WaPa : Instrument Parameter Dependence

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1. INTRODUCTION

The science requirements related to the instrument are usually stated in terms of such parameters as velocity accuracy, coverage and incidence angle. The way in which these and other parameters are inter-related will be outlined in a qualitative manner and Wavemill specific numerical examples given.

2. APPLICABLE DOCUMENTS

3. INSTRUMENT PARAMETER RELATIONSHIPS

There are a multiplicity of inter-dependencies between SAR instrument performance parameters which in the context of a Wavemill / Ocean Surface Current Mission, influence the selection of a operational baseline. The trade-offs between these parameters are sometimes complex, but as the radar parameters will ultimately dictate the quality of the science product that will be available to the end-user, it is critical to have a clear understanding of these relationships.

The key parameters for the Wavemill / OSCM trade-off are the same parameters that are drivers on the design and optimisation of all SAR missions. As shown in Table 3-1, these parameters can broadly be categorised as either:

- **imaging / image quality parameters** – providing metrics of product quality that the science user will be seeking to maximise
- **instrument physical / operating parameters** – defining the technical baseline that instrument/mission designers will challenged to deliver

Imaging / image quality parameters	**Instrument physical / operating parameters**
Swath width	Transmit frequency
Incidence angle (coverage, access)	Transmitted/received pulse bandwidth
Range ambiguity ratio	Transmit pulse duty cycle
Azimuth ambiguity ratio	Pulse repetition frequency
Sensitivity	Antenna length and height
Radiometric resolution	Elevation and azimuth beam pattern
Polarimetry	Transmitted / received polarisation
Revisit	Power (mean, peak)
Around-orbit operating duty cycle	Number of independent looks (range, azimuth)
Spatial resolution (range)	Data rate
Spatial resolution (azimuth)	Data compression (quantisation)
	Orbit
	Instrument/spacecraft thermal control
	Antenna configuration (mass, complexity)

Table 3-1 Imaging and instrument parameters

There are many other parameters which could be included and it could be debated whether some of these should be identified as either imaging parameters, instrument parameters or both. However, it is most important that the influence of any mission system or instrument-level implementation constraints are qualitatively and quantitatively understood so that the science case for Wavemill / OSCM can be made on an informed basis of potential design impacts.

The qualitative relationships between the respective parameters in Table 3-1 are illustrated in Figure 3-1 through Figure 3-11.
Sections 3.1 though 3.10 which follow elaborate on both the theoretical and quantative links between these parameters, giving specific examples of values of the potential imaging performance and respective instrument design options for Wavemill/OSCM.

