CRYOSAT SAR-MODE LOOKS REVISITED

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ABSTRACT

The precision of sea- (or ice-) surface height measurements by radar altimetry improves in direct proportion to the number of statistically-independent waveforms contributing to the measurement average. The closed burst strategy used on CryoSat constrains the amount of averaging to be less than the theoretical limit by a factor of approximately three. Open burst operation would allow capture of nearly all available looks. Optimal performance requires that the radar pulse-repetition frequency (PRF) be less than the usual Nyquist lower bound, which is acceptable for an altimeter viewing surfaces that have relatively small topographic relief.

1. INTRODUCTION

The measurement precision of a radar altimeter improves (smaller standard deviation) for larger number of statistically-independent looks. For a conventional radar altimeter, the maximum number of looks is constrained by the Walsh limit [1]. This may be generalized to the SAR mode, which expresses the minimum burst period that assures uncorrelated burst-to-burst waveform summations. From this perspective, the CryoSat SAR mode offers only about 1/3 of the potentially available number of looks. The additional looks may be captured if the method of transmit and receive sequences were reorganized, as either an open burst approach, or as a continuous pulse-repetition frequency (PRF) design.

2. SAR MODE

Fig 1 shows a synopsis of the CryoSat SAR Mode (delay-Doppler [2]), which uses signal processing techniques (on-board or ground-based) to (1) synthesize narrow antenna beams in the along-track plane by Doppler pass-band means, and (2) track any given surface location through a sequence of Doppler beams as the spacecraft progresses along its orbit. Subsequent processing removes the unwanted extra range at locations away from nadir, and sums all contributing signals to arrive at one (averaged) waveform for each resolved along-track position. Resolved Doppler bins are adjacent on the surface.

The altimeter in effect "stares" at each resolved surface location for as long as that particular cell is illuminated by the antenna as the spacecraft passes over head. The minimum size of such a delay-Doppler-resolved cell is about 250 meters, whose value is determined by system parameters and viewing geometry. Note that each cell is viewed over a larger fraction of the antenna beam than for the pulse-limited case; thus more data are gathered, which leads to substantial benefits, particularly the potential for more looks.

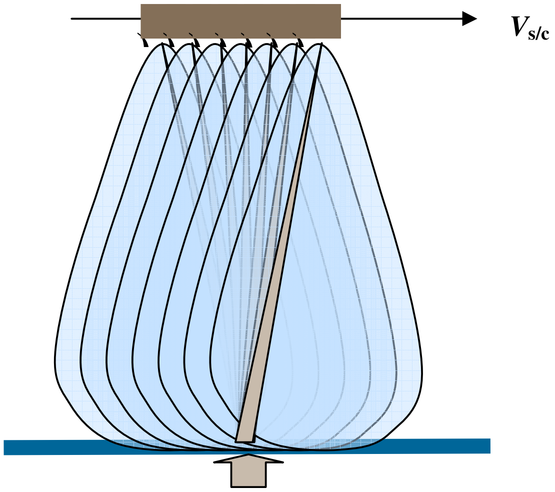

Figure 1. SAR mode operation

If only one such cell were illuminated, the measurements could not keep up with the forward velocity of the antenna footprint. The system gets around this objection by operating many of these spotlight beams simultaneously. A typical design would generate 64 parallel Doppler beams, but not all of these fall within the main lobe of the antenna. Thus, in practice there will be data from ~40 beams combined in the processor to generate the final (averaged) waveform from each resolved cell.

