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Key Points:

- Doppler scatterometry (WaCM) could measure simultaneous surface winds and currents globally
- Ocean surface currents are resolved at scales of 10 km in most locations for wind speeds greater than 5 m/s without temporal averaging
- Typical effective wavelength resolution for surface current relative vorticity and divergence are 15 km and 25 km without temporal averaging

Supporting Information:

- Supporting Information S1
- Figure S1
- Figure S2

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On the Surface Current Measurement Capabilities of Spaceborne Doppler Scatterometry

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Abstract Wide-swath spaceborne Doppler scatterometry is a promising technique for the simultaneous measurement of global ocean surface winds and currents. The technique has been proven from airborne platforms, and here we use the lessons learned to examine a range of implications for a spaceborne system. We use a Doppler scatterometer simulator and a state-of-the-art global circulation model to generate surface current measurements and their random errors. We find that a feasible instrument could measure 5 km gridded surface currents with typical random errors between 10 and 25 cm/s. For higher wind speeds, the random error in surface current decreases logarithmically. This level of accuracy allows for the computation of surface current relative vorticity and horizontal divergence with typical wavelength resolutions of 15–30 and 25–60 km, respectively. Unlike previous studies, we find that these measurements do not require multiday averaging, opening up new avenues for monitoring global ocean circulation.

Plain Language Summary Our understanding of the ocean, the atmosphere, and the Earth system as a whole has been profoundly bettered by the global perspective of space-based sensors. For decades, radar scatterometers have measured global ocean winds from space, contributing significantly to our scientific understanding of the atmosphere and improving forecast models. With a similar instrument, and the addition of "Doppler" capability, a Doppler scatterometer can measure ocean winds and ocean surface currents simultaneously, which opens new avenues to understanding the ocean, the atmosphere, and how they interact. This type of instrument has been successfully built and proven to work on airborne platforms but has yet to be implemented on a satellite. In this work, we have simulated the measurements of a spaceborne Doppler scatterometer to understand the oceanic scales that such an instrument might be able to observe. We find that ocean currents and their derivatives could be measured at scales better than 30 km. This enables the study of many currently unobserved ocean processes, including the vertical circulation of the ocean and the transport of plastics, kinetic energy, heat, and gasses.

1. Introduction

The Earth is a complex and coupled system that maintains balance, in part, through air-sea interactions taking place within the marine-atmospheric boundary layer (MABL). On the atmospheric side of the MABL, winds apply sustained forcing to the ocean surface that drives large-scale ocean circulation and regulates the air-sea transfer of gasses, heat, and energy. On the ocean side of the MABL, large-scale ocean currents shed mesoscale ocean eddies that account for nearly 80% of the oceans kinetic energy (Ferrari & Wunsch, 2009) and modulate surface wind stress both through kinetic effects (Kelly et al., 2005; Pacanowski, 1987; Sullivan & McWilliams, 2010) and temperature-induced boundary layer stratification (Bourassa & Hughes, 2018; Chelton et al., 2004; Cronin et al., 2019; Geernaert, 1990; Liu et al., 1979). Along the edges of these eddies, and elsewhere, smaller-scale filaments form that can lead to mixing and vertical velocities thought to strongly influence the exchange of heat (Su et al., 2018), carbon dioxide (Ott et al., 2015), and kinetic energy (Byrne et al., 2016) between the surface and the deeper ocean. Currents and winds at the surface are also responsible for the transport of biological particles, pollutants (Henaff et al., 2012), and an increasing amount of man-made waste whose ultimate fate is not well understood (van Sebille et al., 2020).

