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Satellite Doppler observations for the motions of the oceans

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Corresponding Author:	Fabrice Ardhuin, Ph.D. CNRS Plouzane, FRANCE
Corresponding Author's Institution:	CNRS
First Author:	Fabrice Ardhuin, Ph.D.
Order of Authors:	Fabrice Ardhuin, Ph.D.
	Bertrand Chapron
	Christophe Maes
	Roland Romeiser
	Christine Gommenginger
	Sophie Cravatte
	Rosemary Morrow
	Craig Donlon
	Mark Bourassa
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Author Comments:	Johnny Johannessen : Johnny.Johannessen@nersc.no Jeroen Molemaker: nmolem@atmos.ucla.edu

Dear Editor,

Please find attached a revised version for the article entitled "Doppler observations for the motions of the oceans" that we would like you to consider for publication in the Bulletin of the American Meteorological Society.

Its only modifications are the detailed corrections following the eding you suggested, and the addition of one reference (Ballarotta et al. 2019) that is particularly relevant for the discussion of the resolving power of today's satellite altimeters.

We look foward to hearing from you,

Best regards,

Fabrice Ardhuin

Satellite Doppler observations for the motions of the oceans

Fabrice Ardhuin *, Bertrand Chapron, Christophe Maes

LOPS, Brest, France

Roland Romeiser

RSMAS, Miami, FL

Christine Gommenginger

NOC, Southampton, UK

Sophie Cravatte, Rosemary Morrow

LEGOS, Toulouse, France

Craig Donlon

ESA, Nordwijk, the Netherlands

Marc Bourrassa

Florida State University, Tallahassee, Florida

* *Corresponding author address:* LOPS, Brest, France

E-mail: ardhuin@ifremer.fr

ABSTRACT

Abstract not required.

(Capsule Summary)

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 sub-kilometer scales to the global ocean.

When: 10-12 October 2018

Where: Brest, France

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 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 Figure 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. Yet, it requires less power and processing, making possible less expensive global monitoring missions. 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 non-geophysical velocities 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 ESA and NASA, including SKIM (Ardhuin et al. 2018), 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 radar Doppler 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 the 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 1300 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 of order 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, in particular the heat balance near the equator. This is important for the Pacific and Atlantic cold tongue 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 Nino events.

At high latitude, 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 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, 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 et al., 2014, Suzuki et al., 2016). Finally, the joint analysis with other remote sensing measurements of temperature, salinity and sea surface height (e.g. SWOT, Morrow et al. 2019) can be key in separating from slower features the fast sub-daily 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 Figure 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 transport of heat, fresh water 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, although a repeat coverage that would allow monitoring the time evolution of structures smaller than 20 km requires a 1 or 2-day repeat orbit with data covering only a small fraction of the ocean.

For 1-component velocities only, data at few kilometer resolution should be available shortly from Sentinel-1, after correction of non-geophysical signatures. Indeed, the stringent accuracy required by oceanographers is typically of the order of 5 cm/s, and raw satellite Doppler radar measurements, using either InSAR or DC, contain contributions from the satellite velocity, typically 7 km/s. 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). Corrections of non-geophysical 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 back-scatter power which 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 (MetOP 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 SCA instrument onboard MetOP. WaCM is designed to measure both wind and current vectors with the same instrument and a 1700 km wide swath similar to that of 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 larger than 12 hours means that semi-diurnal 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 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: this includes 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. This 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.

- 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.

- 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. This can use data-driven strategies/schemes for the exploitation and assimilation of new non-geostrophic 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.

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LIST OF FIGURES

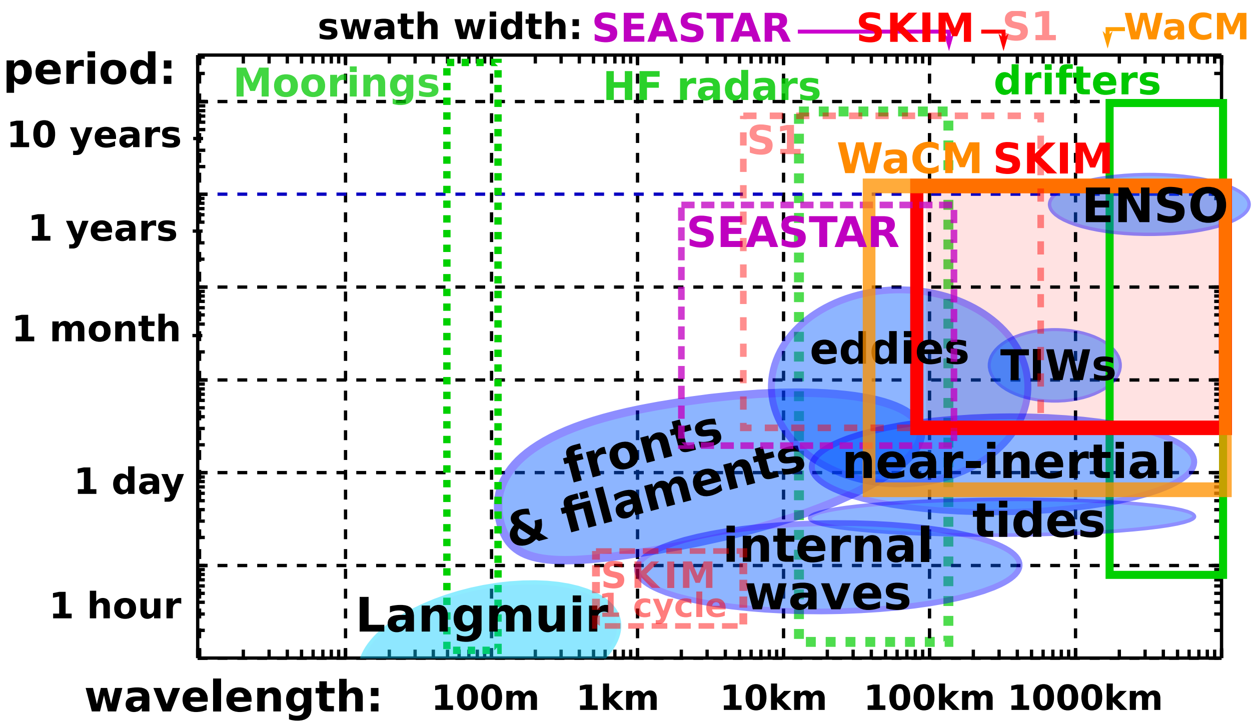

FIG. 1. Spatial and temporal scales of surface velocities of processes of interest and resolving power of existing and proposed observing systems. Dashed boxes correspond to observation that do not have a global or near-global coverage, e.g. HF radars are limited to a few coastal areas and SAR-based satellite systems such as Sentinel 1 (S1) 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.

We appreciate the detailed editing performed on the text that improved its clarity.

We have thus incorporated all changes suggested with 2 exceptions :

1) Line 36 : « Squinted » is actually a technical term for radar. It indicates the fact that the radar beam is steered to a direction that is not perpendicular to the cross-track direction. I am not sure how to best replace this jargon with something more understood by a wider community.

2) Line 77 : I have made explicit what a « lead » is by adding : « measured in ice-free channels known as `leads' »

Also, a recent paper appeared to deserve to be cited, so I have taken the liberty to add a reference to Ballarotta et al. on page 67.

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Initial Estimation Worksheet

BAMS_Worksheet_FA.pdf