# The Delay-Doppler Radar Altimeter: Robust and Improved Measurement Capabilities

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**Abstract - A delay-Doppler radar altimeter exploits coherent signal processing in addition to incoherent waveform averaging to achieve significantly better measurement precision and instrument efficiency than are possible from a conventional incoherent instrument such as TOPEX or Jason-1. The required processing can be built into the on-board system, whose output waveforms yield geophysical parameters with the analysis algorithms already developed for conventional altimetric data. The approach enables new architectures, ranging from a single-frequency geodetic instrument (Abyss-Lite), to a three-satellite constellation of TOPEX-class altimeters (WITTEX) small enough to fit into one launch vehicle.**

## I. INTRODUCTION

The state-of-the-art measurement precision of sea surface height (SSH), significant wave height (SWH), and surface wind speed (WS) by conventional space-borne radar altimeters (RA) is benchmarked by TOPEX [1], now being superceded by Jason-1. The inherent precision of such measurements is determined primarily by the number of degrees-of-freedom (incoherent averaging) in the post-processed waveform. The delay-Doppler altimeter (DDA) [2] uses innovative signal processing techniques to increase degrees-of-freedom, resulting in a significantly improved approach to ocean-observing radar altimetry. The key techniques are adapted from synthetic-aperture imaging radar. Results from analysis [3] and airborne prototype tests [4, 5] verify that a space-based delay-Doppler altimeter will have better measurement precision by as much as a factor of two, will make better use of the transmitted power by a factor of ten, and have a much smaller along-track footprint whose size is not dependent on SWH, all in comparison to an otherwise comparable RA. Additional benefits follow from the DDA approach, including an ability to maintain fine range-gate track to within a few kilometers of shorelines, and applicability to the DDA waveforms of the analysis algorithm heritage developed for conventional RAs.

The DDA implemented as a space-based instrument will be a smaller and more capable radar altimeter as compared to any competing and otherwise similar RA. This opens the way to several operational scenarios. The most elementary version, Abyss-Lite [6], would use a Ku-band DDA to measure deflection of vertical gravity at the ocean's surface, after the precedent of Geosat during its geodetic mission [7]. The improved height precision of the DDA coupled with an optimized orbit will raise this class of measurements to their physical limits. A more elegant embodiment in an oceanographic application is WITTEX [8], a constellation of (nominally) three DDA satellites, having quasi-parallel surface tracks. Each of these altimeters would have two frequencies and water-vapor radiometers, similar to the TOPEX instrumentation. WITTEX would be able to resolve the two-dimensional current flow associated with mesoscale eddies [9, 10], among other benefits.

## II. THE DELAY-DOPPLER RADAR ALTIMETER

Conventional space-borne pulse-limited radar altimeters are incoherent, in the sense that no phase relationship between successive pulses is intended or exploited [11]. Signal processing in an RA consists primarily of integrating the powers of a sequence of received waveforms. Such incoherent integration (averaging) is required to reduce the speckle noise that dominates each individual waveform. For each averaged waveform, the precision of estimated geophysical parameters (SSH, SWH, or WS) is improved in proportion to the square-root of the number of waveforms integrated incoherently.

The DDA [2] exploits coherence within a set of received radar pulses, as well as using incoherent integration. Taking full advantage of the coherence requires that the radar's pulse repetition rate be substantially higher than that of an RA. Broadly speaking, DDA processing consists of two stages. The first stage, operating in the complex (phase and amplitude) range domain, takes Fourier transforms at each range delay over groups of received pulses. In each block of data so processed, these FFTs remap the data into the range-Doppler domain. In each Doppler bin, whose location index is a scaled replica of the altimeter's along-track beam pattern on the surface, these data can be shifted in range to remove the unwanted extra delay imposed by the radar's wavefront curvature at that position. In short, the thrust of the coherent FFT integration is to parse the data in each block into Doppler bins, where they can be range-curvature-corrected[1].