Over the last decade, the importance of air-sea interactions and mesoscale-or-smaller ocean currents have come to light, largely thanks to estimates made by global high-resolution computer models that have surpassed our observational capabilities. Our present global measurements of ocean currents come from the geostrophic subset of the total ocean surface current field. These measurements, which are estimated using the spatial derivatives of sea surface height fields from spaceborne radar altimeters, resolve time scales of about 2 weeks and spatial scales of about 100 km (Chelton et al., 2011) and do not include important ageostrophic currents, such as Ekman currents (Lagerloef et al., 1999), inertial currents (Alford et al., 2016), tidal currents (Savage et al., 2017), currents driven by mesoscale eddy strain field deformation (McWilliams, 2016), or wave-induced instabilities (McWilliams, 2016). Furthermore, since the geostrophic current field is by definition non-divergent, it is not possible to estimate surface current divergence (or infer vertical velocities) from altimeter measurements. With these limitations, most of the interactions listed above cannot presently be fully constrained at a global scale, even if predicted by computer models. The tropical oceans (e.g., Kessler, 2006), where geostrophy breaks down, exhibit substantial divergence/upwelling important to the global heat budget, as well as tropical instability waves (TIWs) (Chelton et al., 2000; Legeckis, 1977; Philander, 1976), which may impact the occurrence of the ENSO phenomenon (Holmes et al., 2019).

Doppler scatterometry, such as the proposed Ka-band Winds and Currents Mission (WaCM) concept (Rodriguez et al., 2019), is a technique capable of the simultaneous measurement of ocean vector winds and total surface currents over a wide swath, O(1,500 km), with near daily global coverage. The wide-swath WaCM concept is different from the near-nadir SKIM concept (Ardhuin et al., 2018), in that it concentrates on winds and currents, rather than waves and currents, and achieves higher spatial and temporal resolutions. As in conventional wind scatterometry (Bourassa et al., 2019), measurements of the radar cross section by a pencil-beam scatterometer are used to estimate ocean surface equivalent neutral winds. Ka-band, like the more traditional Ku-band, can be used for wind estimation (Rodríguez et al., 2018; Yurovsky et al., 2016) and brings the added benefit of improved spatial resolution, which improves by a factor of nearly 3 for the same antenna size. By also retaining radar phase information, the motion of total ocean surface currents can be estimated from the phase shift between subsequent radar pulses (Rodríguez et al., 2018; Villas Bôas et al., 2019). Unlike the estimates made by altimeters, surface currents estimated by a Doppler scatterometer are sensitive to the full instantaneous surface current field, including the many ageostrophic and divergent processes listed in paragraph two.

Doppler scatterometry has been proven from airborne platforms (Rodríguez et al., 2018; Wineteer et al., 2020) and is used prominently in the ongoing NASA Earth Ventures Suborbital-3 S-MODE (Submesoscale Ocean Dynamics Experiment) mission. To scale to a spaceborne mission, Rodríguez (2018) derived the relationships between radar parameters and surface current random error, while Chelton et al. (2018) thoroughly analyzed the capabilities of a spaceborne Doppler scatterometer assuming a simple, constant random error, including space and time sampling considerations. Here, we combine and expand upon the work of Rodriguez and Chelton et al. to investigate the effective in-swath wavelength resolution, random error, and sampling capabilities of a spaceborne Doppler scatterometer using a purposefully designed Doppler scatterometer instrument and observation simulator.

2. Methods

2.1. Instrument and Mission Design

The National Academies' 2018 Decadal Survey recommended a competed Explorer class mission for surface current measurement, with a spatial resolution of 5–10 km, random error smaller than 50 cm/s, and global coverage times of 1–2 days (National Academies of Sciences, Engineering, and Medicine, 2018). These requirements can be met with the WaCM Doppler scatterometer concept (Rodriguez et al., 2019).

