An Annotated Bibliography (2014)

Selected milestones of oceanic radar altimetry leading to finer height precision, the CryoSat approach, and beyond

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[1] P. M. Woodward, *Probability and Information Theory, with Applications to Radar*, New York: Pergamon Press, 1953.

This little treatise is an essential prime reference, deserving to be on a nearby shelf for anyone interested in radar. Among other attributes, it summarizes compactly the Fourier transforms that describe the fundamental signal processing strategies inherent to unfocussed SAR mode (delay-Doppler) radar altimetry.

[2] R. K. Moore and C. S. Williams, Jr., "Radar return at near-vertical incidence," *Proceedings of the IRE*, vol. 45, pp. 228-238, 1957.

The first treatment of the impulse response of a radar looking at a quasi-smooth horizontal surface from above, introducing the "beam-limited" and the "pulse-limited" waveforms and their associated radar power equations. The pulse-limited form subsequently became the norm for orbital conventional ocean-viewing altimeters. For oceanic surface returns, beam-limited waveforms are "peaky", in contrast to the pulse-limited response, which is, to first order, a step function. Both waveforms are inherent to SAR mode altimetry.

[3] J. R. Klauder, A. C. Price, S. Darlington, and W. J. Albersheim, "Theory and design of chirp radars", *Bell System Technical Journal,* Vol. XXXIX, No. 4, pp. 745-808, 1960.

The first discussion of then just-declassified techniques, all of which are now standard practice in radar altimetry design, including the matched filter, the time-bandwidth product of a modulated waveform, waveform modulation including especially linear fm ("chirp"), and side-lobe suppression techniques using paired-echo analysis and weighting functions.

[4] J. A. Greenwood, A. Nathan, G. Newman, W. J. Pierson, F. C. Jackson, ad T. E. Pease, "Radar altimetry from a spacecraft and its potential applications to geodesy", *Remote Sensing of the Environment*, Vol. 1, pp. 59-80, New York: Elsevier, 1969.

The first open publication to describe the concept of observing the oceanic expression of the Earth's geoid, an idea that considerably helped to motivate the first altimetric missions GEOS-3 and Geosat.

[5] W. J. J. Caputi, "Stretch: a time-transformation technique," *IEEE Transactions on Aerospace and Electronic Systems*, vol. AES-7, pp. 269-278, 1971.

Stretch is a clever technique whereby a short objective range window observed by a radar at very long range may be exploited (conserving the pulse's time-bandwidth product) such that a linear fm signal from the intended window may be stretched over much of the unused range time, thus vastly reducing its fm rate and near-instantaneous bandwidth, which enables subsequent real rate (low bandwidth) data processing. Using the Stretch technique, lossless bandwidth compression factors of 100 and larger have become commonplace.

[6] J. T. McGoogan, L. S. Miller, G. S. Brown and G. S. Hayne, "The S-193 Radar Altimeter Experiment," *Proceedings of the IEEE*, vol.62, pp. 793-803,1974.

Many of the original ideas reported in this summary paper, that have since become bedrock baseline concepts for modern oceanic radar altimetry including the "Brown model" and the "Walsh upper bound" on pulse repetition frequency, were generated through study of the simple proof-of-concept altimeter flown aboard Skylab on its three missions.

[7] R. P. Dooley, F. E. Nathanson, and L. W. Brooks, *Study of Radar Pulse Compression for High Resolution Satellite Altimetry*, Final Report, NASA-CR-137474, Technology Services Corporation, Silver Spring, MD, Dec. 1974.

This would seem to be the first mention of the Stretch technique applied to altimetry, although Caputi's pioneering work is not cited." Full-deramp," a term introduced in this report, becomes the applicable terminology in the radar altimeter context. The implementation of the recommended technique is examined in detail.

[8] J. L. MacArthur, "Design of the Seasat-A radar altimeter," *Oceans*, vol. 8, pp. 222-229, 1976.

