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SEASTAR: A Mission to Study Ocean Submesoscale Dynamics and Small-Scale Atmosphere-Ocean Processes in Coastal, Shelf and Polar Seas

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High-resolution satellite images of ocean color and sea surface temperature reveal an abundance of ocean fronts, vortices and filaments at scales below 10 km but measurements of ocean surface dynamics at these scales are rare. There is increasing recognition of the role played by small scale ocean processes in ocean-atmosphere coupling, upper-ocean mixing and ocean vertical transports, with advanced numerical models and *in situ* observations highlighting fundamental changes in dynamics when scales reach 1 km. Numerous scientific publications highlight the global impact of small oceanic scales on marine ecosystems, operational forecasts and long-term climate projections through strong ageostrophic circulations, large vertical ocean velocities and mixed layer re-stratification. Small-scale processes particularly dominate in coastal, shelf and polar seas where they mediate important exchanges between land, ocean, atmosphere and the cryosphere, e.g., freshwater, pollutants. As numerical models continue to evolve toward finer spatial resolution and increasingly complex coupled atmosphere-wave-ice-ocean systems, modern observing capability lags behind, unable to deliver the high-resolution synoptic measurements of total currents, wind vectors and waves needed to advance understanding, develop better parameterizations and improve model validations, forecasts and projections. SEASTAR is a satellite mission concept that proposes to directly address this critical observational gap with synoptic two-dimensional imaging of total ocean surface current vectors and wind vectors at 1 km resolution and coincident directional wave spectra. Based on major recent advances in squinted along-track Synthetic Aperture Radar interferometry, SEASTAR is an innovative, mature concept with unique demonstrated capabilities, seeking to proceed toward spaceborne implementation within Europe and beyond.

Keywords: satellite, air sea interactions, upper ocean dynamics, submesoscale, coastal, marginal ice zone, radar, along-track interferometry

THE NEED FOR SYNOPTIC HIGH-RESOLUTION OCEAN CURRENT, WIND AND WAVE MEASUREMENTS

Processes at the ocean-atmosphere interface are fundamental regulators of the Earth System, impacting a multitude of phenomena on global to local scales. This section highlights prevailing scientific questions that call for new high-resolution observations of ocean currents, winds and waves. Interested readers are referred to Villas Bôas et al. (2018) for a comprehensive review of relevant phenomena and of present-day observational gaps for ocean surface currents, winds and waves.

Understanding the Ocean Submesoscale, Upper Ocean Dynamics and Vertical Exchanges

High-resolution satellite images of the ocean reveal that, far from being quiescent and uniform, the ocean is teeming with dynamic structures at different scales. Together with the jets and eddies of the energetic mesoscale (scales between 10 and 100 km) and internal waves, the ocean displays intense variability at scales between 0.1 and 10 km known as the submesoscale. These small scale features were ignored until relatively recently but a growing body of research now indicates that the interactions of these small features with the larger ocean mesoscale and the atmosphere make these key drivers of upper ocean mixing, horizontal and vertical transport, air-sea exchanges and marine ecosystem response (Lapeyre and Klein, 2006; Ferrari and Wunsch, 2009; D'Asaro et al., 2011; McWilliams, 2016; Lévy et al., 2018).

High-resolution numerical model simulations were among the first to reveal the role of the submesoscale for ocean stratification, large-scale circulation and climate (Capet et al., 2008; Lévy et al., 2010). Many studies have confirmed the associated high vertical ocean velocities and the subsequent impact on phytoplankton and biological productivity (Lapeyre and Klein, 2006; McGillicuddy et al., 2007; Mahadevan et al., 2008; Lévy et al., 2012; Woodson and Litvin, 2015). At the surface, these processes strongly affect the dispersion of floating materials (e.g., oil, plastics), which accumulate in high concentrations in convergence zones associated with density fronts and cyclonic vortices (Maximenko et al., 2017; D'Asaro et al., 2018). Below the surface, large vertical velocities several orders of magnitude greater than average penetrate to several hundred meters depth, enabling rapid exchange of properties (e.g., heat, CO_2) between the turbulent surface boundary layer and the ocean interior (Lévy et al., 2012; Callies et al., 2015; Balwada et al., 2018).

