Ocean Observations with a Space-based Delay-Doppler Altimeter Constellation

D. L. Porter, R. K. Raney and J. R. Jensen
Johns Hopkins University Applied Physics Laboratory
Laurel, MD 20723-6099, USA
David.L.Porter@jhuapl.edu

Abstract-**A constellation of (nominally) three DDA satellites can all be placed in the same orbit plane by a single launch vehicle. Earth rotation spreads their respective nadir tracks by a spacing that is proportional to their along-orbit separation. This constellation which we have called WITTEX (Water Inclination Topography and Technology Experiment) is a candidate approach that would meet nearly all of the requirements identified by the user community for oceanographic altimetry. The WITTEX constellation can be tuned to favor dense spatial coverage, relatively tight temporal coverage, or other priorities. In addition the constellation can be used in a dual-use mode as was Geosat, in that geoid observations over a dense ground track can be made, after which the constellation can be maneuvered into an oceanographic exact repeat mission.**

I. INTRODUCTION

The delay-Doppler Altimeter (DDA) uses innovative signal processing techniques [1], adapted from synthetic-aperture imaging radar, to achieve better measurement precision and instrument efficiency than are possible from conventional radar altimeters, such as TOPEX or Jason-1 [2]. The DDA, in its simplest configuration, can be flown as a single frequency altimeter without an onboard water vapor radiometer. This elementary version can be employed to measure the deflection of the vertical gravity [3] and/or the mesoscale oceanographic field [4]. The DDA, in its most elegant configuration, can be flown in a constellation of three or more satellites [5], where each has a nadir pointed two-frequency altimeter, a nadir pointed water vapor radiometer, and single frequency bistatic altimeters [6]. This constellation can be employed for measurements on basin scales, for sea level variations, and for vector measurements of currents as well as deflections of the vertical gravity.

The DDA measures the sea surface height (SSH) with an precision twice as good as estimates from conventional altimeters such as TOPEX [7], with an along track resolution of 250 m, within 5 km of shore, and with almost no dependence on the magnitude of the significant wave height. The DDA satellites are small enough that three of them could be launched from one launch vehicle and placed in the same orbit plane [8]. Fig. 1 shows the satellites spaced apart by several hundred kilometers. Their individual ground tracks are laterally separated by the Earth's rotation. For this type of spacing the measurements occur within minutes of each other. Thus, the cross-track surface gradient can be measured as well as the usual along-track gradient. This allows both components of the geostrophic current to be calculated.

Only two-dimensional near-simultaneous surface sampling can observe the full spectrum of temporal and spatial scales that occur in ocean circulation. Hence, we call this the Water Inclination Topography and Technology Experiment (WITTEX). It is named in honor of E. Witte who first discovered the geostrophic current equations in 1878 [9]. Normal altimetry can measure only the along-track component of the surface height gradient. Track separation may be adjusted during mission operations by selection and maintenance of the inter-satellite spacing. Thus, measurement of the two-dimensional surface gradient can be optimized during a single flight mission. The sea surface height data are free of off-nadir errors, since all measurements enjoy the accuracy inherent to pulse-limited geometry.

The WITTEX constellation can be tuned to favor dense spatial coverage, relatively tight temporal coverage, or other priorities. A number of scenarios are possible with this constellation, for example: (1) both the along-track and the cross-track surface gradients can have the same horizontal resolution; (2) the tracks can be equally spaced along the equator and/or (3) each succeeding altimeter's track can be on top of the spatially adjacent one, thus generating a short revisit cycle. In addition the constellation can support a dual use mode as was Geosat, in that geoid observations over a dense ground track can be

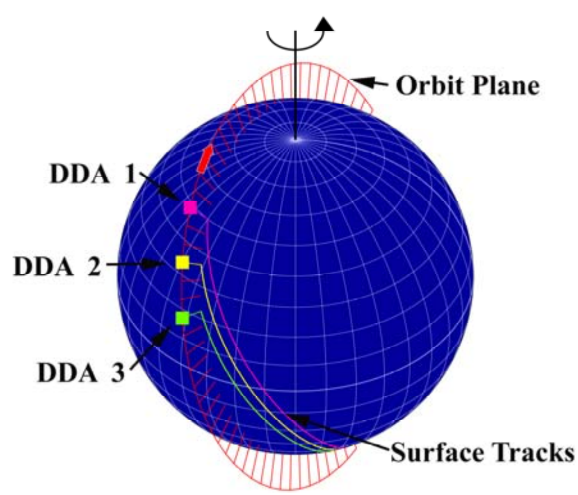

Figure 1. Schematic showing the orbit plane (red) of the constellation of three delay-Doppler altimeter (DDA) satellites with their associated ground tracks.

made, and then the constellation can be maneuvered into an oceanographic exact repeat mission as outlined above.