Figure 3-1 : PRF Dependencies

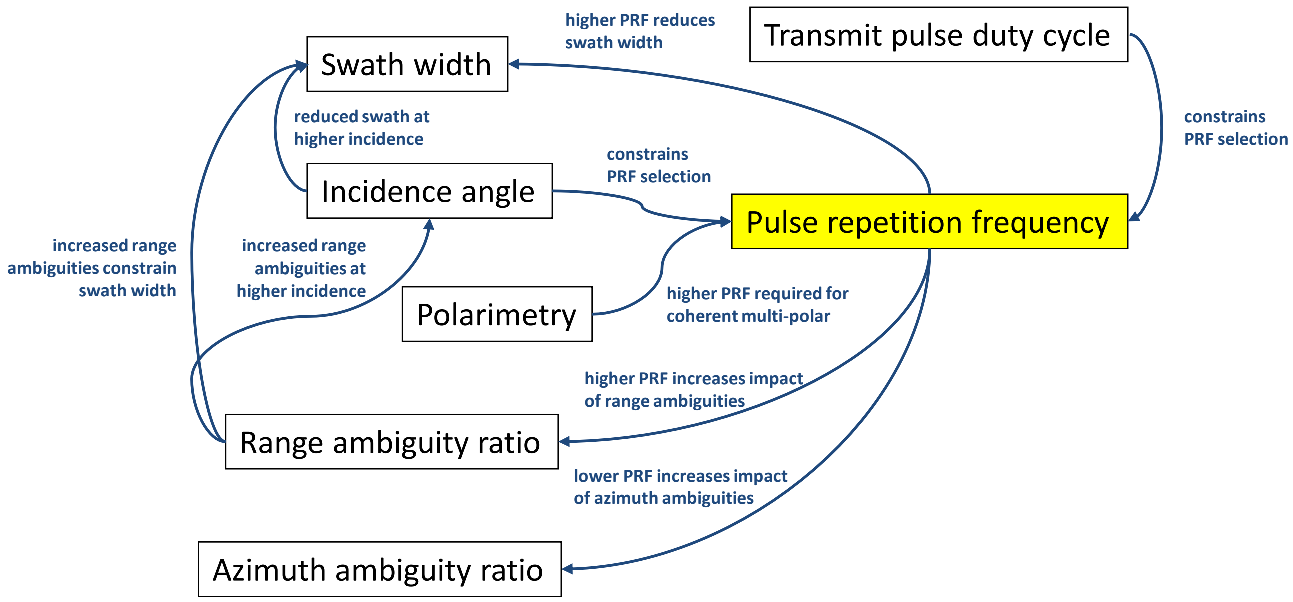


Figure 3-2 : Spatial Resolution (Range) Dependencies

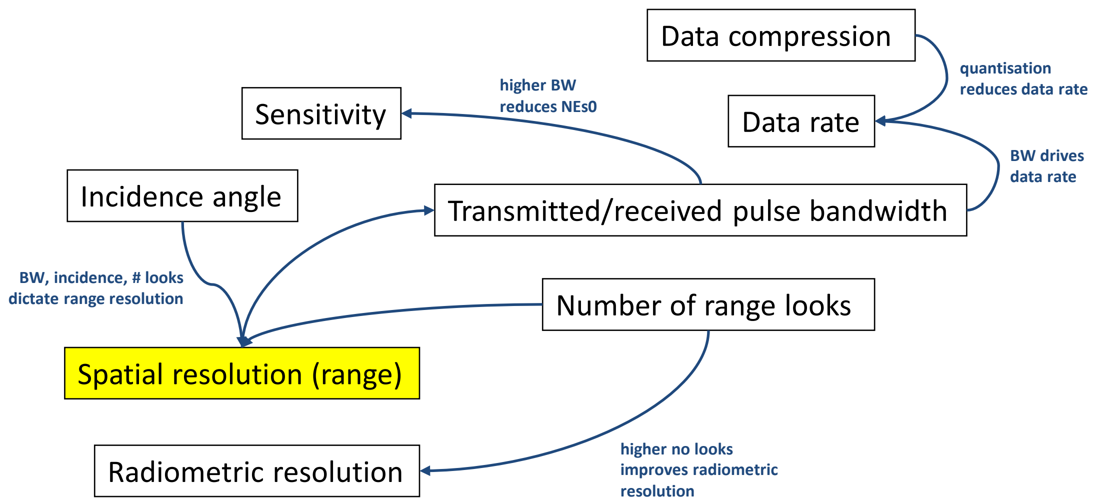


Figure 3-3 : Spatial Resolution (Azimuth) Dependencies

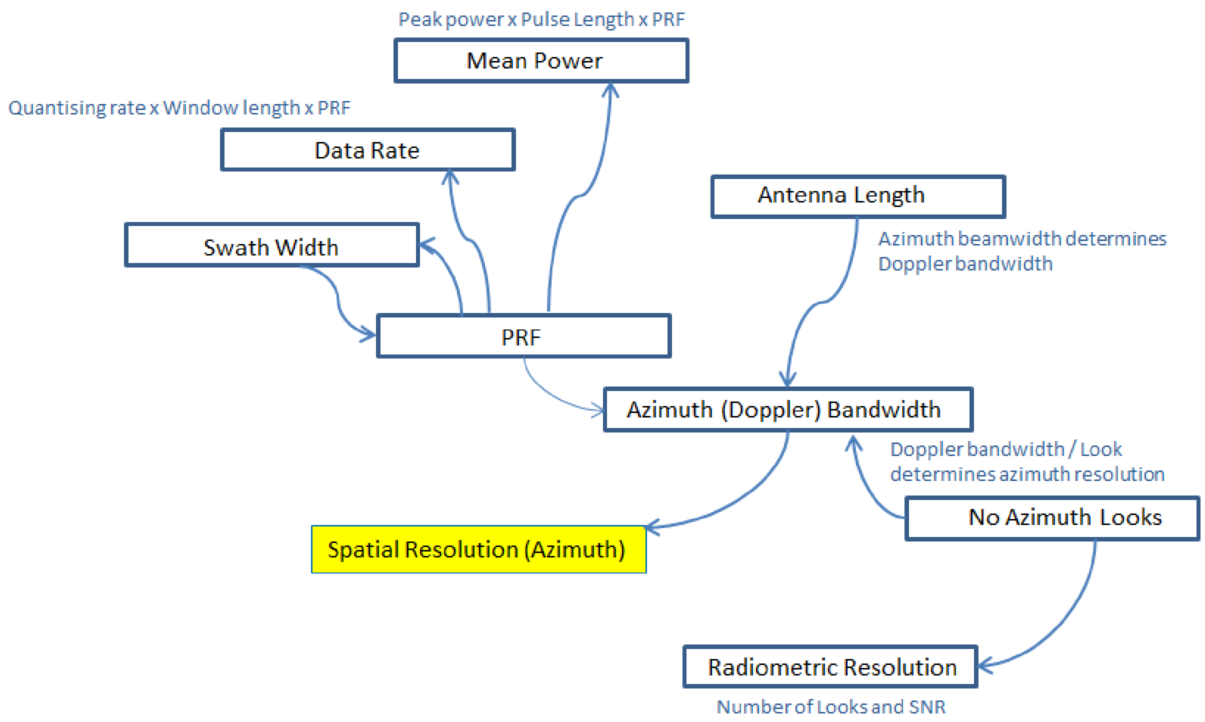


Figure 3-4 : Swath Width Dependencies