[1] This is a subtle but substantially different multi-pulse operation than Doppler beam sharpening, which is a relatively simple coherent integration over a group of returned pulses. That method generates very noisy waveforms that have unacceptably large speckle.

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The process is repeated, block by block, as the altimeter progresses along its orbit.

The second stage of processing consists of incoherently integrating the delay-compensated waveforms that correspond to each along-track position. This entails accumulating waveforms in each bin, as well as adding the contents of each bin to its neighbor as the antenna illumination pattern progresses along track. The upshot of these incoherents integration is that many more waveforms can be summed than is possible with an RA, thus reducing speckle noise.

The combination of coherent and incoherent processing introduced by the delay-Doppler altimeter results in a new concept that emulates a large number (nominally 32) of incoherent pulse-limited radar altimeters all working together. The processing stages can be implemented onboard for an oceanographic instrument. The output waveforms arise at nominally 25Hz, requiring a data downlink of nominally 20KHz bandwidth, comparable to that needed by conventional altimeters.

## III. BENEFITS IN APPLICATIONS

A DDA's output waveforms are each associated with a footprint location on the surface. The along-track resolution of each of these footprints is determined by the width of the Doppler bin. This width would be typically ~250m, assuming a Ku-band altimeter in a Geosat or TOPEX orbit, for example. Unlike the case for a conventional RA, the DDA's along-track footprint width is a constant of the system; it does not get larger as a function of SWH.

Each DDA output waveform has small variance, being the average of many statistically independent returns (looks) derived through integrating the signals at many Doppler frequencies in parallel. The DDA's looks are derived by temporal averages at each Doppler-resolved footprint location, rather than spatial averages over many neighboring pulse-limited footprints. Thus, improved speckle reduction does not necessarily imply poorer spatial resolution, in contrast to the more familiar and less friendly trade-off encountered with a conventional radar altimeter.

Parameter estimates derived from contiguous bin locations can be aggregated, of course, further improving measurement precision, but at the cost of resolution. One-second averaged data would correspond to an along-track pixel size of about 6.5 km, essentially reflecting the ground-projected speed of the satellite. At this level of averaging, the nominal precision of SSH estimation by the DDA is approximately twice as good as that from a conventional RA.

The Doppler dimension formed within the space-borne processor implies that the altimeter "knows" when land is approaching or receding from the field of view of the antenna. For example, data within a Doppler bin whose frequency is positive relative to that of the beam centroid (nominally zero Doppler) come from a known location in the forward half of the illuminated surface. This knowledge can be put to work in a "smart" range-gate tracker, which would favor estimates from the forward half of the beam to anticipate desired changes to maintain accurate lock on waveform timing even when within a few kilometers of the shoreline. There is no comparable way in a conventional altimeter to distinguish the relative location on the surface of contributions to the received signals.

The surface area that contributes to the height track point for an RA is confined to the pulse-limited region. In contrast, useful height track data for a DDA are derived from all areas along-track that lie within (nominally) the central beamwidth of the antenna pattern. The along-track width of the pulse-limited area is much smaller than that of the beam-limited area. Thus, it follows that DDA waveforms concentrate much more of the reflected energy at the nominal height track point than a conventional pulse-limited altimeter. Hence, a DDA needs to transmit less power. Less transmitter power implies a lower power implementation. This feature implies a smaller instrument and spacecraft, thus opening the way to "small-sat" architectures of high-performance radar altimeters.

## IV. ON GEODETIC ALTIMETRY

Sea surface slopes reveal gravity anomalies because the primary component of sea surface height is geoid height, the elevation of an equipotential of the gravity anomaly field. The geoid height at a point is the integral of anomalies over the entire earth [12]. The horizontal derivatives (slopes) of the geoid indicate anomalies in the direction of gravity called deflections of the vertical.

