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SATELLITE GLOBAL OCEAN SURFACE TOPOGRAPHY MEASUREMENTS: CHALLENGES AND OPPORTUNITIES

In Response to CGMS Action 40.01

Executive Summary

Highly precise satellite measurements of global ocean surface topography contribute to climate and weather applications. Two examples are described: global sea level rise for climate and detection of ocean weather. Ocean weather is undersampled with a conventional satellite altimeter, which measures ocean surface topography along the nadir direction. Even if the unlikely, but highly fortunate, situation should arise when five conventional satellite altimeters are simultaneously on orbit with complementary orbits recording ocean surface topography, the composite dataset will be inadequate to sample a substantial portion of mesoscale motions and all submesoscale eddy motions with adequate temporal resolution. Unlike the global atmosphere where mean motion is typically 10 times greater than eddy motion, the oceanic eddy motion is ten times greater than the mean motion. A satellite altimetry ocean surface topography noise level of 1 cm^2 / cycles per kilometer corresponds to a 3 cm s^{-1} geostrophic current error in a 10-km-diameter eddy at 45° latitude. This criterion is an objective of a wide-swath satellite altimeter mission with a launch readiness date of 2020.

Recommendation/Action: (1) Support high-spatial resolution and high-temporal resolution ocean surface topography measurements for improved weather and climate applications. (2) Increase acquisition of all-weather or microwave measurements of sea surface temperature which, when combined with high-resolution ocean surface topography measurements, would improve forecast skill of tropical storm intensity.

Satellite Global Ocean Surface Topography Measurements: Challenges and Opportunities

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1 INTRODUCTION

Highly precise satellite measurements of global ocean surface topography began in 1978 with the United States (US) National Aeronautics and Space Administration (NASA) Seasat satellite mission. The measurement concept was proven and the potential for oceanographic applications was swiftly realized from the hundred-day mission that suffered a catastrophic failure. The accuracy, precision and longevity of ocean surface topography observations required to advance our knowledge of global ocean weather and climate began with the launch of the NASA/CNES (Centre National d'Etudes Spatiales) Topography Experiment (TOPEX)/Poseidon (T/P) satellite in 1992. Soon afterwards, Walter Munk stated at the Opening Ceremony of the 1998 International Year of the Ocean International Conference on Satellite, Oceanography and Society: "Satellite altimetry is now an outstanding success. Its contributions towards understanding ocean processes goes well beyond anything that had been imagined (Munk, 2000)." The T/P results (Munk, 2002) and those from the first European Space Agency (ESA) European Remote Sensing (ERS-1) satellite changed the culture of ocean sciences from one dominated by ships exploring small patches of the ocean to satellites observing the global ocean in the time it would take a ship to observe a small patch, albeit with instruments that penetrate throughout the water column.

Satellite altimetry observations of ocean surface topography contribute to climate and weather applications. Many such applications exist and two will be described. In the first example, the sea level rise displayed in Figure 1 (Nerem et al., 2010) has become an icon of the impact of increasing amounts of atmospheric greenhouse gases. Thermal expansion of the oceans and input of melt water from glaciers and ice sheets, both the result of a warming atmosphere, cause global sea level rise. Analyses of the combination of ocean surface topography measurements, satellite gravity measurements, and in-situ vertical profile temperature measurements provide

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[1] For this paper, David Halpern represents the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific, Cultural Organization (UNESCO), which is a member of GCMS. The World Meteorological Organization (WMO) – IOC Joint Commission on Oceanography and Marine Meteorology (JCOMM) is supporting IOC to accomplish CGMS Plenary Action 40.01, which invited IOC to provide a paper on guidance to CGMS members on ocean surface topography.