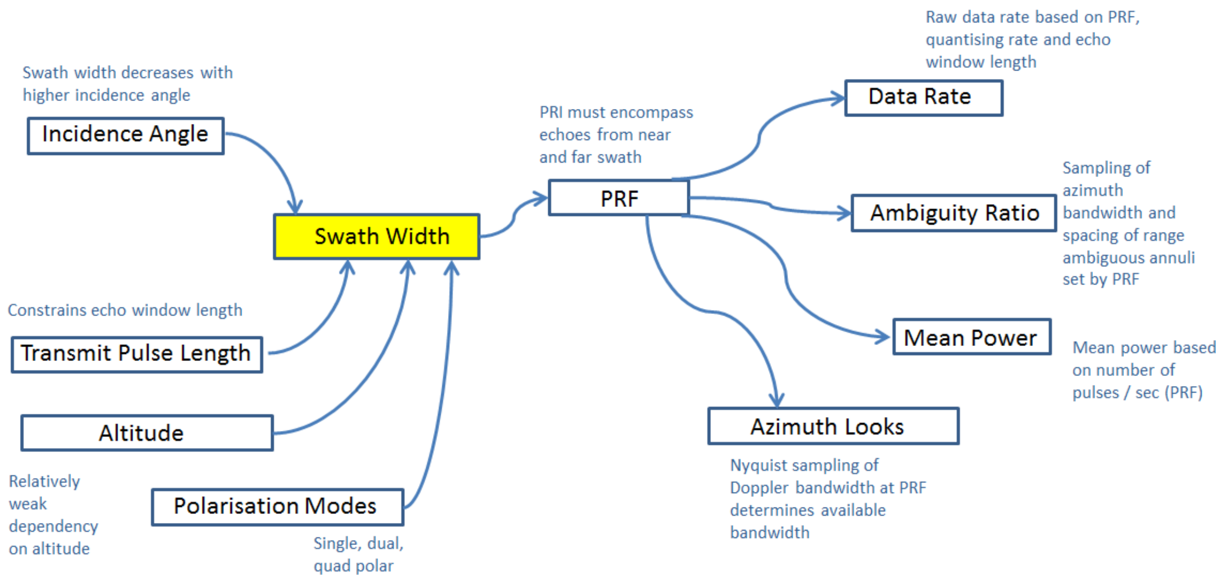


Figure 3-5 : Sensitivity Dependencies

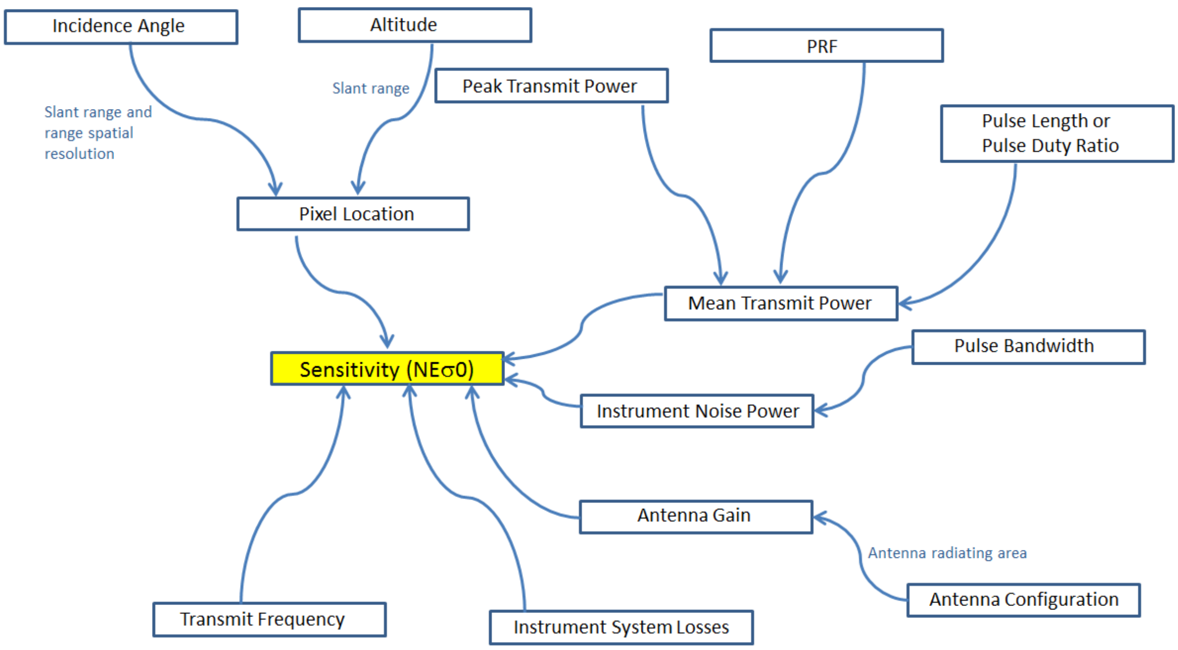
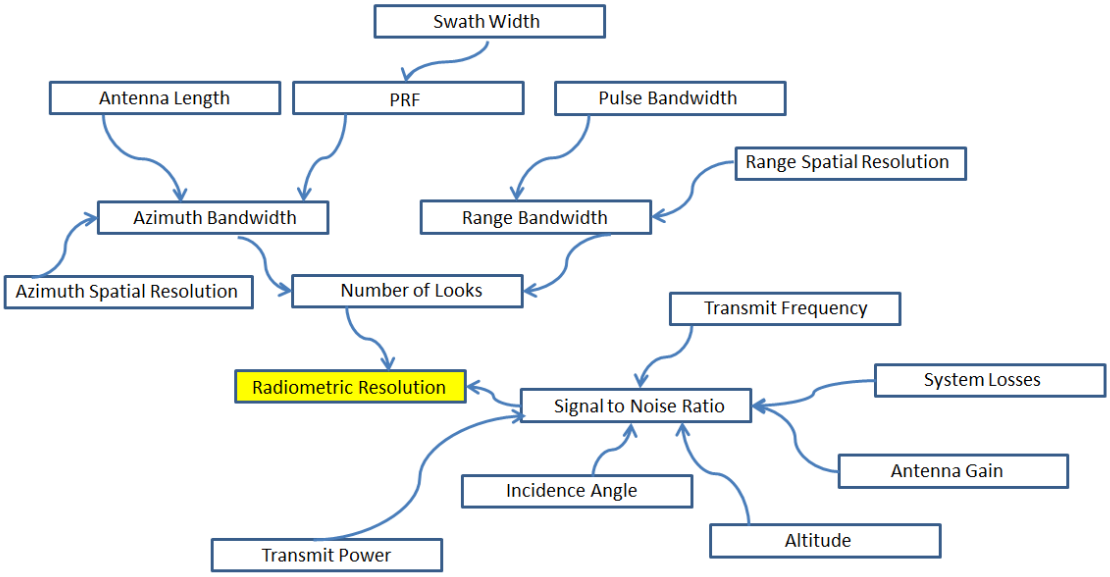


Figure 3-6 : Radiometric Resolution Dependencies



$$\text{Radiometric Resolution } (\gamma) = 10log_{10}\left(1 + \frac{1+\frac{1}{SNR}}{\sqrt{L}}\right)$$