We believe a baseline design utilizing a 5×0.35 m antenna, 400 W transmit power, a 700 km sunsynchronous polar orbit, and an incidence angle of about 56° (Rodríguez, 2018) is both technically feasible and could be built within the NASA Explorer class mission specifications. To reduce cost, an instrument with similar surface current random error and resolution capabilities (meaning similar to the baseline results shown in this paper) could be designed with 100 W transmit power and a steeper, 45° incidence angle. The primary drawback of the reduced cost mission is a reduction in swath width from the baseline 1,700 km, to about 1,200 km, which results in an increased revisit time and an increased time for global coverage. While the baseline mission would achieve near global coverage within 1 day, the reduced cost mission would still meet the Decadal Survey recommendation of global coverage within 2 days. Although the difference in swath width is an important parameter in determining the repeat timing for measurements, which can be used in some cases to help decrease random error through temporal averaging (Ardhuin et al., 2018;





Figure 1. MITgcm 1 km resolution model fields for surface speed (top), relative vorticity (middle), and divergence/*f* (bottom) in the Gulf Stream during November. A single 1,700 km WaCM swath is overlaid on each map.

Chelton et al., 2018), we do not consider it in this study. Instead, we focus on instantaneous (single pass) measurements, for which the baseline and reduced-swath designs have similar results. As an illustration of swath size compared to typical features of surface velocity, relative vorticity, and divergence, Figure 1 shows the baseline, 1,700 km swath of the WaCM instrument drawn over model surface current fields in the Gulf Stream.

2.2. Simulator and Ocean Model Overview

Our Doppler scatterometer simulator simulates all viewing geometries, look vectors, and resulting radar equation parameters given a known orbit, antenna, and radar power/timing information (note that all simulations shown in this work assume parameters according to the baseline design above). From these simulated radar data, surface current errors are estimated according to the relationships given in Rodríguez (2018), which are then added onto collocated model surface current fields. We examine global representative cases from three high-resolution ocean simulations: a 1 km nested simulation implemented in the Gulf Stream region, a 500 m nested simulation implemented in the California Current region, and finally, the LLC4320 1/48° model in the Equatorial Pacific. For the CA current and Gulf Stream simulations, the 500 m and 1 km model resolutions should be sufficiently small enough to recover any small-scale ocean currents that might be observed by the 5 km WaCM grid; the 2–4 km resolution in the Equatorial Pacific should be sufficient given the relatively large-scale currents in the region. Note that when simulating a WaCM measurement, each of these models is smoothed and sampled to the 5 km WaCM grid. All models were run using the Massachusetts Institute of Technology general circulation model including tides (MITgcm, Marshall et al., 1997). The Gulf Stream simulation was run for November, while the California Current and Equatorial





Figure 2. The cross-track and wind speed (U_{10}) dependence of cross-(dashed line) and along-track (dotted line) surface current standard deviation (σ) assuming the baseline design. A cross-track distance of 0 represents the center of the swath, while 1 represents the edges. Speed standard deviation is shown as solid lines, assuming equal surface current component magnitudes and the shown cross/along-track standard deviations.

Pacific simulations were run for April. For more information about the simulator design or ocean modeling setup, we refer the reader to the supporting information. An important aspect of the models used is the inclusion of internal waves, which have been neglected in past studies. As we see below, these features can play a dominant role in the retrieval of surface divergence.

2.3. Evaluating Resolution Capability

Following Chelton et al. (2018), the resolution capability of a measurement is defined using the averaging scale-dependent measurement signal-to-noise standard deviation ratio, γ (Equation 1). A value of $\gamma = 1$ would indicate that spatial variability is equally attributable to noise or a real feature.

$$\gamma = \sqrt{\frac{Var(F)}{Var(F_c - F)}} \tag{1}$$

By smoothing noise-free measurements, F, and the estimated noisy fields, F_e , with spatial Parzen filters of different half-power cutoff wavelengths, we can determine the amount of smoothing necessary to achieve a target

value of γ . We have chosen a γ requirement of $\sqrt{10}$, corresponding to a factor of 10 in spectral power, to be consistent with Chelton et al. (2018); however, we include plots of γ versus wavelength cutoff for each of our comparisons so that the reader can make their own determination of effective wavelength resolution capability. Certainly, the choice of γ requirement depends on the application; the SWOT mission (Durand et al., 2010), for example, uses $\gamma = 1$. We further address the usefulness of these thresholds throughout section 3.