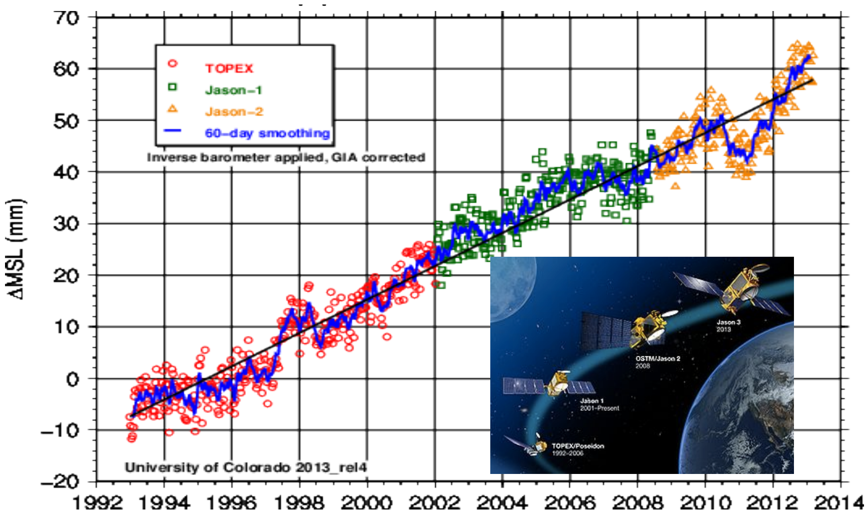


***Figure 1**. Global mean sea level variations extracted from http://sealevel.colorado.edu on 2 June 2013 and determined by Nerem et al. (2010). The record-length average sea level rise was 3.2 ± 0.4 mm/yr, which includes the inverse barometric effect, glacial isostatic adjustment, and removal of seasonal effects. Since 1993, measurements from the TOPEX and Jason series of satellite radar altimeters have allowed estimates of global mean sea level. These measurements are continuously calibrated against a network of tide gauges. When seasonal and other variations are subtracted, they allow estimation of the global mean sea level rate. As new data, models and corrections become available, the estimates are revised about every two months to improve their quality. In the Inset, Jason-1 no longer produces data, Jason-2 continues to provide data, and the Jason-3 launch readiness date is 2015.*

estimates of sea level rise caused by ocean thermal expansion and by increase in ocean mass from addition of fresh water (Lombard et al., 2007). During 1993-2003, thermal expansion and additional mass from melt water contributed 1.6 and 1.2 mm/year, respectively, towards the total sea level rise, which leaves 0.3 mm/year of observed sea level rise to be accounted for (IPCC, 2007; Nerem et al., 2010).

The sustained data record in Figure 1 demonstrates a remarkable technological and management achievement in research-to-operations (R2O) transition and the outstanding ability of the satellite ocean surface topography measurement community to cross a so-called “valley of death” (National Research Council, 2003, 2000). Ocean surface topography observations began as a purely scientific endeavor, as exemplified by the CNES and NASA partnership in TOPEX/Poseidon (T/P) (August 1992 – January 2006) and follow-on satellite mission Jason-1 (December 2001 - present). In the next mission, Jason-2 (June 2008 - present), the CNES-NASA partnership expanded to include the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the US National Oceanic and Atmospheric Administration (NOAA), both of which have well-established capabilities for sustained or operational measurements. In Jason-2, CNES and NASA procured the satellite and instruments while EUMETSAT and NOAA process and distribute data. An outstanding attribute of the T/P – Jason-1 – Jason-2 ocean surface topography time series measurement is the minimum 6-month overlap between satellites for establishing a calibrated inter-satellite dataset. The T/P – Jason measurement series will continue with Jason-3 (launch readiness date 2015) when EUTMETSAT and NOAA will become the major partners, procure the satellite and instruments, and conduct data processing and distribution – CNES and NASA will support science applications of the dataset. After Jason-3, the partners CNES, ESA, EUMETSAT, NASA and NOAA plan to continue operationalizing the T/P-Jason time series with Jason Continuity Series (Jason-CS) missions (http://www.aviso.oceanobs.com/en/missions/future-missions/jason-cs.html), although the sharing of responsibilities has not yet been defined. The 1991-2012 record length of ERS-1, ERS-2 and Environmental Satellite (Envisat) ocean surface topography time series would have been longer than the T/P, Jason-1, and Jason-2 series had a gap not developed before launch of the ISRO (Indian Space Research Organisation) – CNES SARAL (Satellite with Argos and AltiKa) mission in February 2013. An estimate of the R2O transition period from the launch of T/P to the anticipated launch of Jason-3 will be slightly more than two decades (Figure 1 inset). This time interval was about the same as the NOAA-research-to-NOAA-operations transition (1976-1996) for the instrumented moored buoy array in the equatorial Pacific Ocean to monitor El Niño and La Niña. For operationalizing the Keeling Curve of atmospheric carbon dioxide measurements at Mauna Loa in Hawaii, the R2O transition period was about twenty years, from 1958 to late-1970s. It seems that the minimum time to transition a research measurement capability to an operational measurement capability is approximately twenty years.