3. THE LOOKS QUESTION

After the processing is complete, the number of looks per second N_{Sec} is given by the product of the number of individual waveforms N_{Bin} in each Doppler bin, the number of useful Doppler bins N_{Useful} that contribute to the averaged waveform in each resolved cell X_{Dop}, and the number of cells traversed by the altimeter's footprint in one second

$$N_{\mathrm{Sec}} = N_{Bin} N_{Useful} \frac{1}{X_{Dop}} \frac{V_{SC}}{1 + \frac{R_E}{h}} \qquad (1)$$

where the closing ratio converts spacecraft orbital velocity to the footprint velocity along the surface. The top-level question is, How many statistically independent waveforms contribute to the final waveform? There are three factors to consider: Doppler bins--independence of the waveforms in different Doppler bins; Usefulness--waveform degradation as a function of Doppler; and the Walsh limit--independence of waveforms from different bursts in the same Doppler bin and at the same surface location.

The Doppler factor is readily handled, since data having non-overlapping spectra are statistically independent. Hence, waveforms from the same surface location seen through different Doppler beams are assured to be uncorrelated.

The Usefulness factor also is easily handled. In spite of diminishing returns, simulations [3] and analysis [4] have shown that there are significantly more looks available from the SAR mode than from a conventional altimeter. However, the transition of waveforms from "very useful" (close to nadir) to "feeble" (far from nadir) is gradual. In order to provide a non-slippery reference point for quantitative comparisons in the following discussion, the cut-off of useful Doppler bins is stipulated to occur at $3r/X_{\mathrm{Dop}}$, where r is the single-pulse range resolution. Waveforms from larger Doppler bins will be excluded.

4. USEFUL BINS

The individual waveform in each resolved Doppler bin has a shape (Fig 2) that is equivalent to the response of a fan-beam (narrow in the along-track direction) looking towards the surface. Such responses are sharpest at nadir (90^{o} incidence), but become weaker and more spread in range as the angle of encounter decreases from 90^{o}. The most useful Doppler bins for altimetric measurements are those that are clustered about nadir; others suffer from diminishing returns.

5. GENERALIZED WALSH BOUND

In his classic paper [1], Walsh reported studies of the correlation between waveforms from a conventional altimeter as a function of the radar's PRF. The so-called Walsh bound is the maximum PRF for which sequential returns are uncorrelated. This upper bound may be generalized to an altimeter using burst mode transmissions. The result is a lower bound on burst period BP_{MIN}

$$V_{SC}\, BP_{MIN} = h \frac{\lambda}{2X_{Dop}} \qquad (2)$$

which yields to easy interpretation. The term on the left is the distance traversed by the radar between bursts. The ratio on the right hand side corresponds to the angular beamwidth of an aperture of diameter $2X_{\mathrm{Dop}}$ radiating at wavelength λ. The multiplicand of 2 operating on X_{Dop} is a result of the fact that the aperture actually is illuminated by the radar and then reflecting, thus doubling the two-way phase across the aperture thence halving the beamwidth, a standard situation that is well known in synthetic aperture radar analysis. Thus, the complete term on the right hand side of the equation is the arc length along the orbit that falls with the effective beamwidth corresponding to the Doppler-resolved along-track footprint on the surface.

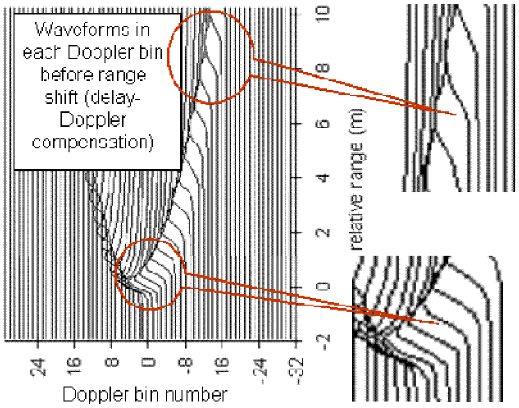

Figure 2. Waveforms as a function of Doppler

Eqn 2 is an important reference for understanding the looks question for a SAR mode altimeter. Using parameter values from CryoSat in this equation, the minimum burst period allowed by the generalized Walsh limit is 3.8 msec, which is about three times shorter than the CryoSat burst period of 11.7 msec. Thus, there is a potential for three times more uncorrelated looks from CryoSat operations than are available from the SAR mode as now configured.