Besides the surface currents themselves, we specifically consider *F* to be the surface current relative vorticity, $\zeta = \partial v/\partial x - \partial u/\partial y$, and horizontal divergence (divergence hereinafter), $\delta = \partial u/\partial x + \partial v/\partial y$, because these quantities are related to important physical processes (see, e.g., Vallis, 2006) and place stringent requirements on surface current random error. We compute derivative quantities using central differences of the spatially smoothed noise-free and noisy surface current component fields before evaluating Equation 1.

3. Results

3.1. Error Model

As in traditional pencil-beam scatterometry, measurement error for surface currents grows at the center and edges of the swath but decreases near the "sweet spots" between the center and edges. These relationships were explored extensively in Rodríguez (2018) for a typical ocean wind speed of 6 m/s.

Since the radar signal-to-noise ratio (SNR) depends on the amount of radiation backscattered from the ocean surface, higher wind speeds will increase the radar SNR and decrease surface current random error. We use an empirically derived geophysical model function (GMF) to estimate return power based on a given wind speed and direction. Especially at low wind speeds, this wind GMF is evolving (Rodríguez et al., 2018; Yurovsky et al., 2017) as data become available at Ka-band, which could cause unknown biases in our surface current error model at low wind speeds.

Figure 2 shows the normalized cross-track dependence of swath-oriented surface current standard deviation with curves for 4, 6, and 12 m/s wind speed. These swath-oriented standard deviations represent the surface current error for currents flowing in the along- and across-swath directions and can be propagated through to geographically oriented component errors with information about the satellite flight direction. For wind speeds of 6 m/s, the swath-oriented random errors approach 10-15 cm/s in the sweet spot, slightly better than the result obtained by Rodríguez et al. (2018), Figure 13, primarily due to sampling assumptions. If we define the maximum acceptable speed measurement error as 50 cm/s, the effective swath is about 80% of the total swath width assuming 6 m/s wind. Note that both Figure 2 and Rodríguez (2018) assume 5 km gridding with no smoothing applied, which is equivalent to a feature wavelength cutoff of 10 km.

As the wind speed increases (Figure 2, red lines), the component errors drop to about 6 cm/s in the sweet spot. This wind speed dependence is an important result. It shows that for not uncommon higher wind speeds, we can expect to see lower surface current random error than has been previously assumed. Conversely, lower wind speeds will suffer from larger random error (blue lines).

Based on our error model, we can expect our results to be somewhat different than those obtained in Chelton et al., where a 50 or 25 cm/s random error was added to surface current speed measurements (split equally between components). Indeed, looking at Figure 2, the expected speed errors are well below 25 cm/s for much of the swath at typical ocean wind speeds and vary significantly with speed and cross-track location.

While this error model is realistic in terms of random instrument errors, it does not account for errors due to satellite mispointing, orbit errors, or any geophysical biases due to the atmosphere or ocean waves. While this may make our results optimistic, these types of correlated errors have long-wavelength behavior that has a small impact on surface current derivatives and can be modeled or removed during ground processing (Ardhuin et al., 2018). The ability to remove these effects depends on the specific implementation, but Rodríguez et al. (2018) have demonstrated error removal using a commercial spin motor in an aircraft, a more turbulent environment than space. As discussed by Chelton et al., the ability to resolve derivative fields is driven by the uncorrelated noise due to noise amplification when computing them.

3.2. Expected Performance

Since the ocean surface wind speed is important in determining random errors, we selected a reference ground swath for each of the Equatorial Pacific (EP), the Gulf Stream (GS), and the California Current (CA), colocated with currents from the MITgcm, and simulated surface current random errors based on a range of possible wind speeds. For all spatial plots and γ calculations, we have masked out the center and edges of the swath where errors typically become unacceptable (\geq 50 cm/s).