SNR = Single pulse signal to noise ratio
L = Number of looks

Figure 3-7 : Polarimetry Dependencies

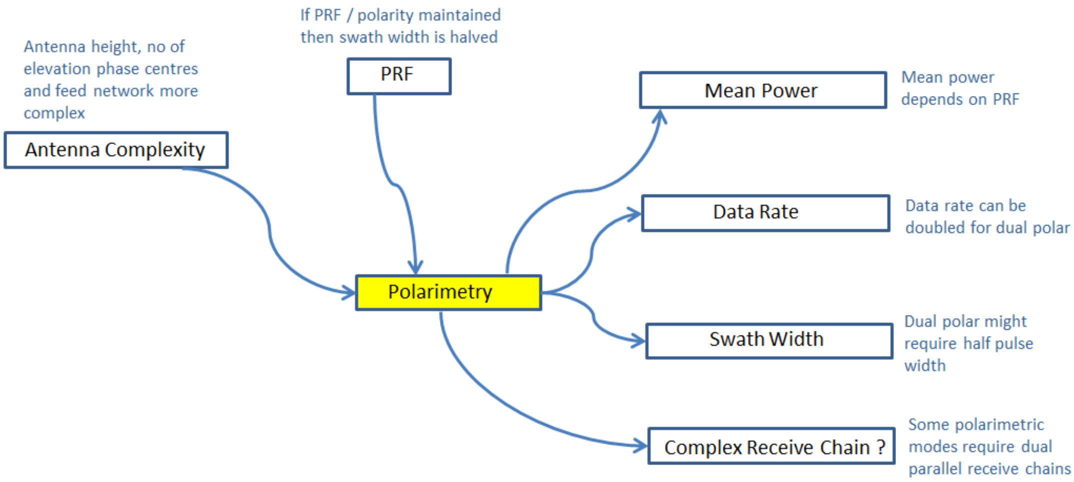


Figure 3-8 : Range Ambiguity Ratio Dependencies

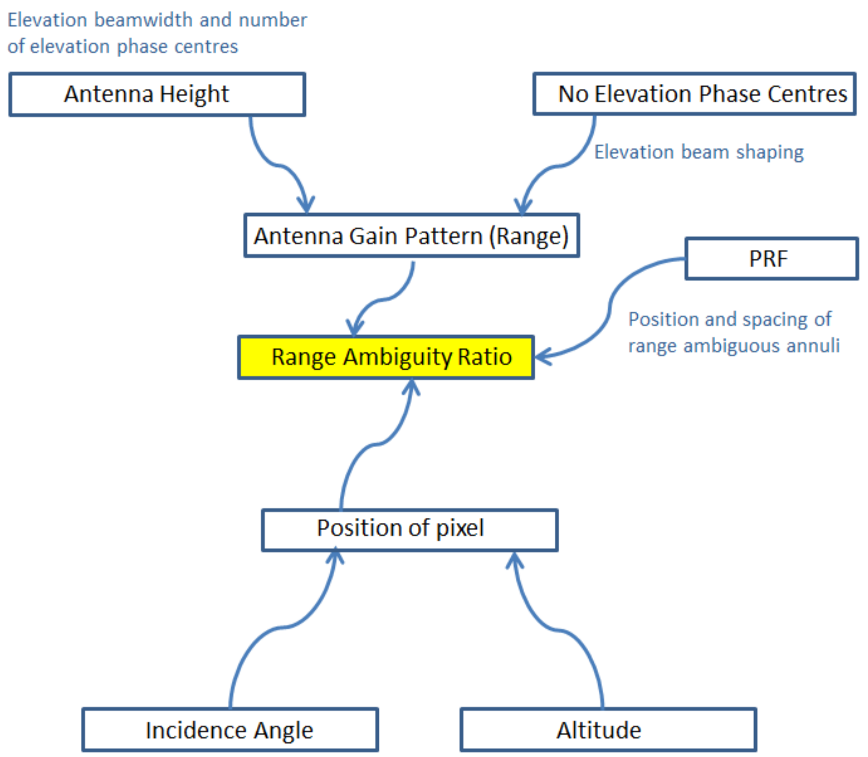


Figure 3-9 : Azimuth Ambiguity Ratio Dependencies

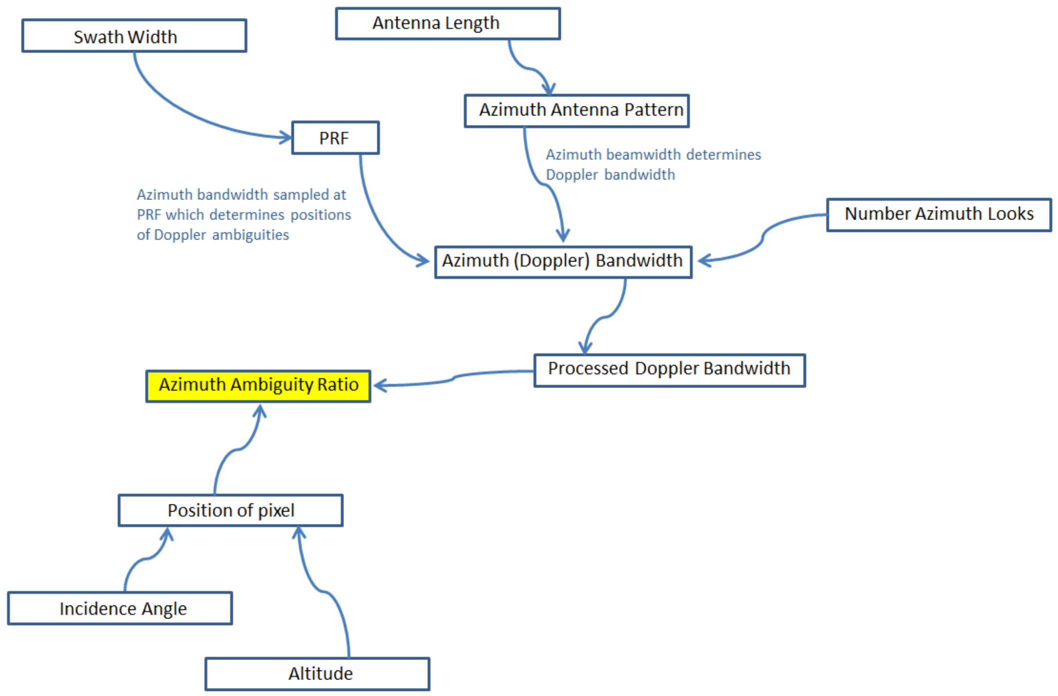


Figure 3-10 : Revisit Dependencies

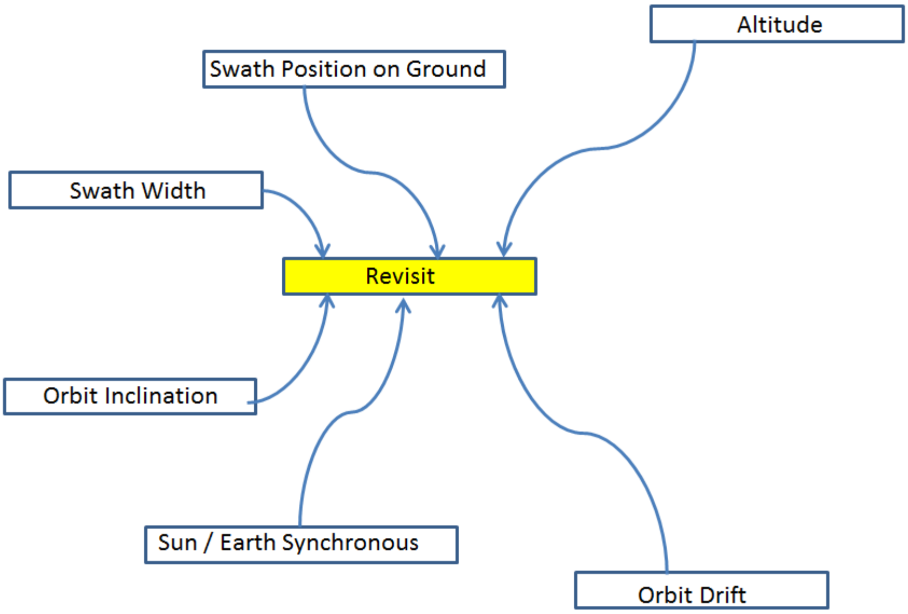
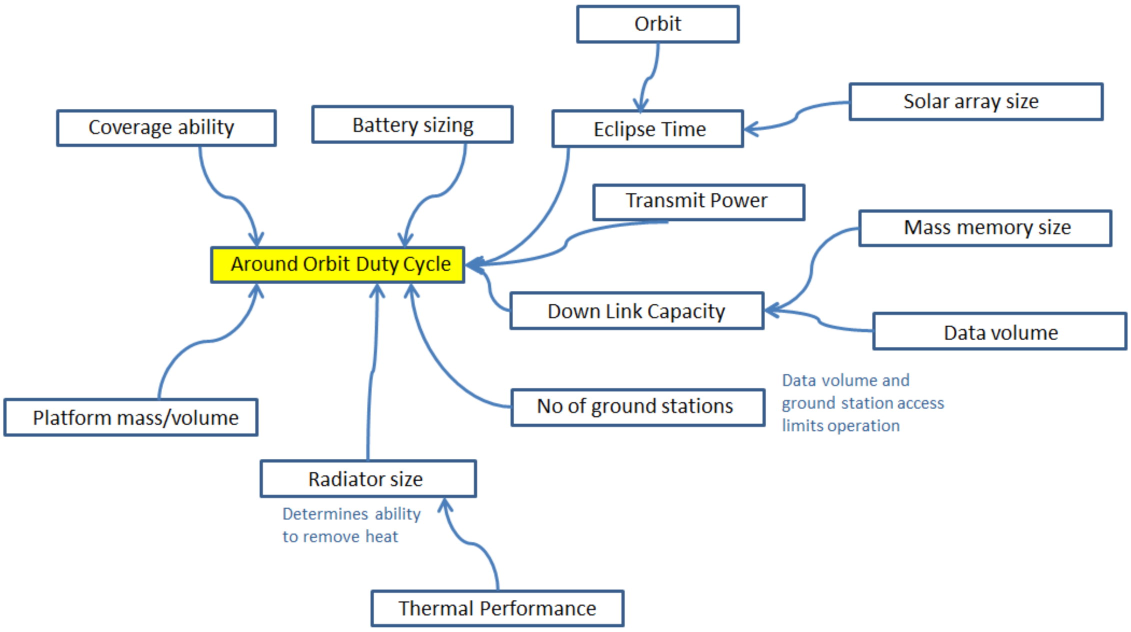


Figure 3-11 : Around Orbit Operating Duty Cycle



3.1 Swath Width and PRF :

The basic requirement for swath width for Wavemill has historically been for 2 x 100 km in which a 100 km swath is positioned either side of the sub-satellite track. Another possibility is for a continuous 200 km swath on one side only. This way a potentially interesting feature such as an eddy is less likely to have the central portion positioned in the gap between the two swaths. Generally speaking, the positioning of swaths is accomplished by using the 'diamond plot' in which the available positions are plotted as a function of PRF and distance from nadir. The 'diamonds' are the accessible regions which are defined by making an allowance for the transmit pulse periods, precautionary guard bands and also the nadir returns.as shown in Figure 3-12.