MacArthur introduced the Stretch technique in the Seasat altimeter (1978), using its altimeter-specific name "full de-ramp", citing Dooley et al (1974). Since then it has been the method of choice for oceanographic altimetry. It is the main reason that bandwidths on the order of 300 MHz (and their associated 0.5-m single pulse range resolution) are transformed into signals having only about 3 MHz bandwidth, thus allowing extensive on-board processing at low data rates.

[9] G. S. Brown, "The average impulse response of a rough surface and its applications," *IEEE Antennas and Propagation*, vol. 25, pp. 67-74, 1977.

Brown generalized Moore's pulse-limited impulse response, casting it as the convolution of three fundamental transfer functions, one of which represents the characteristics of the reflecting surface. This paper is the genesis of the "Brown model," from which tracking (and re-tracking) algorithms extract the three principal parameters SSH, SWH, and WS. (By the way, precision oceanic altimetry was at the time a sensitive issue, because improved knowledge of the global geoid had strategic implications. Gary once told me that one of his papers was re-classified above his clearance level, so that he had to forfeit all copies of it, and he was barred from reading his own work.)

[10] G. S. Hayne, "Radar altimeter mean return waveforms from near-normal incidence ocean surface scattering," *IEEE Antennas and Propagation*, vol. AP-28, pp. 687-692, 1980.

This paper was one of an expanding series that contributed to transforming radar altimetry from a challenging academic exercise into an operational tool. Parameter extraction using Brown's model was widely adopted as the backbone of the technique.

[11] W. F. Townsend, "An initial assessment of the performance achieved by the Seasat-1 radar altimeter," *IEEE Journal of Oceanic Engineering*, vol. OE-5, pp. 80-92, 1980.

This paper provides a concise review of the successful demonstration of the Seasat radar altimeter.

[12] E. J. Walsh, "Pulse-to-pulse correlation in satellite radar altimetry," *Radio Science*, vol. 17, pp. 786-800, 1982.

Early experiments (using the rudimentary proof-of-concept S-193 altimeter on SkyLab) varied the radar's pulse repetition frequency (prf). Walsh' paper summarizes the results, which showed that correlation is introduced between successive returns if the prf is too high. As the primary benefit of averaging was to reduce the standard deviation of parameters derived from the waveform ensemble, such correlation was not wanted. This paper presents an analytical form for the threshold condition, known as the Walsh upper bound on prf.

[13] J. L. MacArthur, P. C. Marth, and J. G. Wall, "The GEOSAT Radar Altimeter," *Johns Hopkins APL Technical Digest*, vol. 8, pp. 176-181, 1987.

This paper describes the design of the Geosat radar altimeter, essentially a more sophisticated version of the altimeter on Seasat. Geosat was the first dedicated oceanographic mission. Its first 18 months were in a non-repeating orbit, intended to collect data sufficient to establish the ocean's geoid (on scales larger than about 20 km), and as such those data remained classified (thus unavailable) for nearly ten years.

[14] D. B. Chelton, E. J. Walsh, and J. L. MacArthur, "Pulse compression and sea-level tracking in satellite altimetry," *J. of Atmospheric and Oceanic Technology*, vol. 6, pp. 407-438, 1989.

This is a classic altimetry paper, co-authored by a multi-disciplinary team of leading individuals (at the time): a radar altimeter engineer (McArthur), a waveform practitioner (Walsh), and a user of the data (Chelton).

[15] A. R. Zieger, D. W. Hancock, G. S. Hayne, and C. L. Purdy, "NASA radar altimeter for the TOPEX/Poseidon project," *Proceedings of the IEEE*, vol. 79, pp. 810-826, 1991.

Thanks to promotion to a new level (literally) by influentials such as Carl Wunsch, radar altimetry was the basis of a new series of dedicated missions aimed at long-term observation of the status and changes in the sea surface topography. This paper describes in some detail the design of the TOPEX altimeter, which was based extensively on the Seasat and Geosat precedents, but also introduced several significant advances.