3.2.1. Spatial Resolution

Figure 3 shows expected surface current estimates in the GS and the EP, including simulated random errors over a range of wind speeds, for single swaths using the baseline instrument design. These plots are shown at the native 5 km instrument gridding. As expected based on our error model discussed above, weak currents are dominated by noise, especially at low wind speeds. As wind speeds increase, surface current measurement error quickly drops off. South of the EP, for example, currents of less than about 0.5 m/s are unresolved at low wind speeds for 5 km spatial gridding. On the other hand, these same weak currents quickly rise above the noise at moderate and higher wind speeds. North of the EP, the Equatorial Counter Current is discernible at 3 m/s wind speed but becomes quite clear with 6 m/s winds. In the case of strong geostrophic GS flow, mesoscale eddies are apparent even at low wind speeds, with smaller-scale features along their edges appearing at moderate wind speeds.

The ability to resolve weaker currents in the EP can be achieved at the cost of spatial averaging, which is appropriate for the larger size of typical Equatorial features, such as TIWs, whose impact on the winds has been detected by low-resolution scatterometers (Small et al., 2008). The γ plots for surface current speed show that along the EP, where surface currents are typically weaker, filtering with a 10–15 km wavelength filter is necessary to reach $\gamma = \sqrt{10}$ with 6 m/s wind speeds. For lower wind speeds, a filter of 25 km or more is necessary to reach our threshold. In the GS, the stronger surface currents reduce the filtering requirement: 10 km filtering results in $\gamma = \sqrt{10}$ with just 4 m/s wind speeds.

Figures 4 and 5 show maps of relative vorticity and divergence normalized by the Coriolis parameter, f, for a range of wind speeds in the GS and the EP. CA current maps are shown in the supporting information. Maps of vorticity and divergence are shown with filter cutoffs of 20 and 30 km, respectively (30 and 50 km for the CA current). Consistent with Figures 2 and 3, as wind speed increases, the signals of ζ/f and δ/f become clearer and coherent structures emerge in both. Wind speeds over 6 m/s result in a vorticity wavelength resolution capability of about 15 km in the GS. In the CA current system and the EP, weaker currents require about 30 km filtering in relative vorticity.

Owing to its measurement of the total surface velocity, the previously unobserved divergence field could be estimated for the first time from Doppler scatterometer measurements. It is, however, the more difficult of the two derivative fields to measure and interpret. Compared to the vorticity γ plots, the divergence γ in the GS and the EP is slower to reach a value of $\sqrt{10}$. We find the filtering requirement to be 25–30 km for a wind speed of 6 m/s. In the CA current system, the divergence requires more filtering, this time to about 60 km.





Figure 3. Noisy surface current speeds (U_s) for simulated passes over the Gulf Stream (left) and the Equatorial Pacific (right). Lower wind speeds (top) result in larger surface current random error than do higher wind speeds (bottom). Bottom row: surface current γ versus wind speed for the Gulf Stream (left) and the Equatorial Pacific (right) for smoothing scale λ_c of 10, 25, and 50 km. Dashed black and blue lines represent thresholds of $\gamma = 1$ and $\sqrt{10}$, respectively.

Even at lower-resolution scales, this would constitute a significant observation of a quantity that cannot be observed by the altimeter constellation and has a significant impact on global gas, heat, and kinetic energy fluxes.

Maps of divergence in all regions reveal conspicuous, but largely incoherent, patterns with non-negligible values for δ/f (~0.4), which are present in the model and are not artifacts of the measurement noise. Numerous studies, starting with Kunze (1985) and Young and Jelloul (1997), have shown that internal gravity





Figure 4. Maps of simulated Doppler scatterometer estimates of normalized relative vorticity (left) and horizontal divergence (right) as a function of a different wind speed conditions in the Gulf Stream region. Prior to the computation of the relative vorticity, noisy velocity components were smoothed using a half-power cutoff wavelength λ_c of 20 km to compute relative vorticity and a half-power cutoff wavelength λ_c of 30 km to compute horizontal divergence. Bottom row: the wind speed and filter cutoff dependency of γ for vorticity (left) and divergence (right). Dashed black and blue lines represent thresholds of $\gamma = 1$ and $\sqrt{10}$, respectively.

