SATELLITE DOPPLER OBSERVATIONS FOR THE MOTIONS OF THE OCEANS

Fabrice Ardhuin, Bertrand Chapron, Christophe Maes, Roland Romeiser, Christine Gommenginger, Sophie Cravatte, Rosemary Morrow, Craig Donlon, and Mark Bourassa

Satellite remote sensing has revolutionized oceanography, starting from sea surface temperature, ocean color, sea level, winds, waves, and the recent addition of sea surface salinity, providing a global view of upper ocean processes. The possible addition of a direct measurement of surface velocities related to currents, winds, and waves opens great opportunities for research and applications.

Velocity can be measured using Doppler radar, using along-track interferometry with two interferometric synthetic aperture radars (InSAR) or the Doppler centroid (DC) from a single radar. Both techniques measure the same surface motions (Romeiser et al. 2014), with different resolving and revisit capabilities, summarized in Fig. 1. InSAR is uniquely able to resolve kilometer-scale patterns in ocean dynamics and is now a mature technology. Adding azimuth diversity to InSAR—for example, with squinted SAR beams—vectors of ocean surface current and wind are measured for each single pass (Martin et al. 2016; Gommenginger et al. 2018), exploring new physical processes including fronts, waves, and submesoscales (McWilliams 2016; Suzuki et al. 2016). The Doppler centroid approach is intrinsically more noisy for the same resolution, but it requires less power and processing, making less expensive global monitoring missions possible. Existing SAR data have already been used to estimate a single component of this velocity vector (Chapron et al. 2005). Further applications have been very limited so far (Rouault et al. 2010; Hansen et al. 2011), due to challenges in removing large nongeophysical velocities

WORKSHOP ON DOPPLER OCEANOGRAPHY FROM SPACE

What: This workshop brought together oceanographers and radar experts to discuss how new radar technology can be used in existing and future satellite missions to directly measure the motions at the ocean surface—namely, currents and waves and their relation to ocean vector winds—for a wide range of applications from subkilometer scales to the global ocean.
When: 10–12 October 2018
Where: Brest, France

AFFILIATIONS: Ardhuin, Chapron, and Maes—Laboratoire d'Océanographie Physique et Spatiale, Brest, France; Romeiser—Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida; Gommenginger—National Oceanography Centre, Southampton, United Kingdom; Cravatte and Morrow—Laboratoire d'Études en Géophysique et Océanographie Spatiales, Toulouse, France; Donlon—European Space Agency, Nordwijk, Netherlands; Bourassa—Florida State University, Tallahassee, Florida
CORRESPONDING AUTHOR: Fabrice Ardhuin, ardhuin@ifremer.fr

DOI:10.1175/BAMS-D-19-0039.1

In final form 18 April 2019

associated with satellite motions, radar pointing, and backscatter gradients (Rodríguez et al. 2018) and the slow development of methods for splitting the measured geophysical velocity into current and wave contributions (Mouche et al. 2008, 2012; Martin et al. 2016; Rodríguez et al. 2018).

Today, several new concepts for Doppler measurements of surface currents are at detailed proposal and design stages for the European Space Agency (ESA) and National Aeronautics and Space Administration (NASA), including sea surface kinematics multiscale monitoring (SKIM; Ardhuin et al. 2018), the Winds and Currents Mission (WaCM; Chelton et al. 2019), and *SeaStar* (Gommenginger et al. 2018).

WORKSHOP OBJECTIVES. In this context, 97 international participants from academia, industry, and space agencies gathered in France in fall 2018 to review the gaps in observational capabilities of currents, winds, and waves; to summarize recent developments in radar technology and processing; and to understand the benefits of existing and proposed Doppler missions for oceanography and air–sea interactions. The objectives of this workshop were 1) to present the achievements and status of spaceborne Doppler radar technology for ocean applications; 2) to review the needs of the oceanographic community in terms of measurements of currents, winds, and waves; and 3) to define a road map for the development of future Doppler radar missions and the uptake of new data. The workshop presentations and video recordings for the first day are available online (https://dofs.sciencesconf.org/).

WHERE CURRENT DATA ARE BADLY NEEDED. Direct measurements of near-surface currents rely on moorings, drifters, ship-based instruments, or shore-based high-frequency (HF) radars in a few coastal regions. The global ocean is sparsely covered by just 1,300 instruments in the Global Drifter Program (GDP; Centurioni et al. 2017). A combination of satellite altimeter sea surface height data and vector winds from scatterometers offers global estimates (Bonjean and Lagerloef 2002; Sudre et al. 2013) but effectively only resolved wavelengths on the order of 200 km and periods longer than 15 days (see also Ballarotta et al. 2019).