II. WITTEX Nadir Constellation

The WITTEX constellation can be tuned to favor dense spatial coverage, relatively tight temporal coverage, or other priorities. A change from one scenario to another would require approximately one day. Using the Geosat 17-day orbit as a reference, we consider four possibilities. (Similar scenarios would apply equally well to a TOPEX-class orbit.)

Scenario I, High spatial resolution (~200 km orbital spacing): Each triplet of sub-satellite orbit tracks would be 24 km wide, and span less than 1 minute. This arrangement would support measurement of both the along-track and the cross-track surface gradients at about the same resolution.

Scenario II, Uniformly dense spatial coverage (~900 km orbital spacing): The nadir triplet of tracks, shown as black in Fig. 2, would have a time spread of about 4 minutes, and all adjacent tracks would be ~53 km apart at the equator. This spacing is nearly optimum for observing oceanic eddy fields and surface energy transport [10].

Scenario III, High temporal resolution (~2600 km orbital spacing): This arrangement would place each succeeding altimeter's track on top of the spatially adjacent one. This would generate three- and six-day revisit cycles, in addition to the normal 17-day Geosat cycle. An alternative version of this scenario would space the satellites ~5200 km apart, resulting in effective six- and twelve-day repeat cycles within each 17-day base cycle. Frequent revisit is desirable to observe the evolution of large-scale features, such as El Niño.

Scenario IV, Site-specific coverage: Given that one of the altimeters would be dedicated to a fixed exact-repeat mission, the others in the constellation could be moved as required upon command. This would allow a user to shift the altimeters' tracks to pass over an area of particular interest, which would have scientific, military or natural hazard applications. With two roaming satellites, any given site could be covered by both an ascending and a descending pass. This guarantees at least one cross-over at the site of interest. Alternatively, the satellites could be timed to generate four cross-overs that would bracket the site.

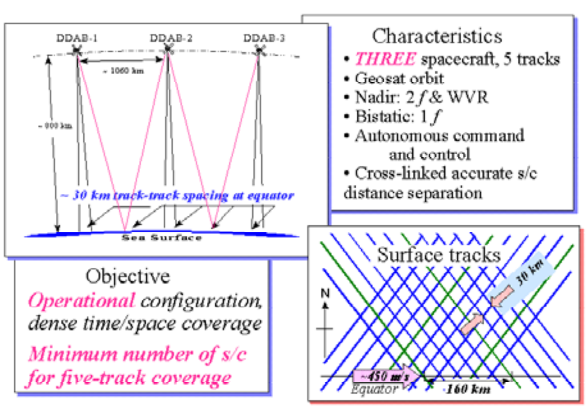

Figure 2. The largest panel shows the three DDA in a Geosat orbit. The black lines represent the nadir beams and the red lines represent the bistatic-beams.

III. Bistatic-WITTEX

A bistatic radar is one in which the transmitter and the receiver are spatially separated, in the case of bistatic-WITTEX on different widely spaced satellites. Bistatic oceanographic altimeter measurements concentrate on the specular area on the surface midway between the transmitter and the receiver. Fig. 2 shows in red the specular point located at the minimum radar range between the two satellites. Its forward reflection (toward the receiver) is relatively strong. Knowledge of the precise range or incident angle of the specular point is not required. We have shown that SSH derived from a bistatic instrument will provide height accuracy that is comparable to that delivered by nadir altimetry.

The nominal bistatic-WITTEX constellation consists of *n* satellites (only three are shown in Fig 2), comprising n nadir altimeters (one on each spacecraft), and (*n-1*) bistatic links (one between each neighboring pair of spacecraft). Together, these gather SSH data along (*2n-1*) surface tracks. They converge at turnover, which is the latitude of the inclination angle of the constellation's orbit plane.

Each nadir altimeter should comprise two frequencies, and a microwave radiometer. Two frequencies are required to estimate and thence to compensate for propagation delay due to free electrons (TEC) in the ionosphere. A radiometer is required to estimate and thence to compensate for propagation path delay due to water vapor (WV) in the atmosphere. We consider each nadir altimeter to be capable of state-of-the-art height accuracy.