waves at large scales are scattered and dispersed by mesoscale eddies, contributing to kinetic energy dissipation. However, there is another mechanism that contributes to the divergence field, that is, balanced mesoscale eddy stirring that promotes the development of divergent motions (Zhang & Qiu, 2018). This eddy-induced divergence field captures most of the vertical velocity field associated with balanced motions and consequently has a significant impact on the ocean energy and carbon export budgets (Sasaki et al., 2014; Su et al., 2018). Future works will be necessary to discriminate the divergence associated with internal wave scattering versus the divergence associated with the balanced part of the flow at scales smaller than 50 km (Torres et al., 2018) from the perspective of Doppler scatterometry.

The Equatorial Countercurrent, at about 5° North, is associated with strong bands of vorticity and divergence. For the 30 km divergence wavelength cutoff shown in Figure 5, it is difficult to discern banding

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Figure 5. Same as Figure 4 but for the Equatorial Pacific region.

patterns over the signature of internal wave divergence. With a larger wavelength filter, banding is much more apparent spatially (see supporting information). Note that Equatorial currents are presently not measurable by satellite altimeters due to the breakdown of the geostrophic equations near the equator. Doppler scatterometry could give us the first synoptic measurement of equatorial currents.

Regardless of the study region, the wind speed will largely determine the measurement random error and thus the resolvable scales for surface currents and derivatives. In the EP, the prevailing winds are typically lower than in the GS, with average wind speeds of 3–6 m/s along the Equator versus 9+ m/s along the GS. This will likely limit the resolvable surface current wavelengths in the Equatorial Pacific to at least 30–50 km and limit resolvable derivatives to 50+ km wavelengths. For processes like Equatorial upwelling and TIWs, these scales may be sufficient; however, studies of smaller-scale processes will likely need to wait for higher

wind speed conditions, which do occur, albeit typically on seasonal time scales. On the other hand, wavelength resolution performance at higher latitudes will be enhanced due to the stronger prevailing winds associated with those regions.

Compared to the results in Chelton et al. (2018), the results presented here show that realistic measurement errors have significantly better resolution capabilities than the uniform error cases examined in Chelton et al. (2018). As a sanity check, we performed the same analysis as Chelton et al. using our California Current model and a constant 25 cm/s random error with consistent results. Our simulator results in the CA current region find a vorticity resolution capability of about 35 km, which is consistent with average surface current measurement errors of about 10 cm/s in Figure 44 of Chelton et al. (2018). This level of error is in line with Figure 2 and Rodríguez (2018).

4. Conclusions and Perspectives

Doppler scatterometry offers a powerful tool for remotely sensing global ocean winds and total surface currents. Our results indicate that an instrument, such as the WaCM concept, fitting within the NASA Explorer class, could significantly exceed the surface current random error and sampling requirements put forth by the National Academy and further measure instantaneous relative vorticity and divergence derivative fields at resolutions between 10 and 50 km, depending on wind speed and location.

Even at these resolutions, the capability of the WaCM mission would exceed the capability of SWOT to measure synoptic relative vorticity (Chelton et al., 2018) and would present the first ever determination of global surface current divergence, which is an important indicator of vertical transports in the ocean. The additional, simultaneous measurement of surface winds would bring a significant advantage in our understanding of air-sea interactions and dynamics of the MABL. These are critical quantities to observe on a global scale to constrain climate and circulation models and would constitute a significant contribution to understanding the Earth's climate.

Data Availability Statement

The MITgcm model data used throughout this study are publicly available from the ECCO project (at https://data.nas.nasa.gov/ecco/).

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Horizontal divergence δ