This leaves important observation gaps. Especially, in the tropics, geostrophy represents a small fraction of the surface current even when averaged over 30 days (e.g., Sudre et al. 2013; Schlundt et al. 2014), and near-surface GDP drifts measured at 15-m depth may be significantly different from surface currents sampled and estimated by the surface drift of Argo floats. This lack of surface current data severely limits our understanding of tropical dynamics, particularly the heat balance near the equator. This is important for the Pacific and Atlantic cold tongues and the forecasting capabilities of patterns such as rain over Central America or the African monsoon but also for the dynamics of the eastern edge of the Pacific warm pool and the onset of El Niño events.

At high latitudes, sea ice is hiding most of the dynamics from the measurement capabilities of satellite altimeters and only the gyre-scale circulation can be monitored from

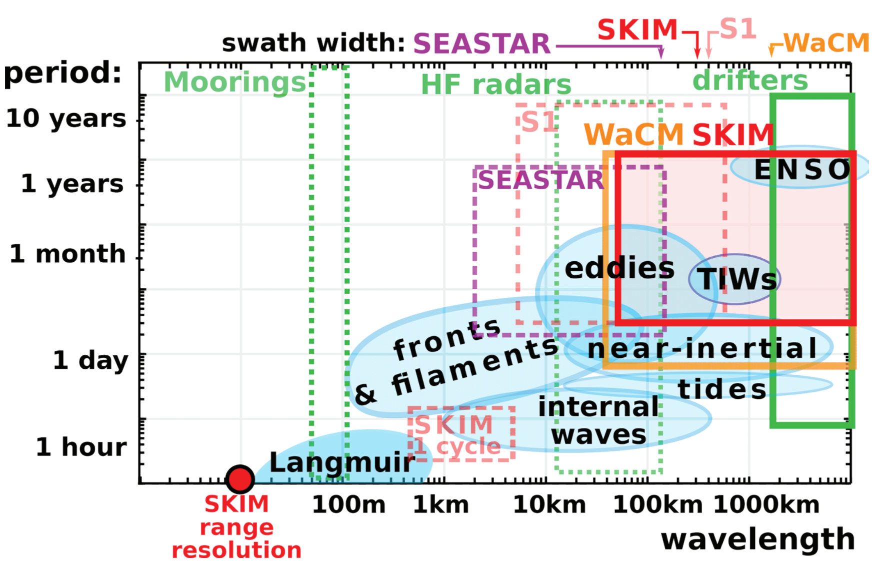

Fig. 1. Spatial and temporal scales of surface velocities of processes of interest and resolving power of existing and proposed observing systems. Dashed boxes correspond to observation that do not have a global or near-global coverage: for example, HF radars are limited to a few coastal areas and SAR-based satellite systems such as Sentinel 1 and *SeaStar* cannot acquire over the full globe due to present technology limitations in power and data downlink capability. The light pink observations (S1 and SKIM 1 cycle) are limited to a single component of the velocity vector. We also note that, away from the equator, the geostrophic part of the surface velocity can be estimated from the combination of satellite altimetry and gravity measurements with resolved wavelengths and periods larger than 200 km and 15 days.

sea level measured in ice-free channels known as "leads" (Armitage et al. 2017). Here, Doppler radars can provide valuable observations to measure near-ice current jets and the mesoscale circulation of the emerging Arctic, which play a dominant role in defining the dynamics of the ice edge and transporting freshwater in the Arctic basin and around Greenland, which are both hugely important in global ocean circulation and regulating the climate and weather.

Finally, in coastal and shelf seas, HF radar coverage is still scarce, and the ocean circulation is characterized by complex and small scale dynamic processes. These include strong ageostrophic components and strong air–sea interactions that call for joint observations of currents, winds, and waves at high resolution.

For both coastal and global scales, the joint measurements of wind, waves, and currents open up great opportunities for science and applications linked to ocean–atmosphere coupling and feedbacks, including the ocean energy cycle, from the wind work to the energy cascade in the ocean circulation. The additional measurement of ocean wave spectra should lead to a better understanding of the relation between currents and waves (e.g., Ardhuin et al. 2017) and their impact on extreme sea states (e.g., Fedele et al. 2016) and upper-ocean turbulence (D'Asaro 2014, Suzuki et al. 2016). Finally, the joint analysis with other remote sensing measurements of temperature, salinity and sea surface height [e.g., Surface Water and Ocean Topography (SWOT); Morrow et al. 2019] can be key in separating slower features from the fast subdaily components of the surface current, including internal tides and near-inertial oscillations. This is a particular issue at wavelengths under 200 km.