In the second example, satellite altimetry reveals regions where subsurface temperatures (neglecting the usually smaller contribution to density by salinity) will be higher or lower than surrounding areas. This measurement characteristic is important for short-term weather forecasts. A surface thermal layer with thickness greater than about 100 m will retain its sea surface temperature characteristics even with passage of a hurricane, unlike a 30- to 40-m thick layer which atmospheric processes could easily mix and lower sea surface temperature. Simultaneous measurements of ocean surface topography and sea surface temperature reveal the occurrence of upper-ocean thermal layers that penetrate from the surface to depths of hundreds of meters. Lin et al. (2010) provide examples how satellite altimetry data revealed areas of anomalously warm subsurface layers. A tropical storm, on encountering a relatively thick layer of upper-ocean warm water, will intensify because the sea surface temperature will not change much by wind-generated vertical mixing, unlike in the surrounding waters where the mixed layer is shallow and easily mixed by the storm. Thus, superposition of tropical storm track and upper-ocean heat content, which is strongly correlated with satellite ocean surface topography measurements, will add critical information to determine potential regions of storm intensification and dissipation (Figure 2). Mainelli et al. (2008) concluded that knowledge of upper-ocean heat content enabled a greater than 5% improvement in the NOAA 96-hour forecast intensity of four category 5 hurricanes in 2004 and 2005; for a single hurricane, the forecast skill improved as much as 20% (Figure 3C).

2 CURRENT AND FUTURE CONVENTIONAL OCEAN SURFACE TOPOGRAPHY MEASUREMENTS

Current ocean surface topography satellite missions appear to be adequate for recording global sea level variations, and this fundamental measurement of proven societal benefit will be sustained at least for another decade. Figure 4 shows launch dates of on-orbit satellites recording ocean surface topography measurements, and launch readiness dates of future satellites intended to record ocean surface topography measurements (www.wmo-sat.info/oscar/satellites). Even if the unlikely, but highly fortunate, situation should arise when five conventional satellite altimeters are simultaneously on orbit with complementary orbits recording ocean surface topography, the composite dataset will be inadequate to sample the submesoscale eddy motions (Figure 5). Conventional altimeters produce 6- to 7-km diameter ocean surface topography measurement footprints centered on the ground track. Although conventional altimeter measurements are made continuously in the along-track direction, instrument and other noise limit the effective along-track wavelength resolution to 70-100 km (Xu and Fu, 2012). For a 10-day repeat period, a spacing of 315 km occurs between individual satellite ground tracks at the equator and in middle latitudes, e.g., T/P mission (Figure 5). For longer repeat periods such as 40 days for ERS-1, ERS-2 and Envisat, the equatorial spacing was about 80 km. ESA Sentinel-

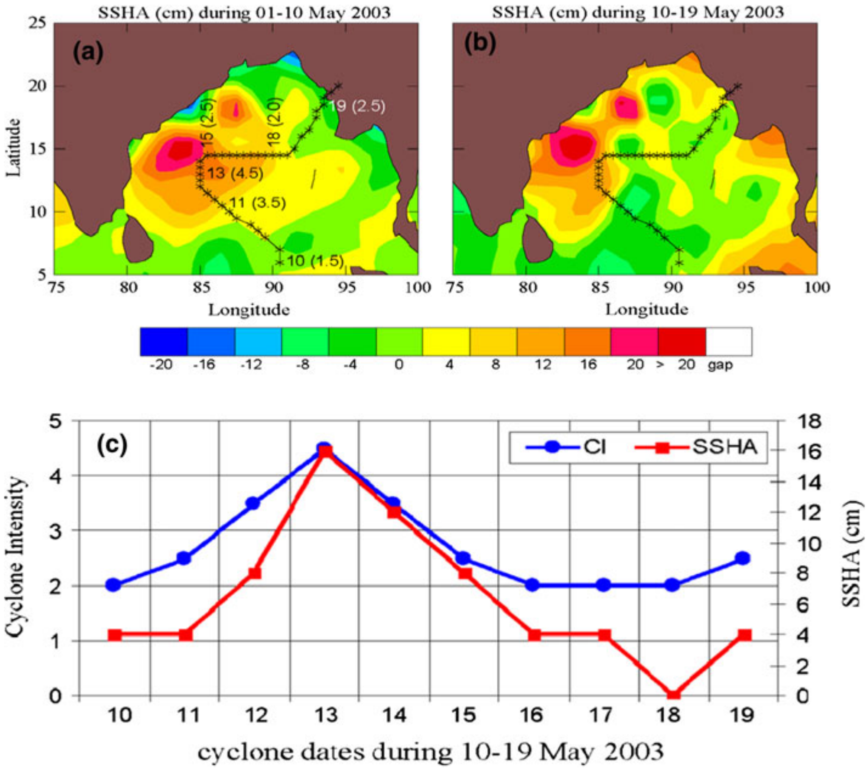


***Figure 2**. Impact of sea surface height anomaly (SSHA) on cyclone intensity in the Bay of Bengal. (A) Cyclone track of 10-19 May 2003 superimposed on SSHA field for 1-10 May 2003. (B) Cyclone track of 10-19 May 2003 superimposed on SSHA field for 10-19 May 2003. (C) Relationship of SSHA and cyclone intensity during 10-19 May 2003. Extracted from Lin et al. (2010).*