Present-day knowledge identifies the critical role for upper ocean mixing of stirring by submesoscale eddies at the km-scale. Capet et al. (2008) was first to identify a clear transition in the eddy field variability as the horizontal grid scale of models reaches O(1) km. Multiple studies since highlighted the need for new synoptic observations of the two-dimensional horizontal structure of the mesoscale flow field. Poje et al. (2014) studied the role of submesoscale processes in the dispersion of oil contamination from the Deepwater Horizon spill in the Gulf of Mexico using data from an unprecedented simultaneous release of about 300 surface drifters, concluding that the experiment allowed "*quantification of the submesoscale-driven dispersion* [that is] *missing in current operational circulation models and satellite altimeter-derived velocity fields*" and that "*Fundamental questions concerning the structure of the velocity field at the submesoscales (100 m to tens of kilometers, hours to days) remain unresolved due to a lack of synoptic measurements at these scales.*"

There is growing awareness also in the climate community that the restratification of the mixed layer by the submesoscale is a leading order process on longer scales (Fox-Kemper and Ferrari, 2008; Flato et al., 2013). As climate models remain too coarse to resolve submesoscales explicitly, models have to rely on parameterizations. The parameterization of Fox-Kemper et al. (2011) was used in some CMIP5 models included in IPCC AR5, but further developments are needed, most notably regarding front-wind and front-wave interactions, for which synoptic two-dimensional observations of currents, winds and waves are essential.

Observing Small Scale Processes in Coastal and Continental Shelf Seas

Coastal and shelf seas provide vital resources and services to society including food, energy, transport and recreation, but also mediate the transfer of terrestrial material from land to the open ocean (freshwater, carbon, nitrogen, plastics, and other pollutants). At the same time, the coastal zone presents mankind with some of the most urgent and challenging environmental hazards, including sea level change, coastal erosion and coastal flooding. Dynamic processes in coastal and shelf seas are more complex and occur on shorter spatial and temporal scales than in the open ocean (Schulz-Stellenfleth and Stanev, 2016; Cavaleri et al., 2018). Major differences from the open ocean include stronger tidal flows, rapidly changing bathymetry, spatially varying ocean waves and sharp water density fronts associated with freshwater river plumes or upwelling. Atmospheric circulation and air-sea interactions are affected too, with surface winds presenting much greater heterogeneity due to coastlines, the orography of nearby land and land/sea surface temperature contrasts (Bricheno et al., 2013; Müller et al., 2013).

Today, the representation of coastal and shelf seas in global ocean models remains inadequate due to the coarse spatial resolution and poor representation of relevant processes in global models. Current state-of-the-art 1/12°global ocean models (∼9 km resolution away from poles) only resolve fine scale processes with sufficient resolution for ∼20% of coastal and shelf seas. It is estimated that to represent them globally would require substantially finer resolution of the order of 1.5 km, which "*would be routinely practical in about a decade given substantial effort on numerical and computational development*" (Holt et al., 2017). State-of-the-art regional coastal and shelf seas models already operate at hourly and km-scale resolutions, but progress is hampered by the scarcity of *in situ* and remote sensing observations available for validation, assimilation and development. Paradoxically given their proximity and relevance to humans, simultaneous synoptic measurements of currents, winds and waves in coastal and shelf seas remain elusive, whether from spaceborne observatories or by other means.

Atmosphere-Wave-Ice-Ocean Interactions in Polar Seas

The rapid decline in Arctic sea ice over the past decades has stimulated much interest in the mechanisms contributing to sea ice breakup, highlighting in particular the role of surface waves, winds and currents in determining the size distribution of ice floes and the dynamics of ice growth and decay. Sea ice extent is a key climate change indicator, responsible for major climate feedbacks through its impact on Earth surface albedo and air-sea heat fluxes. Polar seas are also the sites of globally important water mass transformation and are famously supporting intense primary production and marine life. Finally, there are important strategic and economic considerations associated with the navigability and accessibility of the Arctic with less or no ice in summer (Stephenson et al., 2011; Aksenov et al., 2017).