TECHNOLOGY IS READY TO HELP. One major outcome of the workshop is that the scientific requirements of the oceanography research community can be addressed using recent technical advances in radar technology and our present understandings of Doppler properties of radar backscatter from the ocean. Satellite-based observation systems can thus be developed for surface currents, winds, and waves using mature Doppler radar technology and signal processing that is optimized for accuracy, revisit time, and resolution within programmatic constraints that include cost and technology readiness levels. The only limitation, shown in Fig. 1, is that it is not yet possible to monitor the entire globe at very high resolution using a single satellite. Thus, two complementary observing strategies can be pursued. On the one hand, rotating beam systems such as SKIM and WaCM can achieve global coverage at moderate resolution, addressing questions of the transport of heat, freshwater, and other constituents. Higher resolution, but very noisy information, can be obtained within single measurement cycles of such systems for a single component of the velocity. On the other hand, a SAR-based system such as *SeaStar* can provide kilometer-resolution snapshots of vector current maps. A repeat coverage that would allow monitoring the time evolution of structures smaller than 20 km requires a 1- or 2-day repeat orbit, for which only a small fraction of the ocean can be covered. For one-component velocities only, data with a resolution of a few kilometers should be available shortly from Sentinel-1 (S1), after correction of nongeophysical signatures. Indeed, the stringent accuracy required by oceanographers is typically of the order of 5 cm s^{-1}, and raw satellite Doppler radar measurements, using either InSAR or DC, contain contributions from the satellite velocity, typically 7 km s^{-1}. Any error in the radar beam pointing knowledge will be misinterpreted as surface motion (a 10^{-6}-rad angle typically corresponds to 1 cm s^{-1}). Corrections of nongeophysical biases are thus essential, but this has now been solved for both satellite and airborne systems, with methods developed to remove residual attitude errors that have predictable patterns from the Doppler measurements (e.g., Rodríguez et al. 2018).

For global monitoring applications, the effective resolving power of a satellite system is driven by the revisit time. A faster revisit time with a single satellite requires a wider swath with incidence angles. At high incidence, Doppler measurements show greater sensitivity to horizontal surface currents and the wave contribution to the measured velocity is relatively smaller. The drawback is a lower backscatter power that requires a higher transmitted power and/or a larger antenna. The effective space–time sampling, resolution, and accuracy of different radar solutions is thus determined by the choice of orbit, the noise of individual measurements that have to be averaged, the power available, and the resulting effective swath width (Chelton et al. 2019).

The initial design of SKIM (Ardhuin et al. 2018) was modified to make it fly in tandem with a European operational meteorology satellite [Meteorological Operational Satellite (MetOP) Second Generation B (SGb)], making the swath wider at 330 km for current and wave measurements and fitting contemporaneously in the swath of the wind vector measurements by the scatterometer instrument on board MetOP. WaCM is designed to measure both wind and current vectors with the same instrument and a 1,700-km-wide swath similar to that of Quick Scatterometer (QuikSCAT), resolving surface currents globally on temporal scales of one to several days to improve the representation of wind–current interactions and their impact on global surface fluxes.

ARE WE READY TO USE SUCH DATA? Building on decades of hydrographic surveys used for defining the ocean circulation, the oceanographic community has easily adopted satellite-derived geostrophic currents, with the possible addition of a mean wind-driven "Ekman current." These are particularly used for the analysis of large-scale transports. Bringing new types of current measurements will probably require a learning and adaptation phase. The development of HF radars can certainly help in preparing users to analyze and use direct surface current measurements. Yet, the sampling will probably require specific analysis and assimilation schemes to support the exploitation of new types of observations. In particular, any revisit time longer than 12 h means that semidiurnal signals are hard to follow from one pass to the next.