6. CLOSED vs OPEN BURSTS

In burst mode, the radar has two options when planning transmission and reception strategy (Fig 3). CryoSat uses the closed burst method, in which a pulse group is transmitted, then their respective reflections arrive back at the radar, appearing again as a group. There is no constraint on the interval between transmitted pulses. The alternative is to assure that within each burst there are open intervals between transmitted pulses. The pulse lengths must be shorter than one-half of the pulse repetition period. This is the open burst method which was used so successfully in the TOPEX altimeter [5]. Timing is arranged so that receptions occur during the open intervals between transmitted pulses. Reflections set up by a given burst arrive at the radar during transmission of the next burst. With this method, the radar's PRF may be held constant, but the burst period must be carefully controlled to synchronize the open intervals with the reflected returns, since the round-trip pulse propagation time is proportional to the radar's altitude above the surface.

Rather than burst mode, the PRF could be continuous, which would imply that the radar must

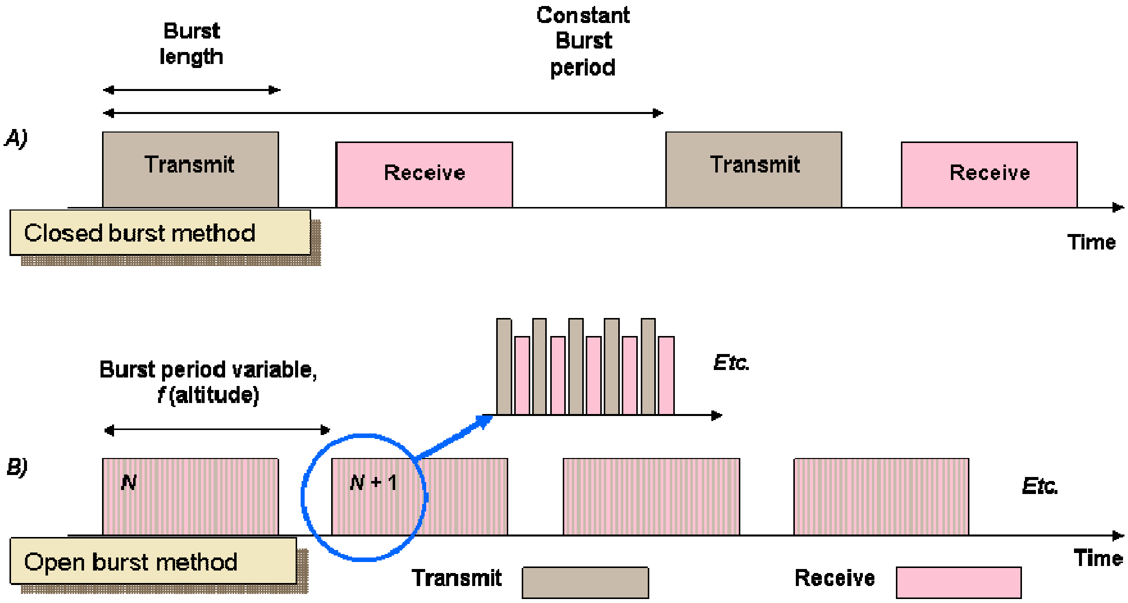

Figure 3. Closed (A) and Open (B) burst transmit and receive phasing

receive data between every transmission, in the same manner as a conventional SAR. This method would necessitate that the PRF be locked to spacecraft altitude, thus continuously variable (or at least, varied from one constant rate to another) as a function of altitude. With the continuous PRF method, there would be more freedom of choice of the number of pulses to include in the delay-Doppler processing group, thus more options for the Doppler cell size and possibilities for number of looks. There is no doubt that the continuous PRF approach could lead to the maximum number of independent looks, but at a cost in system complexity. The open burst option can do nearly as well, and with a simpler implementation.