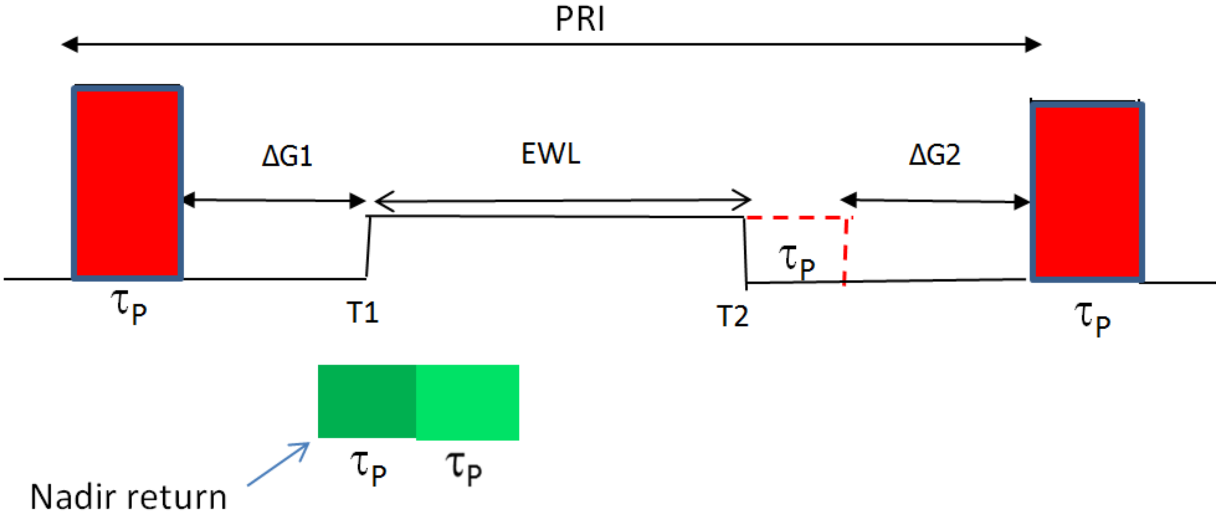


Figure 3-12 : Swath Timing Diagram

Where t_p is the pulse length
EWL is the Echo Window Length
ΔG1 and ΔG2 are the Guard times
PRI is the Pulse repetition interval
EWL = 2/c *(Rf-Rn) where Rf and Rn are the near and far slant ranges

$PRI_{min} \geq EWL + 2Tp + \Delta G1 + \Delta G2$

$PRF_{Max} = 1/PRI_{min}$

In addition to avoiding the transmit periods and guard bands we have to allow for a period at the end of the echo window length for the complete pulse to be received from the far swath position. There is also the strong nadir return which has to be accommodated. This will shorten the available swath width unless we design an antenna which strongly suppresses the nadir return by placing a null in that direction. Good design should always ensure this. A typical 'diamond plot' is shown in Figure 3-13.

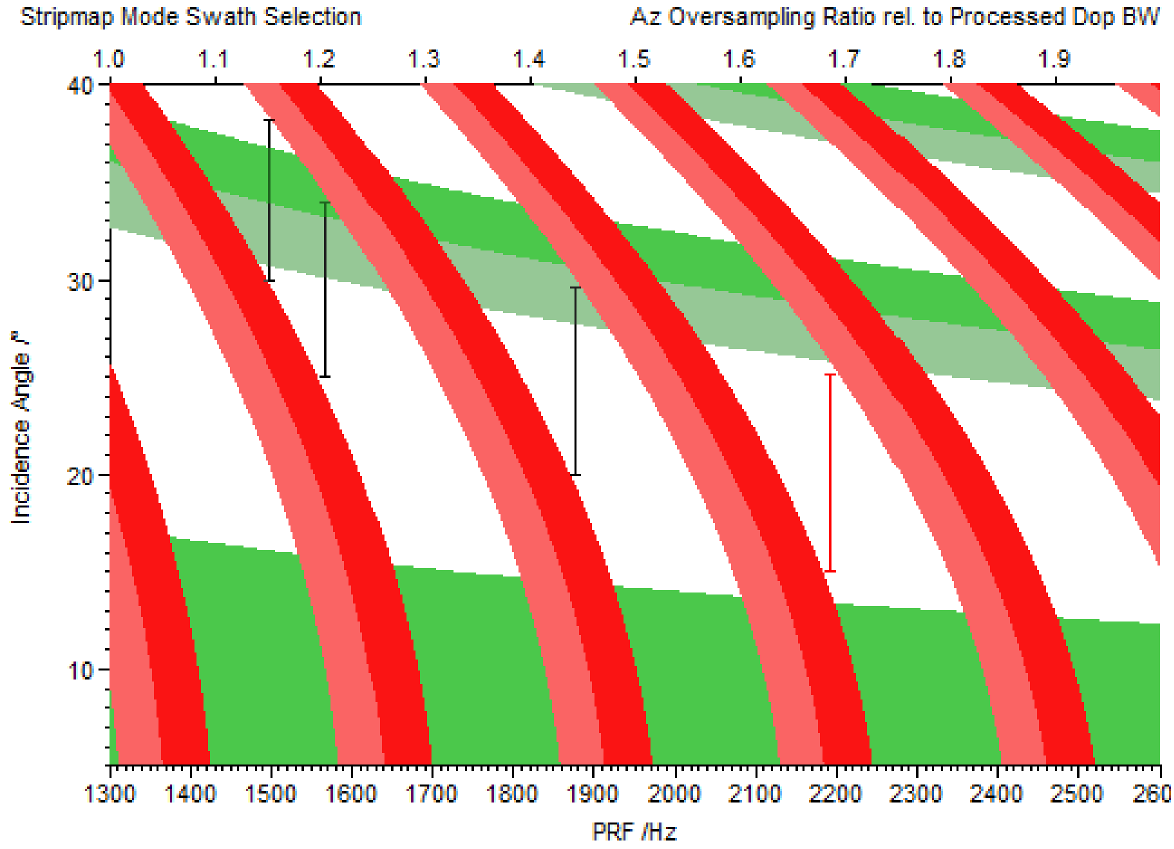


Figure 3-13 : Swath Design 'Diamond Plot'

Four swaths have been created each of length 100 km. Ideally; one should position the swaths in the clear areas. However as the PRF and / or the incidence angle increases, the diamonds get smaller and the possible swaths are shorter. If we allow a swath to overlap a nadir return (the green zones) by suppressing it with an antenna null, then longer swaths can be achieved. Figure 3-13 assumed that the beam is broadside to the antenna face as in a conventional SAR or the Chevron option for Wavemill. In the Javelin configuration, the beam footprint is oriented broadside to the sub-satellite track and so in principle we could have a higher PRF because the time interval between the near edge return and the far edge is a little less than for the case above as can be seen from Figure 3-14.