[16] P. C. Marth, J. R. Jensen, C. C. Kilgus, J. A. Perschy, J. L. MacArthur, D. W. Hancock, G. S. Hayne, C. L. Purdy, L. C. Rossi, and C. J. Koblinsky, "Prelaunch performance of the NASA altimeter for the TOPEX/Poseidon Project," *IEEE Transactions on Geoscience and Remote Sensing,* vol. 31, pp. 315-332, 1993.

In similar spirit as that preceding, this paper looked at the performance expected from the TOPEX mission. On-board data processing and tracking are described in some detail.

[17] R. E. Cheney, B. C. Douglas, D. C. McAdoo, and D. T. Sandwell, "Geodetic and oceanographic applications of satellite altimetry," in *Space Geodesy and Geodynamics*. London: Academic Press, 1986, pp. 377-405.

An excellent example of many hundreds of papers, book chapters, and articles about the benefits and applications of space-based ocean-observing radar altimetry in general, and in particular measurement of the oceanic geoid from which global bathymetry could be estimated.

[18] W. H. F. Smith and D. T. Sandwell, "Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry," *J. Geophys. Res*., vol. 99, pp. 21803-21824, 1994.

Once the geodetic data from Geosat were declassified, then academics such as Smith and Sandwell could publish their methodology and results on measuring the sea surface topography, and, of most interest to many, their back-propagation techniques for estimating the sea's bottom topography and its corresponding depth contours. Geosat data (aided by ERS-1 altimeter data from its long repeat cycle mode) lead to bathymetric charts down to about 20-km spatial scales.

[19] J. R. Jensen, "Design and performance analysis of a phase-monopulse radar altimeter for continental ice sheet monitoring," in *Proceedings, IEEE International Geoscience and Remote Sensing Symposium IGARSS'95*. Florence, Italy: IEEE, 1995, pp. 865-867.

Over the previous two decades there had been several studies seeking ways to extend the useful swath of a radar altimeter beyond the limits of the nadir (sub-satellite) track. This was the first paper to use the interferometric (phase-monopulse) technique to measure and then to correct for the height error induced by a cross-track slope of the intended surface.

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

Expanding on a previous conference paper (IGARSS'95), this was the first journal publication of an unfocussed synthetic aperture radar approach to oceanic altimetry. The result of the delay-Doppler processing described in the paper was a new architecture in which were generated many post-processing beam-limited altimeters, operating in parallel. In this method, the cross-track impulse responses for all beams are pulse-limited. In contrast, each along-track impulse response is beam-limited, and each such beam is pointed at a unique and known off-nadir angle. Both the beam-limited width and pointing angle are established by Fourier transforms aver blocks of received data. (Aside: In Europe the name "delay-Doppler" was supplanted by "SAR-mode", although that term instead should have been the "unfocussed SAR mode", a rather more accurate characterization. A true "SAR-mode" implies an along-track focusing operation, which, if implemented, would result in an improved and useful form of advanced signal-processing radar altimeter.)

[21] D. J. Wingham, et al., "CryoSat: A Mission to Determine Fluctuations in the Mass of the Earth's Land and Marine Ice Fields," University College, London, UK, Proposal to the European Space Agency, October 1998.

The CryoSat radar was based on a design that combined the methods of the previous two papers. Although such an instrument had been unsuccessfully proposed to NASA (1996), the Wingham proposal, which was based on a solid science rationale, was selected by ESA to become the first Earth Explorer mission.

[22] 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.

Delay-Doppler generates more statistically-independent waveforms, hence these when summed render the standard deviation of the retrieved parameters to be smaller than those available from any conventional altimeter. This paper summarizes the results of simulations that verify the theoretical predictions.

[23] J. R. Jensen, "Radar altimeter gate tracking: theory and extension," *IEEE Transactions Geoscience and Remote Sensing*, vol. 37, pp. 651-658, 1999.