Currents associated with eddies at 5–20 km scales play an important role in horizontal and vertical fluxes of heat, mass, momentum and tracers (Horvat et al., 2016) but evidence also points to complicated submesoscale structures at scales of 1 km or less (Carmack et al., 2015; Manucharyan and Thompson, 2017). Upwelling at the sea ice edge generates eddies and ice edge oceanic jets (Bulczak et al., 2015; Rynders, 2017). These interact with surface waves through complex coupling mechanisms with major effects on the near-surface mixing, heat balance and momentum transfer between the atmosphere, sea ice and the ocean (Giles et al., 2012; Thomson et al., 2018). Studies about the future state of the Arctic indicate the need for high-resolution model projections that account not only for changes in sea ice but also changes in ocean circulation, waves and wind (e.g., Aksenov et al., 2017). At present, no parameterization of these interactions is used in any Earth System Model, even though changes affecting the Marginal Ice Zone (MIZ) tend to bear directly on reanalysis discrepancies and climate challenges, e.g., predicted rates of Arctic sea ice loss (Chevallier et al., 2017). Here too, new observations have a crucial role to play to improve understanding and parameterizations of these critical processes in these extremely challenging environments.

THE SEASTAR MISSION CONCEPT

The clearly articulated needs identified in previous sections for simultaneous two-dimensional high-resolution measurements of current vectors, wind vectors and directional wave spectra cannot be addressed by the present-day ocean observing system. Detailed discussions of the observational gaps for currents, winds and waves are beyond this mini-review but can be found elsewhere in this issue (Villas Bôas et al., 2018; Rodriguez et al., 2018; Ardhuin et al., 2019a,b) and in the full SEASTAR mission proposal (Gommenginger et al., 2018).

Objectives of the Mission

The prime objective of SEASTAR is to address the observational gap for synoptic measurements of ocean surface currents and winds at the critical 1 km scale that are required to understand, model and forecast ocean submesoscale dynamics, air-sea interactions and small-scale processes in coastal, shelf and polar seas. Based on innovative interferometric technology, SEASTAR represents a major step forward from existing ground-based and spaceborne observing systems, offering two-dimensional imaging of total ocean surface current vectors and wind vectors at 1 km resolution with unprecedented accuracy, and coincident directional swell spectra. SEASTAR thus directly addresses the challenging but well-articulated multidisciplinary needs of the ocean, air-sea interactions, forecasting and climate communities for new measurements of:

- total surface currents (including ageostrophic currents)
- total Surface Current Vectors (TSCV; measuring two orthogonal vectorial components simultaneously)
- high-accuracy current data at 1 km resolution
- synoptic two-dimensional current field maps (to provide the wider dynamical context)
- TSCV collocated with high-resolution wind vectors and directional wave spectra.

The associated scientific objectives of SEASTAR are:

- to characterize, for the first time, total ocean surface current vectors and wind vectors at 1 km resolution, globally in open waters, coastal, shelf seas and the MIZ, to describe their nature, magnitude, spatial and seasonal variabilities
- to use current and wind derivative products (vorticity, divergence...) to study the relations between horizontal ocean surface circulation, air-sea exchanges and vertical ocean transports
- to use improved observations in the MIZ to better understand the role of surface winds, ocean waves and currents in sea ice dynamics, thermal evolution and break-up
- to exploit synergy with 1 km products from other satellite missions to study the impact of small scale ocean dynamics and air-sea exchanges on vertical transport, heat fluxes and marine biological productivity
- to support the validation of high-resolution models and the development of improved assimilation and parameterizations of submesoscale dynamics and small scale atmosphere-wave-ocean interactions for inclusion in multi-disciplinary Earth System climate models.