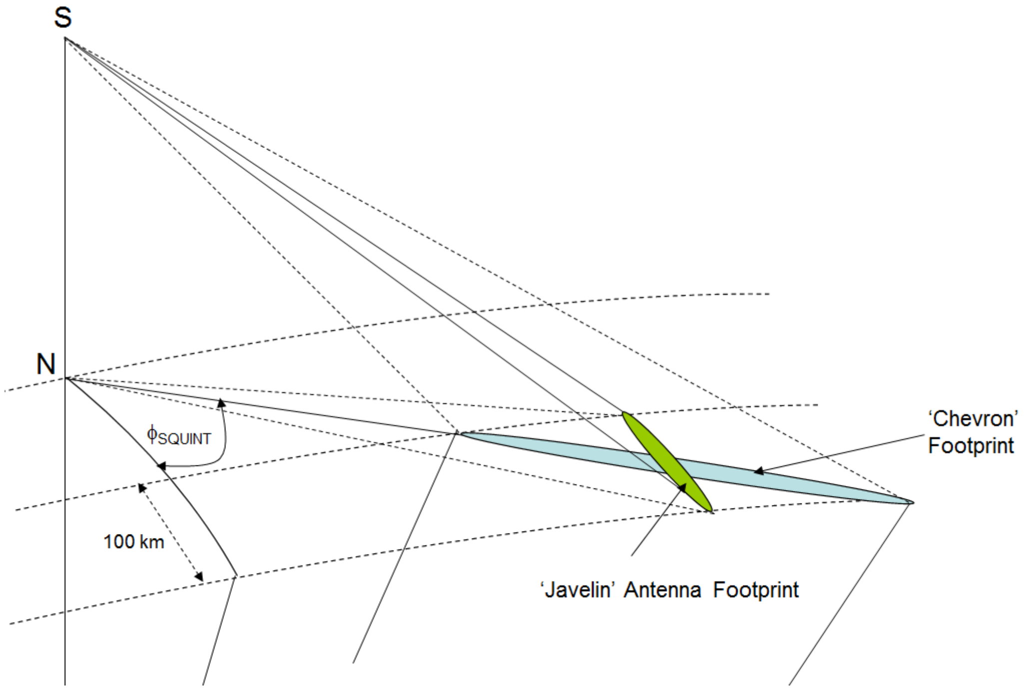


Figure 3-14 : Contrast between 'Javelin' and 'Chevron' beam positions.

The permissible swath lengths as a function of PRF for Javelin ***assuming that we can suppress the nadir return*** are shown in Figure 3-15. An altitude of 546 km, on-ground azimuth squint angle = 45 degrees and a mid swath incidence angle of 30 degrees is assumed.

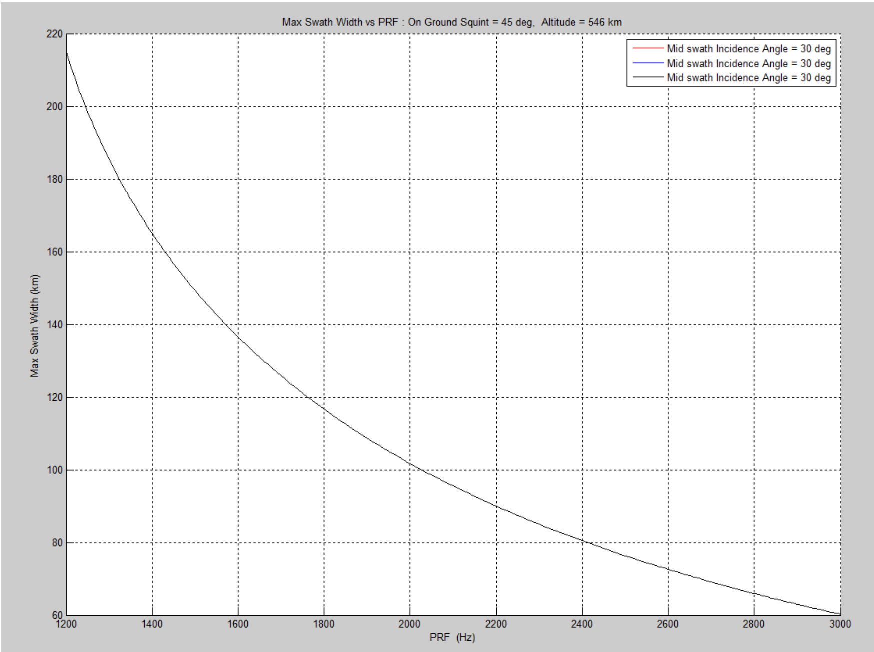


Figure 3-15 : Swath width v PRF for the Javelin configuration

The maximum PRF that would allow a swath width of 100 km is 2025 Hz.

If we have selected a swath width and PRF, then other design consequences manifest themselves.

3.2 Antenna length and PRF :

The length of the antenna in the along-track (azimuth) direction determines the available Doppler bandwidth from the width of the beam. A longer antenna has a narrower beam and lower Doppler bandwidth. In good design the PRF is high enough to sample this bandwidth without aliasing. We usually aim for the PRF to be at least 1.2 x the Doppler spread of the 3dB azimuth beam. A long antenna therefore implies a narrow beam, low Doppler bandwidth, low PRF and a wide swath. It also means a smaller number of available azimuth looks. The maximum length of the antenna is limited by the accommodation of the spacecraft. For a Vega this might be 4m unfolded. Using the 2025 Hz from Figure 4, we can derive an antenna length of 8.5 m which is far too long. Assuming a length of 4 m will result in a wider beam and higher Doppler bandwidth. If a higher PRF is set to sample this, then a swath width of 100 km will not be possible. Alternatively if we choose a lower PRF to accommodate the required swath width, then the available Doppler is under sampled leading to more azimuth ambiguities or we just sample the central portion of the beam which restricts the available number of azimuth looks and also the received echo power.

3.3 Ambiguities and PRF :

The positions of ambiguities are determined by the intersections of range ambiguous annuli and the iso Doppler hyperbolae as shown in Figure 3-16. The position of the range ambiguities is determined from concentric annuli centred on the spacecraft and having a spacing in time equal to the Pulse Repetition Interval (PRI = 1 /PRF). Increasing the PRF results in a higher number of more closely spaced annuli and therefore a worse range ambiguity performance. Range ambiguity performance can be improved by optimising the beam shape in range to position nulls at the range ambiguous positions. This ability is improved by having a larger number of phase centres on the antenna in range (elevation) which implies a higher antenna with commensurately higher mass. Azimuth ambiguities lie on the iso-Dop bands which are hyperbolae. The Doppler spectrum is sampled at the PRF. A low PRF results in an under sampled spectrum and a poor azimuth ambiguity performance. A detailed evaluation of the ambiguity performance requires that the 2D polar plot of the antenna is combined with the intersections of the range ambiguous annuli and the azimuth ambiguous hyperbolae. Echo energy from zones which are range ambiguous and also Doppler ambiguous including energy which is Doppler shifted out of the receiver pass band but aliased back in at the PRF is then the total ambiguous energy. In practice, the range and azimuth ambiguity ratios can be estimated to high accuracy by just examining the response along the principal planes of the antenna rather than the full polar response. Furthermore, most of the ambiguous energy will be too far out and suppressed by the low antenna gain away from the wanted target position. A trade-off is therefore required between high PRF (poor range ambiguity but good azimuth ambiguity performance) and lower PRFs when the situation is reversed. It could be argued that Wavemill could tolerate modest ambiguity performance in open ocean but in coastal regions this could be a major design issue.

