal cycle, made possible by the large number of satellites in a low inclination orbit. Engineering commissioning of the constellation was successfully completed in March 2017. Since then, CYGNSS science data products have been continuously produced.

The articles included in this special issue examine early on orbit performance by CYGNSS. The first paper [item 1) in the Appendix] considers the propulsionless means by which the CYGNSS constellation maneuvered its individual spacecraft into the desired orbital configuration. The second paper [item 2) in the Appendix] addresses another aspect of the spacecraft constellation, but this one particular to bistatic radar remote sensing using GPS transmitters. Spatial and temporal sampling properties are examined and relationships between revisit time and spatial resolution are developed. The next three papers examine engineering issues related to calibration of the CYGNSS surface scattering cross section measurements. Item 3) in the Appendix presents experimental results intended to characterize the navigation signals transmitted by the GPS constellation which are used by CYGNSS. Item 4) in the Appendix describes the data processing algorithm used to convert CYGNSS raw data into measurements of normalized bistatic radar cross section, examines the associated errors, and reports on the overall uncertainty in the measurements. The third paper [item 5) in the Appendix] describes several calibration errors that were present in earlier versions of the data processing algorithm, which were subsequently corrected or significantly reduced by more recent versions.

Three articles address the estimation of ocean surface wind speed from the measurement of scattering cross section. In [item 6) in the Appendix], a relationship is derived between the scattering cross section and the wind speed using empirical matchups between the CYGNSS measurements and near-coincident sources of wind speed "ground truth". In [item 7) in the Appendix], an alternative relationship is developed, this time between the wind speed and a measure of the extent of diffuse scattering of the reflected signal away from the specular direction. This second wind speed-related paper also uses the relationship in a wind speed retrieval algorithm and examines its performance. The third paper [item 8) in the Appendix] evaluates the performance of the baseline wind speed retrieval algorithm used by the CYGNSS mission via intercomparisons with numerical weather predictions model outputs and near coincident overpasses of hurricanes by NOAA "hurricane hunter" aircraft sensors. The wind speed retrieval uncertainty is found in both assessments to be better than 2 m/s at wind speeds below 20 m/s. At higher wind speeds and, in particular, in tropical cyclone conditions, the uncertainty increases proportionally with wind speed.

The last two articles in the special issue provide early looks at some of the scientific applications made possible with CYGNSS. Item 9) in the Appendix considers the nature of the rapid temporal sampling that results from the orbital configuration of the constellation. Samples made by successive spacecraft in the constellation, sometimes just minutes apart from one another, can be used to detect rapid changes in atmospheric state due to convection. The final paper [item 10) in the Appendix] examines the sensitivity of CYGNSS land surface scattering measurements to near-surface soil moisture and to characteristics of the overlaying vegetation canopy (when present). The sensitivity is found to be significant and repeatable enough that the generation of a soil moisture data product should be possible. This suggests that CYGNSS measurements will expand into new land applications in the future.

The Guest Editors gratefully acknowledge the support and assistance of Dr. J. Du, JSTARS Editor-in-Chief, and of the IEEE publications organization. They are also very appreciative of the time and effort provided by the anonymous reviewers who participated in the peer review process for this special issue. Their contributions and, of course, those of the authors, have enabled this collection of early on-orbit results for CYGNSS to be published.