The open burst method has the advantage that more average power may be radiated, which could be helpful over surfaces having smaller reflection coefficients. However, it has the disadvantage that preserving space for reception between transmitted pulses becomes more challenging with higher PRFs, especially for relatively long (linear-FM-modulated) pulses. In the CryoSat case, for example, the upper bound on transmitted pulse length would be on the order of 53 µsec (PRF = 8 kHz) decreasing to about 36 µsec (PRF = 12 kHz), somewhat less on average than the current SAR mode design of 51 µsec (PRF = 17.8 kHz). The issues surrounding pulse repetition frequencies that are less than the traditional SAR-justified Nyquist rate are discussed in section 8.

7. DOPPLER BINS vs PRF

The along-track size X_{DOP} of the Doppler bins is given by

$$X_{Dop} = \frac{PRF\,\lambda h}{2 V_{SC}\, N_P} \qquad (3)$$

where N_P is the number of pulses per burst. For the closed burst method of CryoSat, with 64 pulses per burst and a PRF of 17.8 kHz, the Doppler bin size is about 278 m. If the open burst method is used instead, then the PRF would need to be smaller, to assure sufficient time for reception between transmissions. It follows that the number of pulses must also be smaller, to keep the burst length shorter than the round-trip time to the surface. There are two options; (1) choose N_P to be a power of 2, thus setting up efficient FFT's for the azimuth Fourier transforms, or (2) let N_P be chosen so that the burst length is a constant as a function of PRF.

If the number of pulses is held constant but at a level less than 64, and constrained to be a power of 2, then 32 pulses per burst is the obvious choice. The resulting Doppler bin size is proportional to PRF ranging from just over 200 m for very low PRF to more than 300 m for PRFs in excess of about 9 kHz. Likewise, the burst length is inversely proportional to PRF, so that higher PRFs necessitate shorter bursts. In contrast, if the burst length is held constant, then the Doppler bin size is constant, while the number of pulses per burst increases in proportion to PRF.

The number of useful Doppler bins is inversely proportional to X_{DOP}. Thus, the number of effective looks must decrease for larger PRF if the number of pulses per burst is a constant. In contrast, if the burst length is held constant and the number of pulses per burst increased in proportion to PRF, then the number of useful Doppler bins is constant.

8. RANGE/DOPPLER ALIAS REJECTION

The Nyquist criterion does not apply directly to an altimeter designed to observe the ocean or sea ice. This is true because the original Nyquist criterion, which was developed for a one-dimension data sequence, carries over to a random field if and only if the data ensemble is uniformly distributed in two dimensions. Altimetric data most definitely are not uniformly distributed in two dimensions, since (1) they arise exclusively from a surface that is (nominally) orthogonal to the radar's illumination, and (2) the topographic relief of the surface is bounded by small variations in elevation. It follows that the CryoSat SAR-mode PRF is considerably higher than it needs to be.

Consider the excess range curve shown in Fig 4 (calculated using the CryoSat altitude and beamwidth). When observing a flat surface, the altimeter's observed range at all along-track separations from nadir is larger than the minimum range to the surface. Any ambiguities that should arise from areas away from nadir will appear at the longer range, not at the minimum range. Such ambiguities can be removed from the response by a two-dimensional range-Doppler pass-band filter. For example, backscatter from a surface area 6 km away from nadir will give rise to a response that is 30 m further in range. If this same response should appear as an alias rather than as an intended signal, and if the radar's range gate were chosen such that it tracked the surface through a 40-m window that extended only 20 m above and below the surface, then the potential azimuth ambiguity (alias) would be rejected by the range gate. Then an altimeter observing a nominally flat surface can operate alias-free for PRFs far less than the classical Nyquist rate.