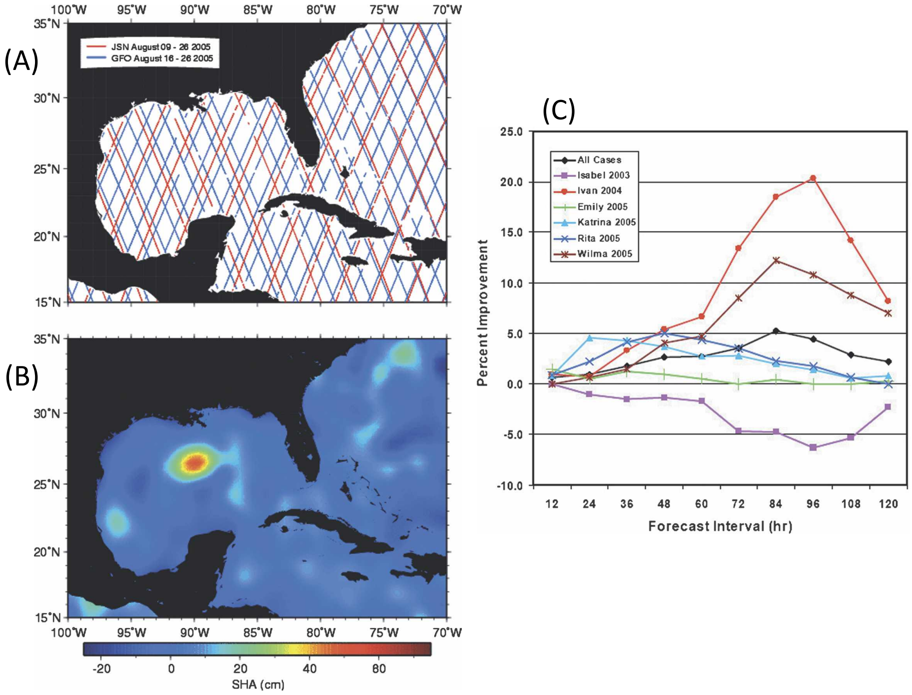
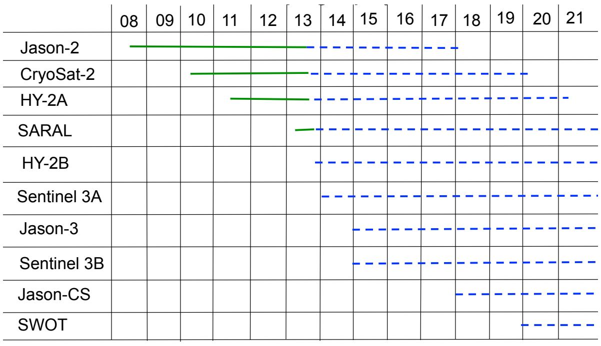


***Figure 3**. (A) An example of satellite ground tracks from Jason-1 on 9-26 August 2005 and Geosat Follow-on on 16-26 August 2005 in the Gulf of Mexico. (B) Objectively analyzed sea surface e height anomaly for the pre-storm analysis of Hurricane Katrina, which made landfall in Louisiana on 29 August 2005. (C) Percent improvement of statistical model forecast of hurricane intensity with incorporation of ocean heat content data determined from satellite altimetry. Parts (A), (B) and (C) were extracted from Mainelli et al. (2008).*



Data from www.wmo-sat.info/oscar/satellites
Dash line represents extension with arbitrary length based on ~ 10 year total operation.

***Figure 4**. Record-lengths of ocean surface topography data currently obtained from on-orbit satellites (green lines) and expected to be obtained from future satellites (dashed blue lines) (www.wmo-sat.info/oscar/satellites). Jason-CS and SWOT missions are pre-decisional and for planning purposes and discussions. An arbitrary length of 10 years was given to a satellite's dataset. The start time of 2008 was chosen because Jason-2 continues to operate successfully. While many other satellites have provided ocean surface topography measurements, such as T/P and ERS-1, they no longer provide data and, thus, are not shown in the diagram.*

3A and 3B missions, with launch readiness dates in 2014 and 2015 (Figure 4), would have a 54-km spacing at the equator. Merging ocean surface topography data from multiple satellite altimeters yielded a globally uniform 0.25° x 0.25° gridded dataset (Ducet et al., 2000) with a wavelength resolution of about 2° latitude by 2° longitude (Chelton et al., 2011).