C. RUF, *Guest Editor*
University of Michigan
Ann Arbor, MI 48109 USA

Digital Object Identifier 10.1109/JSTARS.2018.2885391

E. CARDELLACH, *Guest Editor*
Institute of Space Sciences of
Catalonia
Barcelona 08193, Spain

M. P. CLARIZIA, *Guest Editor*
Deimos Space U.K. Ltd.,
Harwell Oxford OX11 0QR, U.K.

C. GALDI, *Guest Editor*
Università degli Studi del Sannio
Benevento 82100, Italy

S. T. GLEASON, *Guest Editor*
University Corporation for
Atmospheric Research
Boulder, CO 80307 USA

S. PALOSCIA, *Guest Editor*
Institute of Applied Physics
National Research Council
Rome 00185, Italy

APPENDIX
RELATED WORK

1) C. D. Bussy-Virat, A. J. Ridley, A. Masher, K. Nave, and M. Intelisano, "Assessment of the differential drag maneuver operations on the CYGNSS constellation," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2878158.
2) C. D. Bussy-Virat, C. S. Ruf, and A. J. Ridley, "Relationship between temporal and spatial resolution for a constellation of GNSS-R satellites," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2833426.
3) T. Wang, C. S. Ruf, B. Block, D. S. McKague, and S. Gleason, "Design and performance of a GPS constellation power monitor system for improved CYGNSS L1B calibration," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2867773.
4) S. Gleason, S. Ruf, A. O'Brien, and D. S. McKague, "The CYGNSS level 1 calibration algorithm and error analysis based on on-orbit measurements," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2832981.
5) F. Said, Z. Jelenak, P. S. Chang, and S. Soisuvarn, "An assessment of CYGNSS normalized bistatic radar cross section calibration," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2849323.
6) C. Ruf and R. Balasubramaniam, "Development of the CYGNSS geophysical model function for wind speed," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2833075.
7) G. Giangregorio, P. Addabbo, C. Galdi, and M. di Bisceglie, "Ocean wind speed estimation from the GNSS scattered power function volume," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2856498.
8) C. Ruf, S. Gleason, and D. S. McKague, "Assessment of CYGNSS wind speed retrieval uncertainty," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2825948.
9) J. Park, J. T. Johnson, Y. Yi, and A. J. O'Brien, "Using "rapid revisit" CYGNSS wind speed measurements to detect convective activity," *J. Sel. Top. Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2848267.
10) H. Carreno-Luengo, G. Luzi, and M. Crosetto, "Sensitivity of CyGNSS bistatic reflectivity and SMAP microwave radiometry brightness temperature to geophysical parameters over land surfaces," *J. Sel. Top. Appl. Earth Observ. Remote Sens.*, vol. 12, no. 1, Jan. 2019, doi: 10.1109/JSTARS.2018.2856588.

Chris Ruf (SM'85–M'87–SM'92–F'01) received the B.A. degree in physics from Reed College, Portland, OR, USA, and the Ph.D. degree in electrical and computer engineering from the University of Massachusetts at Amherst, Amherst, MA, USA.

He is currently a Frederick Bartman Collegiate Professor of climate and space science with the University of Michigan; and the Principal Investigator of the NASA Cyclone Global Navigation Satellite System mission. He was with Intel Corporation, Hughes Space and Communication, the NASA Jet Propulsion Laboratory, and Penn State University. His research interests include GNSS-R remote sensing, microwave radiometry, atmosphere and ocean geophysical retrieval algorithm development, and sensor technology development.

Dr. Ruf is a member of the American Geophysical Union (AGU), the American Meteorological Society (AMS), and Commission F of the Union Radio Scientifique Internationale. He is a former Editor-in- Chief for the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING and was on the editorial boards of *Radio Science* and the *Journal of Atmospheric and Oceanic Technology*. He has been the recipient of four NASA Certificates of Recognition and seven NASA Group Achievement Awards, as well as the 1997 TGRS Best Paper Award, the 1999 IEEE Resnik Technical Field Award, the 2006 IGARSS Best Paper Award, and the 2014 IEEE GRSS Outstanding Service Award.

Estel Cardellach received the Ph.D. degree in sciences from the Polytechnic University of Catalonia, Barcelona, Spain, in 2002.

She has been working on scientific applications of GNSS for remote sensing of the earth, such as extraction of geophysical information of the GNSS reflected signals, radio occultation, and geodetic techniques. Since 2005, she has been with the Institute of Space Sciences (ICE-CSIC/IEEC), Catalonia, Spain, currently as a Distinguished Researcher. She was the Postdoctoral with NASA/Jet Propulsion Laboratory, Pasadena, CA, USA, during 2002–2003 where she received the National Research Council Award and was a Postdoctoral Researcher with Harvard Smithsonian Center for Astrophysics, Cambridge, MA, USA, 2003–2005.

Dr. Cardellach is the Principal Investigator of the space-borne experiment radio occultation and heavy precipitation aboard the PAZ low earth orbiter (ROHP-PAZ, launched Feb'18); the Local Manager of the EUMETSAT ROM-SAF; and a co-chair of the IEEE GRSS Instrumentation and Future Technologies Technical Committee's GNSS Working Group. She was a co-PI of the mission proposal G-TERN, in response to ESA Earth Explorer 9 (EE9, 2017); a member of the GEROS-ISS proposing team; and a co-chair of the GEROS Scientific Advisory Group.