The bistatic radars are relatively simple, as they require only one frequency and no radiometers. Propagation delays over the bistatic (off-nadir) paths can be interpolated from the values measured by the nadir instruments, since the track separations are smaller than the correlation distance of the delay perturbation phenomena (TEC and WV).

Bistatic range measurement can be converted to an equivalent SSH measurement at the specular point only if the spacing between the two spacecraft (the bistatic baseline) is well known. There are basically four errors that need to be ameliorated. These are discussed in the next section.

Our simulations demonstrate that a bistatic delay-Doppler radar altimeter can achieve the same along-track resolution and produce the same radar waveforms over a quasi-flat surface as a monostatic radar altimeter, in spite of the differences in the measurement geometry [6]. A longer burst length will be required to achieve a given Doppler resolution for the bistatic radar altimeter, but these longer bursts can be accommodated with a realistic burst pattern. The processing of bistatic radar data can be performed with algorithms developed for use with a monostatic altimeter.

Fig. 2 (small right bottom panel) shows the ground tracks of a bistatic DDA altimeter constellation. The spacing of the tracks is 30 km. This spacing is sufficient to capture the mesoscale oceanography as well as the basin scale variability. The configuration of this constellation is fixed, unlike the nadir only satellites, in that the mounting of the bistatic altimeters and the altitude of the satellites determine the ground track separation. However, the benefit is that there are five ground tracks, which previously could only be obtained by employing five satellites. Now with only three satellites and one launch vehicle a two-dimensional surface gradient field that is eddy resolving can be observed. There is also the added benefit of these altimeters being able to track the sea surface to within 5 km of the beach. This design represents a quantum step in the use of satellite altimetry to monitor the ocean's currents.

IV. Associated Error Measurements

The dominant error in the bistatic link is the range error that will occur if the respective time references on the two spacecraft are not in perfect synchronicity. Whereas asynchronicity is always a potential issue with bistatic radar, it can be especially problematic when high range measurement accuracy is required, or when the transmitter and receiver are widely separated.

Errors from differential clock offset can be identified and eliminated. One solution is to implement the bistatic link in both directions. That is, the bistatic altimeters on each satellite should contain a transmitter and a receiver, rather than just one half of a radar at each end of the link as is generally the case. Clock offset is cancelled when the range measurements from the two directions are averaged together.

Also, bistatic sea surface height measurement depends to first order on knowledge of the measurement baseline. Thus, each satellite pair must maintain knowledge of its relative spacing to within a few centimeters. This knowledge can be derived from a transponder link.

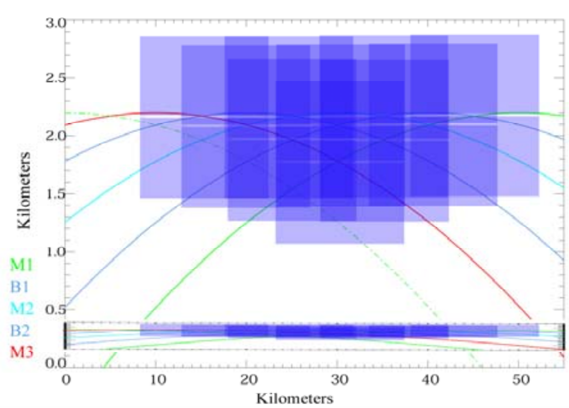

Figure 3. The colored lines represent the ground tracks of the specular point for the nadir (M#) and bistatic (B#) points. At each turnover point the blue shaded area represent the footprint of the instrument used for averaging. This diagram is plotted to scale at the bottom of the image.

In a stand-alone bistatic WITTEX constellation, the nadir instruments would be capable of making direct estimates of path delays due to the ionosphere (TEC) and the wet atmosphere (WV). In such good company, the bistatic instruments need only one frequency, and do not need radiometers. The necessary atmospheric and ionospheric path-length corrections to the bistatic legs can be interpolated from the nadir instruments.

The cross track method can also be used to mitigate systematic track-to-track height errors. Crossover height differences are the best measure of the radial orbit error. This height error also includes actual sea level change, altimeter noise, and correction errors. By using a least-squares method the RMS of the height error can be minimized.