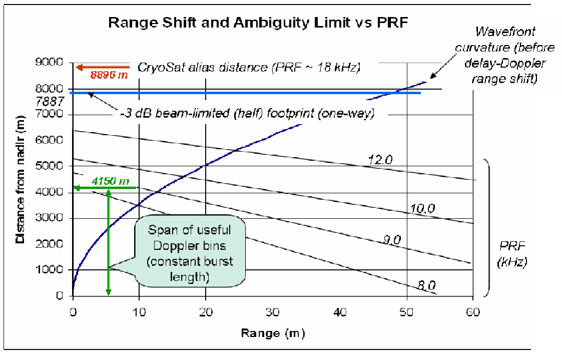

Figure 4. PRF and ambiguity avoidance

In practice the problem is complicated by the fact that interesting surfaces are not perfectly flat. However, the same principle holds: a PRF lower than the classical Nyquist rate would be acceptable as long as its choice took into account the expected range of topographic relief of the observed surface.

The situation is improved when the span of useful Doppler bins are taken into account. For example, if the constant burst length strategy is adopted, then the useful bins extend only to about 4 km either side of nadir. Thus, for a PRF of 10 kHz, the topographic relief would have to be 30 m or more before aliasing would become an issue.

The trade space is suggested in Fig 4. Delay-Doppler processing range-shifts all backscatter as a function of their observed Doppler frequency. If the data are under-sampled by a PRF lower than the Nyquist rate, then all returns from nadir offsets that are larger than the ambiguity distance will appear as aliases. Of course, the processor does not know this, so it introduces range shifts appropriate to the unambiguous frequency span. The aliased returns are also shifted, but not to zero. The resulting range residuals are bounded below by linear limits that are a function of PRF. Range-Doppler responses within each linearly-delimited domain should be free of aliases.

9. OBSERVATIONS AND CONCLUSIONS

The altimeter's measurement precision improves in direct proportion to the number of statistically independent looks (uncorrelated contributing waveforms) accumulated in each output waveform.

The closed burst method of organizing transmit and receive sequences prevents the altimeter from achieving its potential number of looks by a factor of three.

Looks may be maximized (Fig 5) only if the design is based on an open burst strategy, or a continuous PRF strategy. Either approach constrains the design to PRFs less than the classical Nyquist rate. The open burst method should lead to a somewhat simpler radar implementation.

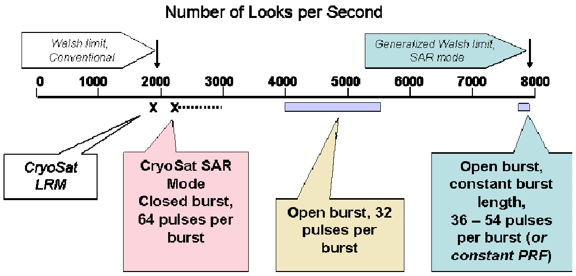

Figure 5. Looks per second

The Walsh minimum burst period is shorter that the round-trip pulse propagation time, so the only way to maximize the number of statistically independent looks is through use of a continuous PRF methodology. However, the difference between the Walsh limit and the best performance offered by the open burst method is so small as to be insignificant in practice.

Although higher PRF (up to the classical Nyquist limit) could be perceived to be better (or even required), the altimeter may operate in SAR mode over rough seas and be free of aliases for PRFs much less than the classical Nyquist rate.

PRFs less than the Nyquist rate enable an open burst strategy, which in turn leads to the number of independent looks closely approaching the maximum theoretically obtainable (the generalized Walsh upper bound) from this instrument.

The constant (open) burst length method usually leads to the number of pulses within each burst not to be a power of 2, hence compromising the implementation of the along-track Fourier transforms. However, this disadvantage is outweighed by the several advantages enjoyed by the constant burst length approach.

Choice of PRF is driven by the desire to keep the PRF as high as feasible, within the constraints of adequately long transmitted pulse, and adequate clear space so that the received data can be captured between transmissions.

The design of future altimeters such as Sentinel that use the delay-Doppler approach should seriously consider the open burst strategy so that the number of looks may be maximized, thus taking full advantage of the potential of this style of radar altimeter.

10. REFERENCES

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