The delay-Doppler altimeter produces a class of waveform previously not seen from space-based ocean-viewing radars. This paper is the first to look carefully at the tracking issues associated with this new non-Brown waveform, and suggests an appropriate tracking approach.

[24] C. Zelli, "ENVISAT RA-2 Advanced radar altimeter: Instrument design and pre-launch performance assessment review," *Acta Astronautica*, vol. 44, pp. 323-333, 1999.

In contrast to operational oceanic radar altimeters that perform tracking and first-order waveform summing on board, the RA-2 was the first to introduce an experimental mode in which short bursts of data in full detail were collected and relayed to the ground prior to processing.

[25] L.-L. Fu and A. Cazanave, *Satellite Altimetry and the Earth Sciences*, Academic Press, 2001.

The state of the art (prior to CryoSat) is elegantly summarized in the Fu and Cazanave book.

[26] W. H. F. Smith, D. T. Sandwell, and R. K. Raney, "Bathymetry from space: technologies and applications," in *Proceedings MTS/IEEE Oceans 2005*. Washington, DC, 2005.

This paper quantifies the benefits of improved SSH precision as applied to charting sea bottom topography. A plea is made for a dedicated new mission using a SAR-mode radar altimeter placed in an inclined non-repeating orbit whose data products would include both oceanographic and bathymetric applications. The resulting bathymetry would have spatial resolution down to the theoretical lower bound on the order of 5 kilometers.

[27] *Coastal Altimetry*, S. Vignudelli, A. Kostianoy, P. Cipollini, and J. Benveniste, Eds.: Springer, 2009.

This book is comprised of peer-reviewed invited chapters, each covering specific aspects of and the unique challenges posed by applying space-based radar altimetry to the near-shore environment.

[28] R. K. Raney, "CryoSat SAR-mode looks revisited," *Proceedings, ESA Living Planet Symposium*, Bergen Norway, 28 June – 02 July 2010, subsequently published in *IEEE Geoscience and Remote Sensing Letters*, vol. 9, pp. 393-397, 2012.

Open publication of the central points in the 2010 Bergan paper, including in particular the first observation that the closed burst paradigm limits the available measurements to only about 1/3 of those possible through continuous along-track data collection. The paper also offers the basic parameters of an improved design approach aimed at capturing all of the potentially available measurements. This idea leads to a optimal PRF that is much lower than the Nyquist lower bound, yet much higher than the Walsh upper bound, thus "breaking out of the box" of both conventional synthetic aperture radar and conventional radar altimetry.

[29] R. K. Raney, “Maximizing the intrinsic precision of radar altimetric measurements,” *IEEE Geoscience and Remote Sensing Letters,* Vol. 10, No. 5, pp. 1171-1174, 2013.

This is the complete version of a conference paper, including the "Vision" section (arguing for simultaneity of LRM and SAR modes) that was presented from the floor during the closing plenary discussion at the 2012 Venice meeting. The principal conclusion is that a fully interleaved (open burst) approach maximizes measurement precision, while accommodating full compatibility with historical conventional altimetric data records.

[30] C. Gommenginger, C. Martin-Puig, L. Amarouche, and R. K. Raney, *Review of State of Knowledge for SAR Altimetry over Ocean,* Version 2.2, EUMETSAT,EUM/RSP/REP/ 14/74930421, November 2013.
https://www.dropbox.com/s/u3mlmkzjmgv243r/SARAltimetry_EUMETSAT_JasonCS_review_v2.2.pdf

This report demonstrates that the SAR interleaved mode is essential for future radar altimeters. It is the only method that would assure continuity between the (unfocussed) SAR mode aboard Jason-CS, and data from all other (conventional) altimeter missions. Adopting the original closed-burst approach on Jason-CS would compromise the continuity of the 20-year high-precision sea level time series.