IV. Dual Use: Geodetic and Oceanographic uses

In the 1980's the Geodetic Mission (GM) of the altimetric satellite Geosat was to map the ocean's sea surface with a random orbit [11]. This was accomplished in 18 months and the satellite was maneuvered into the exact repeat cycle that SEASAT had once occupied. The Exact Repeat Mission (ERM) of Geosat lasted almost five years and provided the means to map the mesoscale variability of the world's oceans [4]. The same paradigm could be used with a WITTEX or bistatic-WITTEX constellation. In a GM a single altimeter would take about six years to collect enough cycles of the closely spaced orbits to reduce the noise in the geodetic signal. Using bistatic-WITTEX the same mission could be done in a little over a year. Then the constellation could be maneuvered into an ERM for the remainder of its life. This dual-use would bring on more sponsors in developing an ocean observing system and provide not only the oceanography required, but the bathymetry as well [12].

IV. Conclusions

The delay-Doppler altimeter enables a constellation of altimeter satellites to be launched from a single launch vehicle. Each altimeter can measure the sea surface height with an accuracy twice as good as measurements from conventional altimeters such as TOPEX. The delay-Doppler altimeter has an along track resolution of 250 m, can track the ocean's surface to within 5 km of the shore, and is essentially independent of growing sea states (increased significant wave height). This constellation allows various scenarios depending upon operational requirements and system design. These constellations allows a system where even the loss of one or two satellites still ensures an altimeter system that is still better than the performance of conventional altimeters.

Acknowledgments

We wish to thank the Integrated Program Office for support over the years that much of this research was accomplished.

References

[1] R. K. Raney, "The delay Doppler radar altimeter," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 36, pp. 1578-1588, 1998.

[2] R. K. Raney, J. R. Jensen, and D. L. Porter, "The Delay-Doppler Radar Altimeter: Robust and Improved Measurement Capabilities," presented at Ocean 2003, San Diego, 2003.

[3] R. K. Raney, W. H. F. Smith, D. T. Sandwell, J. R. Jensen, D. L. Porter, and E. Reynolds, "Abyss-Lite: Improved Bathymetry from a Dedicated Small Satellite Delay-Doppler Radar Altimeter," presented at IGARSS2003, Toulouse, France, 2003.

[4] S. M. Glenn, D. L. Porter, and A. R. Robinson, "A Synthetic Geoid Validation of Geosat Mesoscale Dynamic Topography in the Gulf Stream Region," *Journal of Geophysical Research*, vol. 96, pp. 7145-7166, 1991.

[5] R. K. Raney and D. L. Porter, "WITTEX: An innovative three-satellite radar altimeter concept," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 39, pp. 2387-2391, 2001.

[6] R. K. Raney, D. L. Porter, and F. M. Monaldo, "Bistatic WITTEX: an Innovative Constellation of Radar Altimeter Satellites," in *Proceedings of the International Geoscience and Remote Sensing Symposium IGARSS02*. Toronto: IEEE, 2002.

[7] J. R. Jensen and R. K. Raney, "Delay Doppler radar altimeter: Better measurement precision," in *Proceedings IEEE Geoscience and Remote Sensing Symposium IGARSS'98*. Seattle, WA: IEEE, 1998, pp. 2011-2013.

[8] R. K. Raney and D. L. Porter, "WITTEX: An Innovative Multi-Satellite Radar Altimeter Constellation," in *Report of the High-Resolution Ocean Topography Science Working Group Meeting (Reference 2001-4)*, D. B. Chelton, Ed. Corvallis, Oregon: Oregon State University, 2001, pp. 170-178.

[9] E. Witte, *Über meeresströmungen (On Ocean Currents)*: Pless, Verlag von A Krummer, 1878.

[10] D. Stammer and C. Dieterich, "Space-borne measurements of the time-dependent geostrophic ocean flow field," *Journal of Atmospheric and Oceanic Technology*, vol. 16, pp. 1198-1207, 1999.

[11] D. T. Sandwell and W. H. F. Smith, "Marine gravity anomaly from Geosat and ERS 1 satellite altimetry," *Journal of Geophysical Research*, vol. 102, pp. 10039-54, 1997.

[12] D. T. Sandwell and W. H. F. Smith, "Bathymetric Estimation," in *Satellite Altimetry and Earth Sciences*, *Intl. Geophys.*, L.-L. Fu and A. Cazenave, Eds. New York: Academic Press, 2001, pp. 441-457.