CONCLUSIONS AND RECOMMENDATIONS. Lively discussions at the workshop defined the possible next steps in the developments of Doppler oceanography from space. Participants identified issues that can be addressed in the short term, including the following:

- the processing of existing satellite Doppler radar data to a usable quality level to produce single-component current estimates for dissemination and exploitation by the wider scientific community, including existing *Envisat*, Sentinel-1, and Radarsat data;
- the implementation of at least one mission dedicated to total ocean surface current vector monitoring: these future missions should attempt to maximize joint measurements of total current and geostrophic currents in order to better understand what is missing in past satellite-derived products, which may be an area where data-driven approaches combining other measurements can help in enriching past datasets;
- continued exploration of high-resolution Doppler measurements and future radar systems to retrieve kilometer-scale currents and wind vectors;
- continued research to use Doppler information in future scatterometers, possibly increasing the sensitivity of wind vector retrievals at high wind speeds; and
- continued research to examine how currents modify and respond to coupling between the atmosphere, ocean, and surface waves.

Longer term, looking to the next decade and the implementation of Doppler measurements in satellite instruments, important steps have to be taken to

- refine our understanding of ocean motions and current velocities in the top few meters of the ocean and of their sensing by different radar systems;
- develop robust surface current validation strategies based on sound understanding of the abilities, limitations, and specificities of in situ sensors and HF radars;
- leverage and (if possible) optimize the existing in situ/HF radar measurement systems for currents to validate satellite measurements and provide intelligence about the temporal evolution between satellite-derived fields from successive satellite passes; and
- last but not least, prepare numerical models, possibly coupled ocean–wave–atmosphere systems, in order to best take into account the relations between measured quantities on the one hand and wind, waves, and currents on the other hand, which can use data-driven strategies/schemes for the exploitation and assimilation of new nongeostrophic surface current products.

In conclusion, Doppler oceanography from space holds great ocean observing opportunities, with two important avenues. One uses high-resolution methods that can provide insights into small-scale processes that can only be investigated by models or airborne instruments. The other can provide global maps of currents, down to 50-km wavelength, including in the tropics. These will be best used when carefully integrated with other observation methods to constrain the World Ocean circulation and contribute to improved understanding of the global Earth system.

ACKNOWLEDGMENTS. The workshop was supported by CNES and ANR under grants for ISblue (ANR-17-EURE-0015) and LabexMER (ANR-10-LABX-19). The authors thank all the speakers and attendees for a very lively discussion and participation.

REFERENCES

Ardhuin, F., N. Rascle, B. Chapron, J. Gula, J. Molemaker, S. T. Gille, D. Menemenlis, and C. Rocha, 2017: Small scale currents have large effects on wind wave heights.