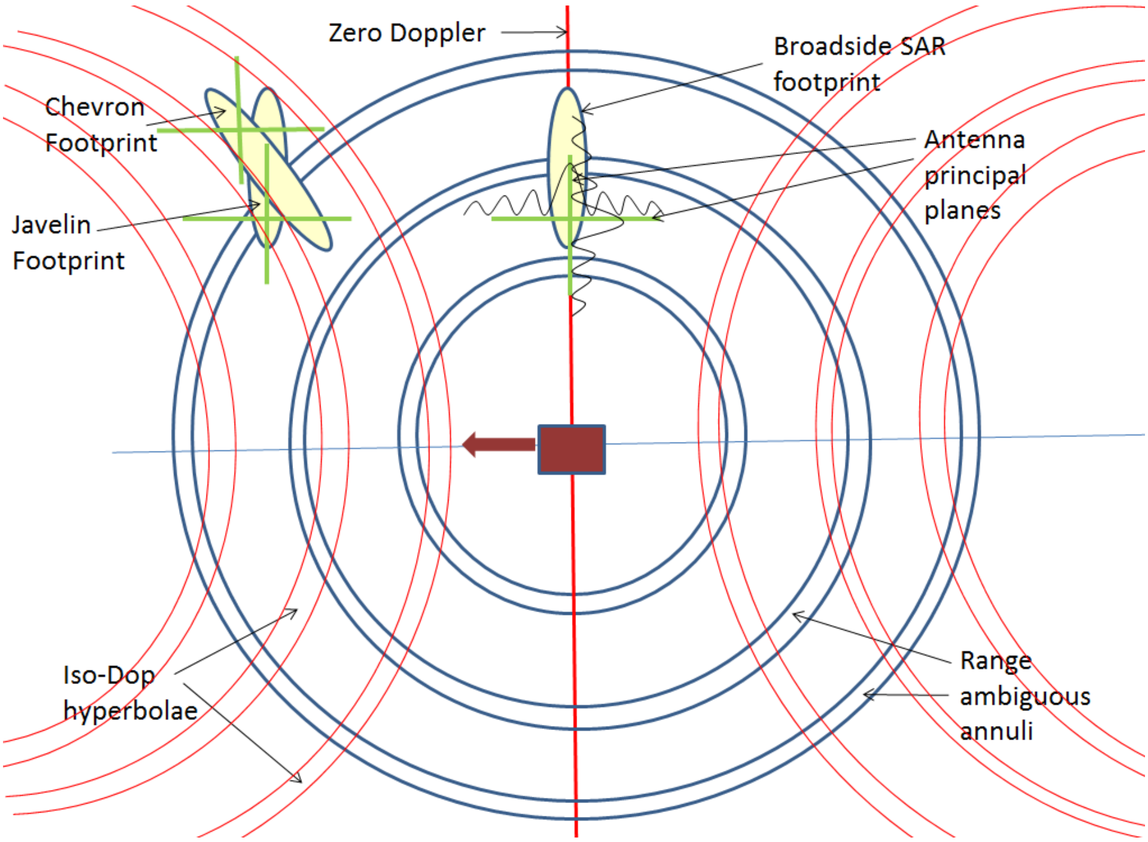


Figure 3-16 : Positions of the ambiguous zones.

3.4 Data Rate and PRF :

Increasing the PRF increases the input data rate. If the echo window length (Figure 3-12) is EWL, NB the number of bits in the quantiser, SR the sample rate of the quantiser, then the input data rate DR is given by

$$D_R = EWL\ x\ S_R\ x\ N_B\ x\ PRF$$

3.5 Mean Power and PRF :

If the peak transmit power is P_t and the uncompressed pulse length is t_P, then the mean transmit power is given by

$$P_{mean} = P_t\ x\ \tau_P\ x\ PRF$$

3.6 Radiometric Performance and PRF :

The sensitivity of a SAR instrument (NEσ0) improves with the number of pulses coherently integrated. A higher PRF also enables a wider Doppler spectrum to be unambiguously sampled thus permitting more azimuth looks. However as seen above, a higher PRF also implies a degraded azimuth ambiguity ratio and a narrower swath.

3.7 Swath Width, Elevation Beam Width and Gain :

A swath will be illuminated by a beam which ideally would just fit the angular spread of the beam. For example, if H = 546 km, mid swath incidence angle = 30 degrees, on ground squint = 45 degrees, swath width = 100 km, then the swath subtends an angle of 9.2 degrees. Wide swaths subtend a large angle which require a shorter antenna in elevation. Such an antenna would have a lower gain and less elements in elevation thus limiting the flexibility for beam shaping. Alternatively a narrow swath requires a narrow beam for efficient illumination and therefore a wider antenna having greater mass. This situation could be exacerbated with dual polarisation which might require interleaved waveguides effectively doubling the antenna mass.

3.8 Very Wide Swaths :

It has been suggested by the science community that one very wide swath on one would be preferable to narrower swaths on each side which would avoid a gap in the measurement region of interest. As seen above, to illuminate a very wide swath would require a narrow antenna having a lower gain which could only be compensated by increasing the length which might not be possible. A common alternative technique in SAR systems is ScanSAR in which the wide angle is divided into two or more sub-swaths. Narrower beams of higher gain are then directed at these sub-swaths in sequence and the available dwell time is therefore divided accordingingly. Because the dwell time and number of echoes received per sub-swath is reduced, the maximum spatial resolution possible is degraded. The rapid switching of the beams in elevation requires an electronic beam steering capability and therefore a more complicated antenna design which in the past usually implies an active phased array. This might not be possible at Ku band because of the lower power of the available sources whilst a ScanSAR design based on a waveguide antenna would be very complex with a significant mass penalty.

Switching beams between two or more sub-swaths increases the coverage but at the expense of spatial resolution. If we multi-look in azimuth, the number of pulses coherently integrated over an azimuth sub-aperture is less than over the whole synthetic aperture. The sensitivity and SNR is also unchanged because, even though the number of pulses coherently integrated from each swath is reduced, the reduced number of pulses in an azimuth look results in a shorter synthetic aperture length per look which would have a wider beam and therefore increased echo area in azimuth, the echo area increases by the same ratio as the aperture length is reduced. By a similar logic, we get the same result if we multi-look in range. Dividing the bandwidth by ‘N’ reduces the system noise by ‘N’. However if the power is unform over the passband, the power in the reduced bandwidth is reduced by the same ratio so the signal to noise ratio is unchanged. We therefore maintain sensitivity if we multilook but suffer degraded spatial resolution.

A further consideration of very wide swaths is the variation of performance with range. Figure 3-17 shows two swaths on the same side covering a total range of 200 km assuming the Chevron concept.. The overlap region of 11.2 km width is close to 30 degree incidence angle. The near edge of the coverage range is at an incidence angle of 19.3 degrees where the the data might contain an unacceptably high vertical velocity component. The far edge is at an incidence angle of 37.4 degrees where detection of the very weak echo will be very difficult.