Except for Seasat in 1978, all previous and current missions have infrequent repeat sampling of the ocean surface topography field (Figure 5). Infrequent sampling could cause major misinterpretation of the measurements, e.g., an ocean eddy moving in middle latitudes with a translational speed of 3 cm s^{-1} will travel 2.6 km in a day and 10 days later it will be nearly 25 km from where a satellite, such as Jason, will have first “seen” the eddy. Some ocean surface topography variations will have time scales less than the repeat time of the satellite, and, thus, will escape detection.

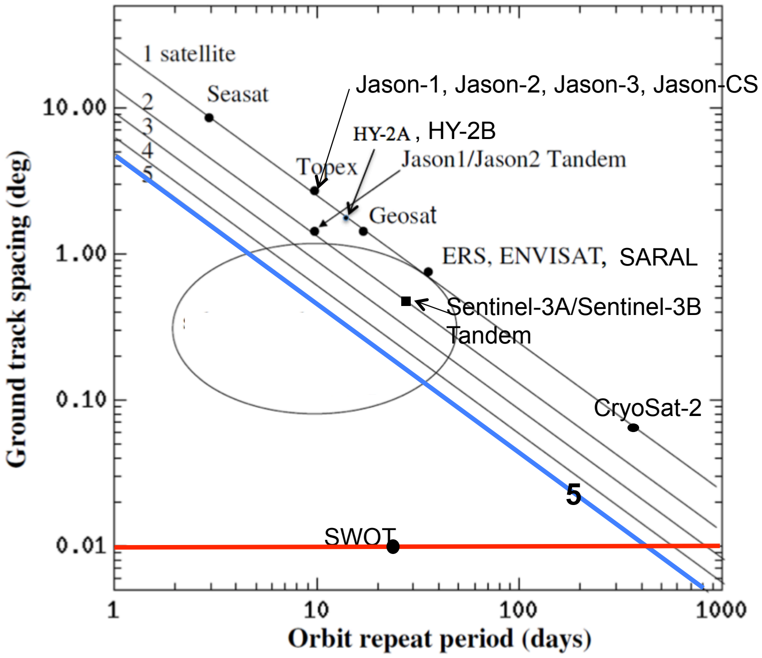


***Figure 5**. Sampling characteristics of satellite altimetry missions, with updates added to the original chart (Fu et al., 2012) for SARAL, Sentinel, Jason-1, Jason-2, Jason-3, and the proposed Surface Water Ocean Topography (SWOT) missions and removal of WSOA (which was a predecessor of SWOT) from the original chart. The various straight lines represent the combination of different numbers of satellite altimeters. Red line represents noise level assumed for the SWOT concept. Ellipse represents mesoscale motions.*

Integration of ocean surface topography observations from multiple satellites or measurements from a wide-swath altimeter (Fu and Ubelmann, 2013) will mitigate the error caused by insufficient sampling.

Large spacing and infrequent sampling degrade estimates of (i) ocean currents in the along-current direction, which rarely is in favorable orientation with respect to a satellite's ground track and which typically contain meanders with dimensions less than 300 km; (ii) upper-ocean heat surpluses or deficits, which influence weather forecast skill; (iii) upper-ocean vertical velocity associated with divergence and convergence of mesoscale (10- to 100-km dimensions) and submesoscale (1-10 km) eddy motions; (iv) coastal ocean processes, which influence search and rescue operations and pollution trajectory analyses; and (v) other applications such as ocean mixing, internal gravity waves, and ocean biogeochemistry. Mesoscale and submesoscale eddy motions are very energetic compared to the mean flow (Sharffenberg and Stammer, 2010) (Figure 6) and the typical radius of eddies is less (greater) than 100 km poleward (equatorward) of about 20° latitude (Chelton et al., 2011) (Figure 7). To capture mesoscale and submesoscale eddy motions, a satellite