J. Geophys. Res. Oceans, **122**, 4500–4517, https://doi.org/10.1002/2016JC012413.
——, and Coauthors, 2018: Measuring currents, ice drift, and waves from space: The sea surface kinematics multiscale monitoring (SKIM) concept. *Ocean Sci.*, **14**, 337–354, https://doi.org/10.5194/os-14-337-2018.
Armitage, T. W. K., S. Bacon, A. L. Ridout, A. A. Petty, S. Wolbach, and M. Tsamados, 2017: Arctic Ocean surface geostrophic circulation 2003-2014. *Cryosphere*, **11**, 1767–1780, https://doi.org/10.5194/tc-11-1767-2017.
Ballarotta, M., and Coauthors, 2019: On the resolutions of ocean altimetry maps. *Ocean Sci. Discuss.*, https://doi.org/10.5194/os-2018-156.
Bonjean, F., and G. S. E. Lagerloef, 2002: Diagnostic model and analysis of the surface currents in the tropical Pacific Ocean. *J. Phys. Oceanogr.*, **32**, 2938–2954, https://doi.org/10.1175/1520-0485(2002)032<2938:DMAAOT>2.0.CO;2.
Centurioni, L., E. Charpentier, A. Horáyani, C. Cardinali, and R. Lumpkin, 2017: A global ocean observing system for measuring sea level atmospheric pressure: Effects and impacts on numerical weather prediction. *Bull. Amer. Meteor. Soc.*, **98**, 231–238, https://doi.org/10.1175/BAMS-D-15-00080.1.
Chapron, B., F. Collard, and F. Ardhuin, 2005: Direct measurements of ocean surface velocity from space: Interpretation and validation. *J. Geophys. Res.*, **110**, C07008, https://doi.org/10.1029/2004JC002809.
Chelton, D. B., M. G. Schlax, R. M. Samelson, J. T. Farrar, M. J. Molemaker, J. C. McWilliams, and J. Gula, 2019: Prospects for future satellite estimation of small-scale variability of ocean surface velocity and vorticity. *Prog. Oceanogr.*, **173**, 256–350, https://doi.org/10.1016/j.pocean.2018.10.012.
D'Asaro, E. A., 2014: Turbulence in the upper-ocean mixed layer. *Annu. Rev. Mar. Sci.*, **6**, 101–115, https://doi.org/10.1146/annurev-marine-010213-135138.
Fedele, F., J. Brennan, S. P. de León, J. Dudley, and F. Dias, 2016: Real world ocean rogue waves explained without the modulational instability. *Sci. Rep.*, **6**, 272715, https://doi.org/10.1038/srep27715.
Gommenginger, C., B. Chapron, A. Martin, J. Marquez, C. Brownsword, and C. Buck, 2018: SEASTAR: A new mission for high-resolution imaging of ocean surface current and wind vectors from space. *Proc. EUSAR 2018*, Aachen, Germany, IEEE, 1–6.
Hansen, M. W., J. A. Johannessen, K. F. Dagestad, F. Collard, and B. Chapron, 2011: Monitoring the surface inflow of Atlantic Water to the Norwegian Sea using Envisat ASAR. *J. Geophys. Res.*, **116**, C12008, https://doi.org/10.1029/2011JC007375.
Martin, A. C. H., C. Gommenginger, J. Marquez, S. Doody, V. Navarro, and C. Buck, 2016: Wind-wave-induced velocity in ATI SAR ocean surface currents: First experimental evidence from an airborne campaign. *J. Geophys. Res. Oceans*, **121**, 1640–1653, https://doi.org/10.1002/2015JC011459.
McWilliams, J. C., 2016: Submesoscale currents in the ocean. *Proc. Roy. Soc. London*, **427A**, https://doi.org/10.1098/rspa.2016.0117.
Morrow, R., and Coauthors, 2019: Global observations of fine-scale ocean surface topography with the Surface Water and Ocean Topography (SWOT) mission. *Front. Mar. Sci.*, **6**, 232, https://doi.org/10.3389/fmars.2019.00232.
Mouche, A. A., B. Chapron, and N. Reul, 2008: Predicted Doppler shifts induced by ocean surface wave displacements using asymptotic electromagnetic wave scattering theories. *Waves Random Complex Media*, **18**, https://doi.org/10.1080/17455030701564644.
——, F. Collard, B. Chapron, K.-F. Dagestad, G. Guitton, J. A. Johannessen, V. Kerbaol, and M. W. Hansen, 2012: On the use of Doppler shift for sea surface wind retrieval from SAR. *IEEE Trans. Geosci. Remote Sens.*, **50**, 2901–2909, https://doi.org/10.1109/TGRS.2011.2174998.
Rodríguez, E., A. Wineteer, D. Perkovic-Martin, T. Gál, B. W. Stiles, N. Niamsuwan, and R. R. Monje, 2018: Estimating ocean vector winds and currents using a Ka-band pencil-beam Doppler scatterometer. *Remote Sens.*, **10**, 576, https://doi.org/10.3390/rs10040576.
Romeiser, R., H. Runge, S. Suchandt, R. Kahle, C. Rossi, and P. Bell, 2014: Quality assessment of surface current fields from TerraSAR-X and TanDEM-X along-track interferometry and Doppler centroid analysis. *IEEE Trans. Geosci. Remote Sens.*, **52**, 2759–2772, https://doi.org/10.1109/TGRS.2013.2265659.
Rouault, M. J., A. Mouche, F. Collard, J. A. Johannessen, and B. Chapron, 2010: Mapping the Agulhas Current from space: An assessment of ASAR surface current velocities. *J. Geophys. Res.*, **115**, C10026, https://doi.org/10.1029/2009JC006050.
Schlundt, M., P. Brandt, M. Dengler, R. Hummels, T. Fischer, K. Bumke, G. Krahmann, and J. Karstensen, 2014: Mixed layer heat and salinity budgets during the onset of the 2011 Atlantic cold tongue. *J. Geophys. Res. Oceans*, **119**, 7882–7910, https://doi.org/10.1002/2014JC010021.
Sudre, J., C. Maes, and V. Garçon, 2013: On the global estimates of geostrophic and Ekman surface currents. *Limnol. Oceanogr. Fluids Environ.*, **3**, 1–20, https://doi.org/10.1215/21573689-2071927.
Suzuki, N., B. Fox-Kemper, P. E. Hamlington, and L. P. van Roekel, 2016: Surface waves affect frontogenesis. *Geophys. Res. Lett.*, **121**, 3597–3624, https://doi.org/10.1002/2015JC011563.