Maria Paola Clarizia (M'14–SM'18) received the master's degree in telecommunications engineering from the University of Sannio, Benevento, Italy, in 2007, and the Ph.D. degree in ocean remote sensing using GNSS-R from the University of Southampton, Southampton, U.K., in 2012.

She has more than 10 years of experience in remote sensing, with a focus on GNSS-Reflectometry, working in both academia and private industry. She has been a Research Engineer with Starlab, Barcelona, Spain, a Research Scientist with the National Oceanography Centre, Southampton, U.K., and a Postdoctoral Research Fellow with the University of Michigan, Ann Arbor, MI, USA, and with the University of Southampton, working on the CYGNSS Mission for ocean and land applications. She is currently a GNSS-R Technical Manager with Deimos Space, Harwell Oxford, U.K. Her research interests include GNSS-Reflectometry, altimetry and scatterometry, electromagnetic scattering models, retrieval algorithms, data analysis, and statistical processing.

Dr. Clarizia is a member of the CYGNSS Science Team.

Carmela Galdi received the Dr.Eng. and Ph.D. degrees in electronic engineering from the Università degli Studi di Napoli "Federico II," Naples, Italy, in 1992 and 1997, respectively. In 1995, she spent a period for study and research in the Signal Processing Division, University of Strathclyde, Glasgow, U.K.

In 1997, she was a Visiting Scientist with the University College of London, London, U.K., and with the Defense Evaluation and Research Agency, Malvern, U.K, working on statistical models of radar backscattering from natural surfaces. In 2000, she joined the Università degli Studi del Sannio, Benevento, Italy, where she is an Associate Professor in telecommunications. She has cooperated with the National Oceanography Centre (NOC), Southampton, U.K., on a project about GNSS-R of the ocean surface. Currently, she is associated with the NASA CYGNSS project as an external science team member, working on statistical models for GNSS-R signals in different ocean conditions and on retrieval of wind speed from delay-Doppler maps. Her research interests include the field of statistical signal processing, non-Gaussian models of radar backscattering, and global navigation satellite system reflectometry.

Scott Thomas Gleason (M'10–SM'11) received the B.S. degree in electrical and computer engineering from the State University of New York at Buffalo, Buffalo, NY, USA, the M.S. degree in engineering from Stanford University, Stanford, CA, USA, and the Ph.D. degree from the University of Surrey, Guildford, U.K.

He is a Project Scientist III with the University Corporation for Atmospheric Research, Boulder, CO, USA. He is a Co-Investigator with the science team and Instrument Scientist for the NASA CYGNSS mission. He has worked in the areas of astronautics, remote sensing and Global Navigation Satellite Systems for over 20 years, including at NASA's Goddard Space Flight Center, Stanford's GPS Laboratory, Surrey Satellite Technology Limited and Concordia University.

Simonetta Paloscia (F'12) has been with the National Research Council (C.N.R.) since 1984. Her research currently concerns the study of microwave emission and scattering of soil (bare and snow-covered) and vegetation. Since 2004 she is scientific responsible of the Microwave Remote Sensing group at IFAC-CNR (Institute of Applied Physics), and the research line "Microwave Remote Sensing of natural surfaces", in the EO Project of CNR. In 2010, she was nominated Head of Research at the National Research Council. She is the author and co-author of more than 90 works published on international journals and books, of more than 150 papers published on proceedings of international meetings.

She was a PI and Co-I of many national and international projects (ASI, EC, ESA, JAXA). Since 1996, she has been the Principal Investigators in JAXA Science Team of AQUA/AMSR-E and GCOM/AMSR-2 for algorithms development of soil moisture and vegetation biomass retrieval. She is a member of the SMAP JPL/NASA Science Team.

She was member of organizing and steering committees of international meetings (Specialist Meeting on Microwave Radiometry and IGARSS). She is member of the permanent Steering Committee of MicroRad Meeting and she was a General Co-chair of the MicroRad 1999 and 2008 and URSI-F 2010 meetings organized in Florence. She is an Associate Editor for the *International Journal of Remote Sensing*, IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS IN REMOTE SENSING, and *European Journal of Remote Sensing*. She had a temporary teaching contract of "Microwave Remote Sensing Applications" for the Professional Master "Geomatics and Natural Resources Evaluation" at the "Istituto Agronomico per l'Oltremare" of the Ministry of Foreign Affairs in Florence from 1994 to 2010. She is a Fellow of Electromagnetics Academy of Cambridge (Cambridge, MA, USA). She is the Chair of URSI commission F since 2014.