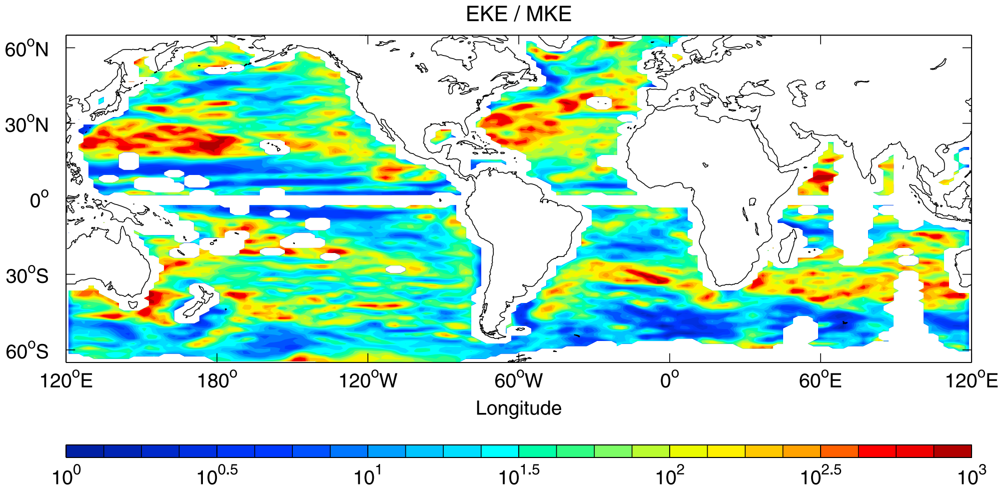


***Figure 6**. The ratio of eddy kinetic energy of surface geostrophic currents, which was computed from T/P and Jason-1 data, to the mean kinetic energy, which was computed from the Rio and Hernandez (2004) mean dynamic topography. On average, the EKE/MKE was 6.5. Extracted from Sharffenberg and Stammer (2010).*

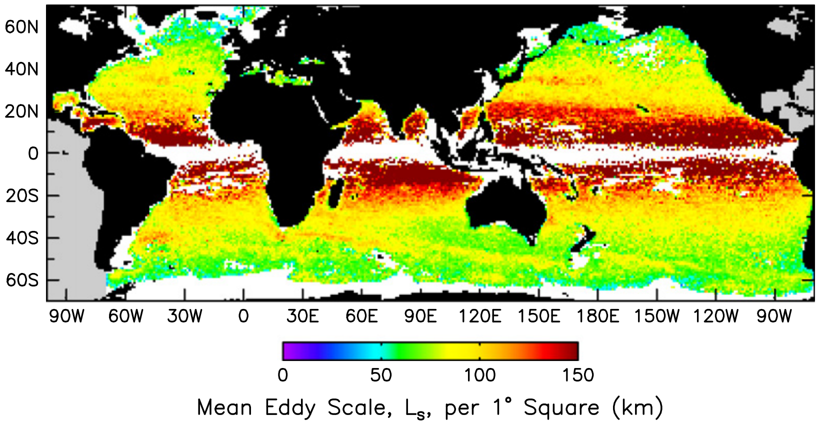


***Figure 7**. Average speed-based radius scale for eddies with lifetimes ≥ 16 weeks for each 1°-latitude x 1°-longitude region. Extracted from Chelton et al. (2011).*

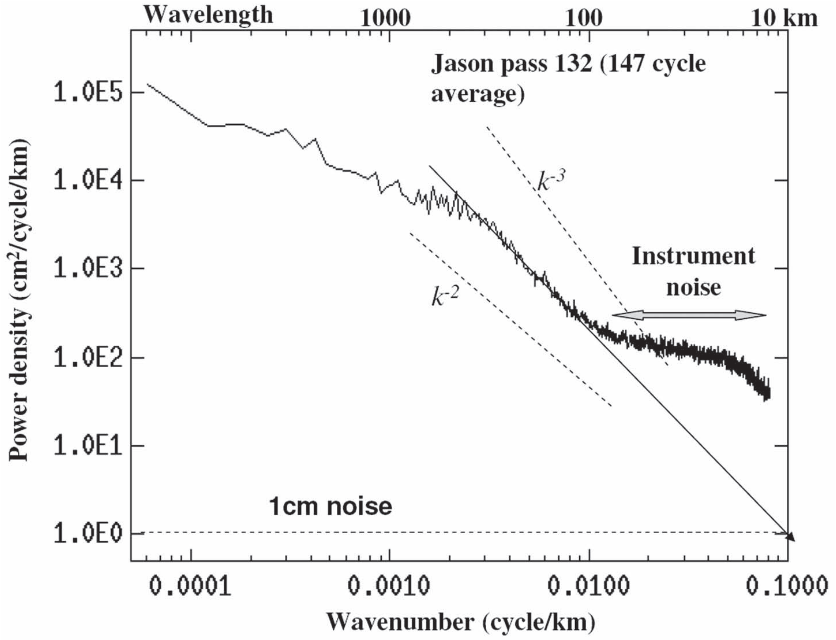


Figure 8*. Spectrum of sea surface height anomaly from Jason altimeter data. The two slanted dashed lines represent two spectral power laws with k as wavenumber. The red line represents the threshold of measurement noise at a 1-km sampling rate. The slanted solid straight line represents a linear fit of the spectrum between 0.002 and 0.01 cycles per kilometer. It intersects with the threshold noise level at the 10-km wavelength. The 1-cm^2/cycle/km noise level corresponds to a 3 cm s^{-1} geostrophic current error in a 10-km-diameter eddy at 45° latitude. Extracted from Fu and Ferrari (2008).*

altimeter would have a spectral noise level of 1 cm^2/cycle per km, which would be 200 times smaller than that achieved with the Jason-1 altimeter (Fu and Ferrari, 2008) (Figure 8).