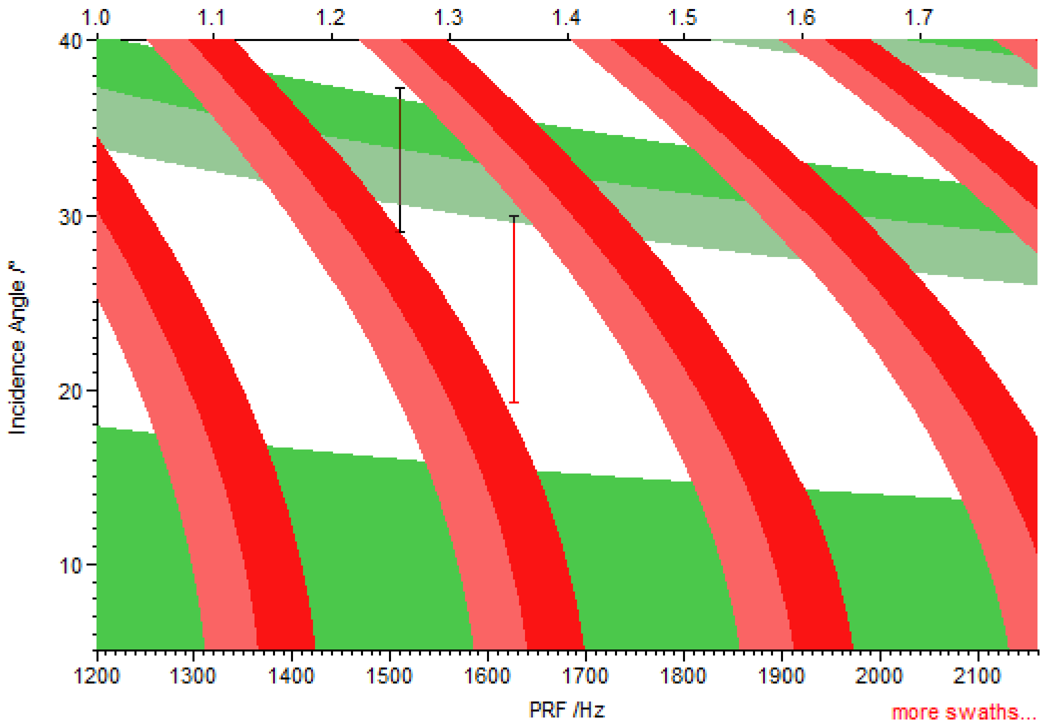


Figure 3-17 : Single sided 200 km coverage centred on 30 degrees (Chevron)

3.9 Incidence angle :

The range spatial resolution of a SAR is dependent on the pulse bandwidth B_P and the incidence angle and is given by : -

$$\rho_R = \frac{c}{2B_P \sin(inc)}$$

This means that at higher incidence angle, we could in principle have more range looks available for a given pulse bandwidth and spatial resolution. Of course at high incidence angle the range is much greater and the received echo weaker which reduces the benefit of the extra looks.

3.10 Dual Polarisation :

The science case for dual polar operation is extremely strong and if possible, two orthogonal polarisations should be provided. However there are major implications for both the instrument design complexity and system operation. If we wish to maintain the PRF associated with a single polar mode such as VV, one option is to insert the orthogonal polarisation (H) between the V pulses. This way the original PRF for each polarisation is maintained. However, we are now transmitting twice as many pulses as previously so the mean transmit power and input data rate are doubled. The time interval between transmit pulses is halved and so the swath width is also halved by the logic described in 3.1 If we wish to maintain the original mean power and data rate then the each pulse is transmitted at the original PRF regardless of polarity. The number of pulses per polarisation is then halved with commensurate loss of radiometric performance. Another possibility is compact polarimetry in which the transmit signal is circularly polarised and H & V are received simultaneously, but in this case the transmit power in either H or V is shared between the two polarisations and so is half that of single polar operation. In these and other options it is usual to have parallel receive chains for each polarisation thus doubling the data rate.

Dual polar also implies a more complex antenna. It is difficult to have radiating slots which are dual polar and so it's probable that two sets of interleaved waveguides would be required to provide good quality dual polar signals with an associated more complex feed network effectively doubling the antenna mass. Another consideration is the integrity of the orthogonality with highly squinted beams. Maintaining orthogonality is much easier for broadside beams than for the highly squinted beams required by Wavemill, particularly in the Javelin configuration.

A compromise mode employed by Envisat ASAR is Alt-Pol mode. In this mode alternate bursts of H and then V were transmitted. The bursts of short duration were directed at the same region and so the target terrain was illuminated by both H and V as the beam progessed. In this way a pseudo–dual polarity is implemented without the necessity of doubling the receive channels to simultaneously receive H & V.

In summary, dual polar operation is possible but because of the demands and conflicting effects on power, data rate, swath width and instrument complexity, such a mode would only be an option available for relatively short periods of operation. The salient features of typical dual polar modes are summarised in

Table 3-2.

Polarisation Option	Pro	Con
Transmit VV and HH simultaneously, each at original PRF	• PRF / polarisation preserved • Dwell time and number of pulses preserved	• Power from platform doubled • Swath width halved • Data rate doubled with dual transmit and receive chains • Rapid switching of polarisation difficult • Double antennas might be required to form orthogonal signals with complex feed network • Potential increase in the number of HPAs
Burst of VV-polar then burst of HH-polar at original PRF in ScanSAR mode like ASAR AltPol	• Same power from platform • Swath width retained • Data rate unchanged • Scalloping	• Dwell time halved so might need pulse power increase to compensate • Might need dual receive chain • Beam forming and switching in elevation necessary
Dual polar imaging on one side only	• Retains dwell time and swath width	• In orbit calibration potentially more challenging
Orthogonal pulses alternately at original PRF	• Same region imaged in both polarisations	• PRF / polarisation halved so less looks, phase noise and azimuth ambiguities increase
Compact Polarimetry : Transmit circularly polarised pulses	• Swath width, mean transmit power and PRF unchanged	• 3dB less in each polarisation • Two receive channels probably needed • Data rate doubled

Table 3-2 : Typical polarisation operational options

4. SUMMARY

The major science requirements will determine the system and instrument design parameters. The relationships between these requirements have been briefly outlined qualitatively so that so that the implications of the requirements can be appreciated and the importance of a particular requirement assessed against the design consequences.

Requirement	System / Instrument Parameter	Additional Consequences
Swath Width	PRF Antenna Dimensions	Coverage / Revisit Data Rate Mean power Azimuth looks Azimuth ambiguity ratio
Coverage / Revisit	Orbit Swath width	
Polarisation	PRF Swath width Mean power Data rate	Coverage Thermal Antenna mass and complexity Orbit duty cycle
Max current velocity	Along track phase centre separation	Spacecraft length Accommodation
Min current velocity	Minimum phase shift	Phase accuracy
Spatial resolution	Pulse bandwidth Azimuth bandwidth	Instrument noise Antenna length No available looks
Sensitivity	Transmit power PRF Pulse bandwidth Antenna dimensions	Visible sea state Received echo power

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