The slope signals required to estimate bathymetry are band-limited (12 km to 400 km full-wavelength). Hence, a geodetic altimeter needs to maintain relative accuracy of its height measurements only over this relatively narrow band. It has been shown that geoid slope is best obtained by taking the along-track derivative of the instantaneous sea surface height signal. In most situations this is within 1 microradian of the geoid slope [13]. Indeed, efforts to correct for path delays usually add noise to slope estimates [14]. Almost all sources of path delay error known to oceanographic radar altimetry have negligible impact to geodetics. Hence, a geodetic altimeter needs only one frequency, and does not need a water vapor radiometer.

Slope measurements provided by the Geosat and ERS-1 radar altimeters[2] during the geodetic phase of their respective missions furnish the best resolution oceanic gravity from space to date. The resulting bathymetric resolution is limited to about 25 km north-south, and to even poorer resolution of east-west slope components.

## V. ABYSS-LITE

Abyss-Lite is essentially a modern version of Geosat. The design[3] is based on the DDA, and employs modern instrument and spacecraft methodology. The delay-Doppler altimeter provides the enabling technology, especially its better height precision in the face of increasing SWH. Figure 1 compares the height precision of a DDA and a conventional

[2] These altimeters each had only one frequency (Ku-band), and no water-vapor radiometer.

[3] Based on a study completed at JHU/APL in 2003, under support from NOAA.

RA as a function of SWH. The plot shows that the DDA meets the height precision requirement derived from first principles to satisfy optimal oceanic geodesy by an altimeter [15]. The figure also shows that the DDA is about half as sensitive as an RA to increasing SWH. This is important for Abyss-Lite, as measurement precision degraded by larger significant wave heights proved to be a major source of noise in Geosat surface slope estimates [14, 16].

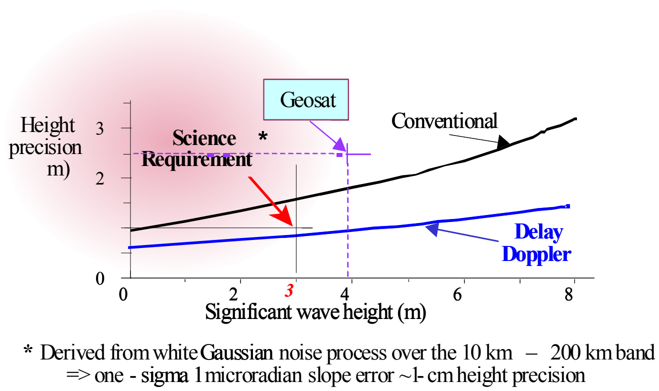


Figure 1. Altimeter precision and significant wave height

The Abyss-Lite peak transmitted power is 2.5W, in contrast to the 20W of Geosat. The lower power of Abyss-Lite is due in part to its higher gain antenna, and also due to the delay-Doppler paradigm. Although Doppler ambiguities will be generated by the 1-m antenna combined with the ~13 KHz effective pulse repetition frequency, these can be suppressed through frequency- and range gate selection. In flight configuration, the antenna phase center is directly below the spacecraft center-of-gravity (Fig. 2), which will minimize height errors that could be induced by spacecraft pitch or roll motions. The nominal mass and size of Abyss-Lite fit within the Pegasus launch constraints with adequate margin. The cost of the altimeter and spacecraft is less than $60M, including reserves.

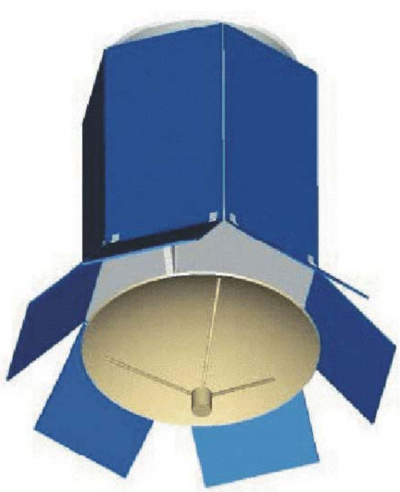

Figure 2. Abyss-Lite (on-orbit configuration)

The geodetic mission of Abyss-Lite is best served by an orbit which does not repeat for ~1.2 years, to yield an average ground track spacing of 6 km [16]. Its inclination should be near 50°-63° (or 113°-120° retrograde) to resolve north and east slopes nearly equally, and to cover the lower latitudes where existing data are inadequate. Note that oceanographic radar altimeter missions (TOPEX/Poseidon, Jason-1, ERS1/2, Envisat, and Geosat ERM/GFO) normally are placed into exact-repeat orbits (10 to 35 days), and as a consequence have widely spaced (80 km to 315 km) ground tracks. Such orbits cannot resolve the short-wavelength two-dimensional surface slopes required for useful geodesy and bathymetry.