3 NEXT GENERATION OCEAN SURFACE TOPOGRAPY MEASUREMENTS

To measure mesoscale and submesoscale eddy motions, CNES and NASA are proposing to partner on a new revolutionary ocean surface topography mission called Surface Water and Ocean Topography (SWOT). The Canadian Space Agency (CSA) would also make contributions to the mission. Projected SWOT high-spatial-resolution measurements with 1-km separation distances in the cross-track and along-track directions would estimate lake and river levels (the “SW” in SWOT) and ocean surface topography (the “OT” in SWOT). Also, the European Commission and ESA are considering a single synthetic aperture radar (SAR) operational mode for Sentinel-3A and Sentinel-3B missions to record 300-m resolution along-track ocean surface topography measurements over the open ocean and not only in the coastal zone within 300 km of land (Donlon et al. 2012). Potential launch readiness dates for the proposed SWOT and Sentinel 3A/3B missions are 2020 and 2014/2015, respectively (Figure 4).

In conventional radar altimetry, an altimeter transmits a radar pulse along the vertical or nadir direction. The pulse is reflected by the sea surface and returns to the altimeter, where the measured travel time is related to the distance between the satellite and the sea surface. The proposed SWOT satellite would transmit and receive signals from two SAR antennae. Measurement of time delay and phase shift between the two received signals, which can be made with very high precision, is related to ocean surface height (Figure 9). The 10- to 70-m SAR footprint would yield a large number of independent estimates, which would be averaged to reduce the noise of 1-km data. SWOT 1-km x 1-km gridded measurements will have a 22-day repeat period. ESA Sentinel-3 ocean surface topography observations will be repeated every 27 days. Fu and Ferrari (2008) expect that the SWOT 1-cm random noise threshold associated with the 1-km sampling rate would be considerably smaller than the Jason noise level at 1-km sampling (Figure 8). The along-track 300-m resolution SAR altimeter capability on the ESA CryoSat-2 mission, although designed to monitor variations in the extent and thickness of polar ice, has potential to measure ocean surface topography with lower noise than conventional altimeters (Donlon et al., 2012). Dibarboure et al. (2012) noted that the CryoSat-2 altimeter, which can capture 50-66% of mesoscale variability measured by Envisat or Jason-1, contributes to mesoscale observations when merged with other altimeter data, such as Envisat and Jason-2.

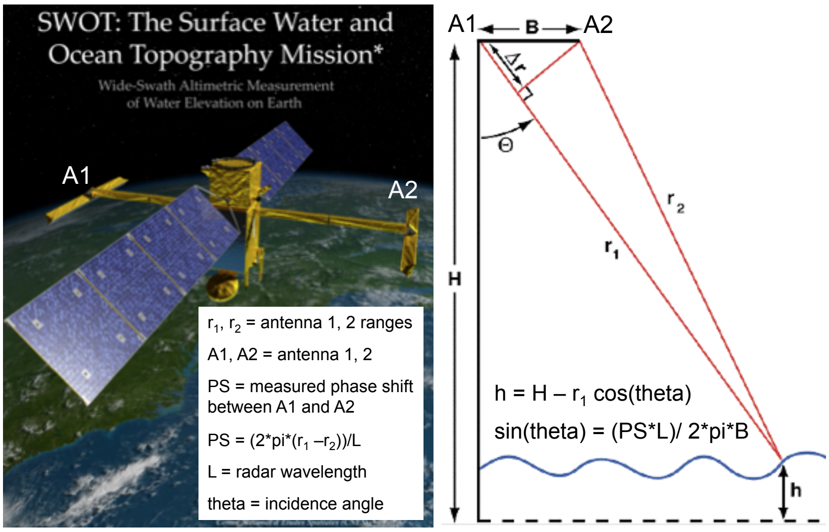


***Figure 9**. Schematic diagram of the SWOT concept and radar interferometry principle of SWOT measurement technique. The range of a target can be precisely determined by the round-trip travel time measured by the radar's timing system. Radar interferometry determines the location of the target by measuring the relative delay or phase shift between the signals from two antennae that are separated by a baseline distance. Using geometry, the location of the range measurements in the plane of the observations can be determined. Extracted from Fu et al. (2012).*

