An Annotated Bibliography:

Selected milestones of oceanic radar altimetry leading to finer height precision and the CryoSat heritage

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[1] 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 equation. The pulse-limited form since then has been the norm for orbital ocean-viewing altimeters. Beam-limited waveforms are "peaky", in contrast to the pulse-limited response, which is, to first order, a step function.

[2] 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 traded (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 bandwidth, which enables subsequent real rate data processing.

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

MacArthur introduced the Stretch technique into radar altimetry, changing its name to "full de-ramp" (without appropriately acknowledging Caputi). The method was first used on the Seasat altimeter (1978), and since then 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) submit to extensive on-board processing.

[4] 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 represented 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.)

[5] 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 a expanding series that contributed to transforming radar altimetry from a challenging academic exercise into an operational tool. Parameter extraction using Brown's model was the backbone of the technique.

[6] 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.

[7] 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 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.

[8] 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, the first dedicated oceanographic mission. The first 18 moths of the mision 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 were classified for nearly ten years.

[9] D. B. Chelton, E. J. Walsh, and J. L. MacArthur, "Pulse compression and sea-level tracking in satellite altimetry," Journal 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).

[10] 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 mission 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 included several significant advances.

[11] 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.

[12] 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.

[13] 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.

[14] 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 a synthetic aperture radar approach to oceanic altimetry. In perspective, the result of the delay-Doppler processing described in the paper was a new altimeter architecture in which the cross-track impulse response was pulse-limited, whereas the along-track response was beam-limited. In this case, the beam was limited by its Doppler bandwidth (and offset), which were determined by specific properties of the radar design.

[15] 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, became the first ESA Earth Explorer mission.

[16] 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 reduce the standard deviation of the retrieved parameters. This paper summarizes the results of simulations which verify the theoretical predictions.

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

The SAR-mode (delay-Doppler) altimeter produces a class of waveform previously not seen. This paper is the first to look carefully at the tracking problems associated with this new non-Brown waveform.

[18] 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 which 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.

[19] L.-L. Fu and A. Cazanave, *Satellite Altimetry and the Earth Sciences*, Academic Press, 2001, pp. 463.

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

[20] 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 limit on the order of 5 kilometers.