Abyss-Lite will provide geodetic and bathymetric data that cannot be gleaned by any other means from satellites. The spatial resolution of gravity anomalies is degraded in proportion to the distance between the gravimetric source and the observed signal. Hence, the in-orbit gravity measurements of GRACE and GOCE cannot observe anomalies at wavelengths smaller than their altitudes above the Earth, about 485 km and 250 km, respectively. Even though Abyss-Lite is also a space-based instrument, its resolution will be two orders of magnitude better, about 6 kilometers (half wavelength). This is the physical limit for any method (including ship-based gravimetry) that can be achieved through observations at the ocean's surface.

## VI. WITTEX

WITTEX [8] is named in honor of E. Witte, who first discovered the geostrophic current equation in 1878 [17]. It also is an acronym for Water Inclination Topography and Technology Experiment. WITTEX is a constellation of three co-planar small-satellite radar altimeters[4]. The concept is cost-effective, because one vehicle is sufficient to place three DDA satellites into the same orbit plane. The satellites would be spaced apart by several hundred kilometers. Their sub-satellite tracks are laterally separated because of the Earth's rotation. The Earth's equatorial rotation rate of ~450 m/s, combined with a track-repeat tolerance of ~1 km, translates into an along-orbit relative position control requirement of only ~9 km, which is a standard that is routinely met by conventional altimeter mission management.

The two-dimensional geostrophic current can be derived if two orthogonal components of the surface height gradient can be observed – hence WITTEX. To date, satellite radar altimeters have been able to measure only the along-track component of surface slope using data from a single ascending or descending pass. WITTEX would overcome that limitation. At any given latitude, neighboring measurements occur within minutes of each other, so that the cross-track surface gradient can be measured as well as the usual along-track gradient. Track separation may be chosen in response to mission objectives by selection and maintenance of the inter-satellite spacing. Systematic height errors between tracks can be mitigated by analysis of crossover differentials at maximal latitudes [18].

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[4] See "Ocean Observation Monitoring with a Space-based Delay-Doppler Altimeter Constellation", these Proceedings.

The notional instrument for WITTEX has two frequencies (Ku- and C-bands) and an on-board water vapor radiometer, similar to TOPEX [19]. The DDA approach, combined with recent advances in spacecraft technology, leads to substantial miniaturization; the mass of each WITTEX satellite is predicted to be less than 200 Kg.

## VII. CONCLUSIONS

The delay-Doppler altimeter blends the most advantageous features of the pulse-limited and the beam-limited methods. Pulse-limited altimeters have the very great advantage that their accuracy of height measurement is immune (to first order) to angular orientation errors of the antenna beam. Beam-limited altimeters have the advantage that the size of the surface area that contributes to the received signal is determined (to first order) by the radar system, rather than being enlarged the roughness of the surface. Both of these advantages are incorporated into the DDA. In addition, the combined coherent and incoherent processing strategies convert more of the transmitted energy into useful received signal, implying better efficiency, and therefor less transmitter power, and a smaller instrument. Parsing the data into Doppler bins provides additional information to the tracker sub-system so that reliable performance closer to shore is feasible. Finally, the output waveforms enjoy substantially greater averaging, which is expressed as better measurement precision.

As a smaller and better altimeter, the DDA opens the road to cost-effective applications, such as a new geodetic mission (Abyss-Lite), or a constellation of oceanographic altimeters (WITTEX), to cite two examples.

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