Each Sentinel mission will have a single dual-frequency (Ku- and C-band) SAR antenna and record high-spatial ocean surface topography measurements only in the along-track direction. The proposed SWOT mission would have two SAR Ka-band antennae and record high-spatial ocean surface topography measurements in both the along-track and cross-track directions. The SWOT cross-track coverage would be a 50-km swath on each side of the ground track beginning 10 km from the ground track. The SWOT orbit would be non-sunsynchronous while the Sentinel-3 mission orbit would be sun-synchronous, which aliases solar tides to frequencies of interest to the analyses of ocean circulation. Comparisons of Sentinel-3 and SWOT datasets would be an important requirement for building a constellation of satellites and SAR instruments for ocean surface topography measurements. Both SWOT and Sentinel-3 satellites would also contain a conventional altimeter for nadir measurements of ocean surface topography for consistency and integrity of the new SAR measuring system with the old nadir system, which Fu and Ubelmann (2013) indicate is necessary to extend into the future the time series data begun with the launch of T/P on 10 August 1992.

4 CONCLUDING REMARKS

Conventional satellite ocean surface topography measurements have changed ocean sciences and society by advancing fundamental knowledge of ocean circulation and creating new economic, health and safety, and national and homeland security applications. High-spatial-resolution measurements will likely produce new breakthroughs in understanding ocean circulation, such as improving accuracy of model currents (Figure 10). Someday, we envision a constellation of satellites recording high-spatial resolution ocean surface topography observations in both the along-track and cross-track directions and formation flying to produce high-temporal resolution measurements at any location in the global ocean.

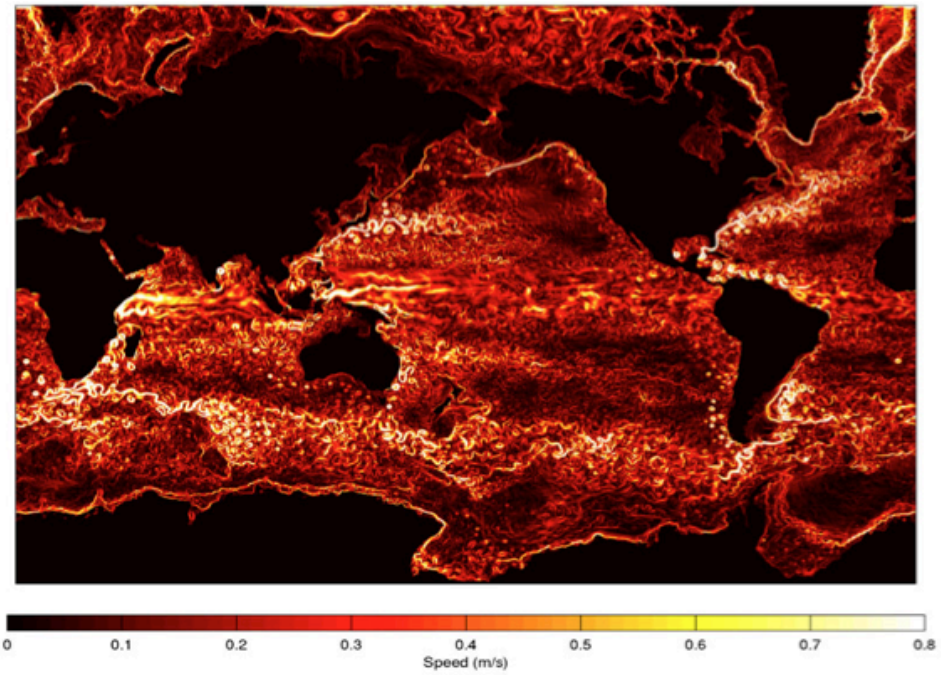


***Figure 10**. ECCO2 solutions of 6-hour average ocean current speed (m s^{-1}) at 15-m depth with 19-km x 19-km resolution. Courtesy of D. Menemenlis (JPL).*

5 ACKNOWLEDGEMENTS

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8 ACRONYMS

CNES	Centre National d'Etudes Spatiales
CS	Continuity Series
CSA	Canadian Space Agency
ECCO	Estimating the Circulation and Climate of the Ocean
EKE	Eddy Kinetic Energy
Envisat	Environmental Satellite
ERS	European Remote Sensing
ESA	European Space Agency
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
HY	Hai Yang
IOC	Intergovernmental Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organisation
MKE	Mean Kinetic Energy
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
R2O	Research to Operations
SAR	Synthetic Aperture Radar
SARAL	Satellite with Argos and AltiKa
SSHA	Sea Surface Height Anomaly
TOPEX	Topography Experiment
T/P	TOPEX/Poseidon
UNESCO	United Nations Educational, Scientific, Cultural Organization
US	United States
SWOT	Surface Water Ocean Topography
WMO	World Meteorological Organization
WSOA	Wide Swath Ocean Altimeter