Technical Concept

SEASTAR consists of a single active microwave instrument on a single satellite flying in sun-synchronous Low-Earth orbit. The payload is a squinted Synthetic Aperture Radar along-track interferometer (SAR ATI) with two pairs of beams pointing fore and aft of the satellite at ± 45° in azimuth, plus a standard SAR beam pointing broadside (**Figure 1**). The basic measuring principle of SEASTAR relies on Along-Track Interferometry (ATI), whereby the line-of-sight motion of the ocean surface is measured from the Doppler shift between two SAR images acquired within a few milliseconds of each other in a single satellite overpass. The use of beams squinting fore and aft of the satellite is a highly innovative solution that makes it possible to retrieve both components of the ocean surface motion vector in a single pass. SEASTAR is the first mission to propose squinted ATI from space.

The SEASTAR instrument operates at Ku-band and produces a single-sided 170 km swath covered in 3 sub-swaths in ScanSAR mode. The inherent spatial resolution of SAR and InSAR images is 30 × 150 m (range × azimuth), which are processed to Level 2 ocean surface current vectors and wind vectors at 1 km resolution over the full swath. The accuracy requirements for current vectors at 1 km resolution are 0.1 m/s and 20°, and are achievable using the Level 2 products and instrument specifications. The two squinted beams operate in VV polarization whereas the broadside beam provides dual-polarization capability and additional azimuth diversity to retrieve unambiguous current and wind vectors at Level 2.

The satellite flies in a sun-synchronous orbit (SSO) around 550 km altitude, which gives the option of alternating short-revisit (1–2 day repeat) and medium-revisit (7–30 days) orbital phases. SEASTAR does not depend on data from other satellites but important scientific benefits can be expected from synergy with Sentinel-3 (particularly the high-resolution Sea Surface Temperature and Ocean Color images and high-resolution SAR altimetry), Sentinel-1 (Radial Velocity and Backscatter Coefficient data), Sentinel-2 (ultra-high resolution images in nearshore regions) and Jason-CS/Sentinel-6 (high-resolution SAR altimetry). A high level of scientific complementarity exists also with the Chinese-French Oceanography Satellite (CFOSat) and the Surface Water and Ocean Topography (SWOT) mission, as well as with the proposed SKIM and WACM mission concepts (Rodriguez et al., 2018; Ardhuin et al., 2019b).

Retrieval Performance Assessment

The SEASTAR inversion algorithm seeks to retrieve wind and current vectors from the SEASTAR data alone without reliance on ancillary information from models. Martin et al. (2018) propose a Bayesian approach derived from scatterometry to perform inversion and evaluation retrieval performance for currents and winds. The method accounts for the wind relative to the surface current and the effects of the Wind-wave Artifact Surface Velocity (WASV), a bias in all microwave Doppler data linked to the motion of ocean waves on the sea surface (Martin et al., 2016). **Figure 2** shows the root-mean-square error (RMSE) of the retrieved current and wind estimated by Monte-Carlo simulations for the proposed instrument specifications, revealing excellent retrieval performance for both currents (better than 0.1 m/s and 10°) and winds (better than 0.5 m/s and 10°). Performance degrades slightly when wind direction is aligned with either squinted look directions but errors for currents typically remain below 0.1 m/s across the 170 km swath. Overall, SEASTAR proposes to deliver observations of complementary ocean dynamic properties that have never before been measured simultaneously from space at this level of resolution and accuracy, and which far outstrip the capabilities of existing and proposed satellite ocean surface current missions.

Airborne Demonstration and Validation Against HF Radar Data

The measuring principle of SEASTAR was successfully demonstrated experimentally and scientifically with data from the Wavemill airborne demonstrator proof-of-concept campaign over the Irish Sea (Martin et al., 2016). Level-0 data were successfully processed to produce Level-1 interferograms and Level 2 ocean surface current vectors maps corrected for aircraft attitude fluctuations and wind-wave induced biases. Surface current vectors were retrieved at 100 m resolution and subsequently averaged for validation against coastal HF radar data (Martin and Gommenginger, 2017). At 1.5 km resolution, current RMS errors against HF radar were typically below 0.1 m/s and 10°. The airborne system also detected sharp current jets over known deep bathymetry channels, giving confidence that the observing principle remains valid in complex coastal environments. A new airborne instrument called OSCAR is currently under development for ESA to demonstrate the three-look SEASTAR configuration with airborne trials planned in July 2019.

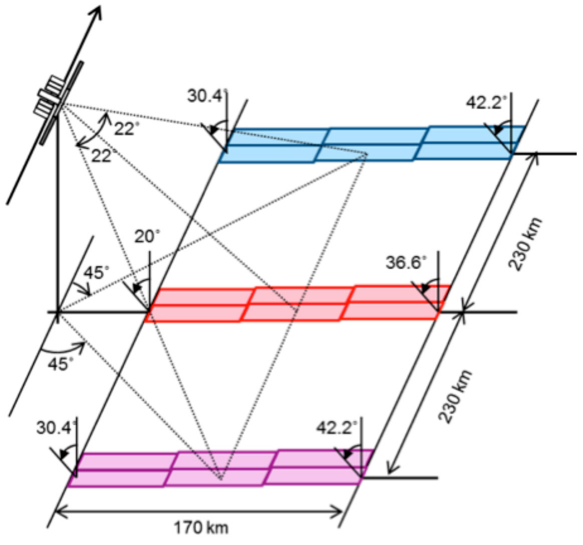

FIGURE 1 | SEASTAR observation geometry.

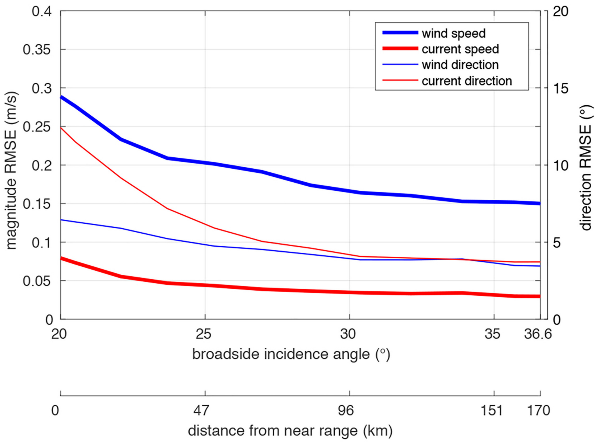

FIGURE 2 | SEASTAR root-mean-square error (RMSE) for current (red) and wind (blue) speed (thick lines) and direction (thin lines) across a 170 km swath based on numerical Monte-Carlo simulations for a wind speed of 8 m/s and a current speed of 0.6 m/s.

CONCLUSION AND RECOMMENDATIONS

High-resolution ocean color and sea surface temperature images reveal an abundance of fronts, swirls, vortices and filaments at scales below 10 km but measurements of ocean surface dynamics at these scales are rare.

Large numbers of numerical and experimental studies highlight the global role played by small ocean features in air-sea interactions, upper-ocean mixing, ocean vertical transports and marine ecosystem response.

Small-scale processes also visibly dominate ocean dynamics in coastal, shelf seas and polar seas, where they mediate important exchanges between land, the ocean, the atmosphere and the cryosphere (e.g., freshwater, nutrients, pollutants).

Advanced numerical models and *in situ* observations highlight the need for synoptic two-dimensional imaging of ocean surface properties at 1 km resolution where fundamental changes in dynamics are known to occur.

Present-day observing systems do not deliver the synoptic high-resolution measurements of current and wind vectors and directional wave spectra needed to observe small scale processes and improve their representation through parameterizations in multi-disciplinary Earth System models used for forecasting and climate projections.

SEASTAR is a new satellite mission concept to address the observational gap for synoptic measurements of ocean surface currents and winds at the critical 1 km scale that are required to understand, model, validate and forecast ocean submesoscale dynamics, air-sea interactions and small-scale processes in coastal, shelf and polar seas.

Based on innovative interferometric technology, SEASTAR represents a major step forward from existing ground-based and spaceborne observing systems, offering new capability and unprecedented accuracy, and addressing the challenging but well-articulated multidisciplinary needs of the ocean, air-sea interactions, coastal processes, cryosphere, forecasting and climate communities.

SEASTAR is an innovative, mature and demonstrated mission concept looking for opportunities to proceed toward spaceborne implementation within Europe and beyond.

AUTHOR CONTRIBUTIONS

CG drafted and revised the manuscript. All authors reviewed the manuscript and approved the submitted version of the manuscript.

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