Extended Chirp Pulsed Radar (ECMPR) Scheme for MicroXSAR onboard 100 kg Micro-satellite

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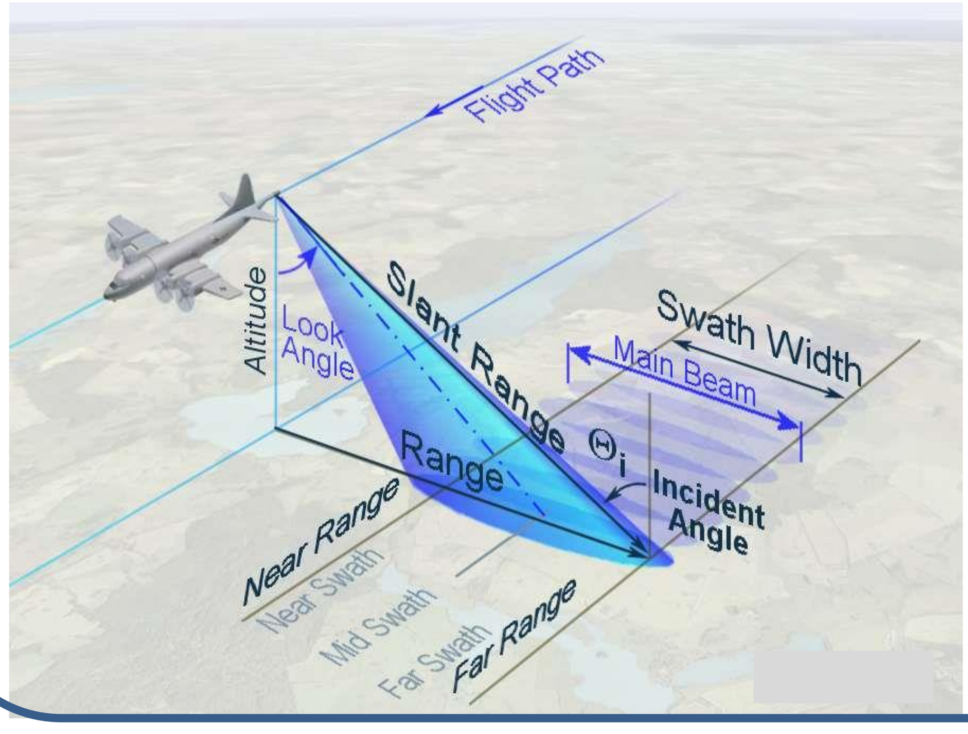
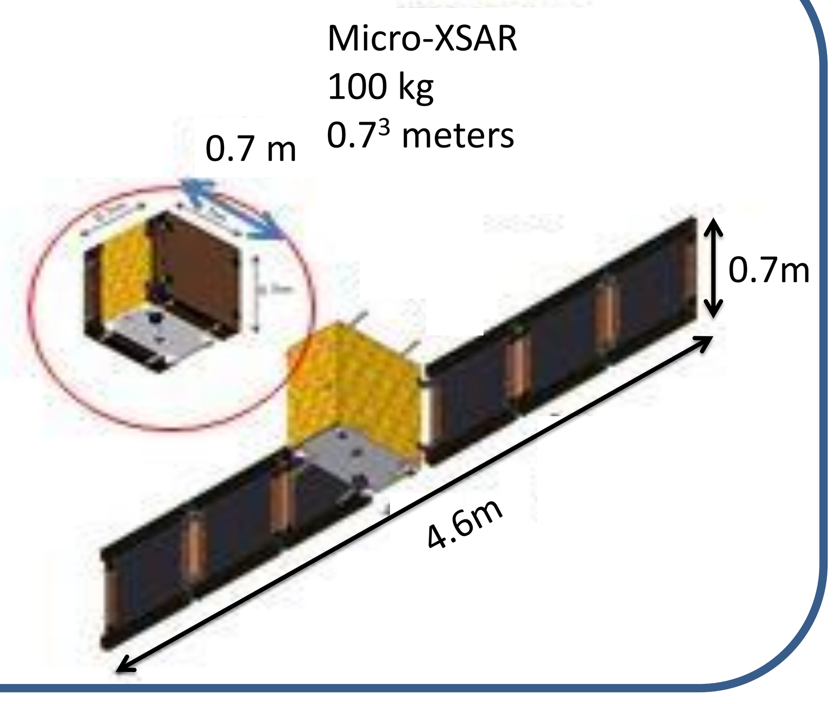
CHALLENGES of Practical Implementation of MicroXSAR System :

- **Antenna Design in Range and Azimuth to reduce the Range Ambiguities and Azimuthal Ambiguities and Ambiguity Calculation**
- **Efficient Pulse Repetition Frequency (PRF) Selection Scheme allowing high duty cycle for better SNR as well as high enough chirp-bandwidth to achieve the desired SAR Image Resolutions.**

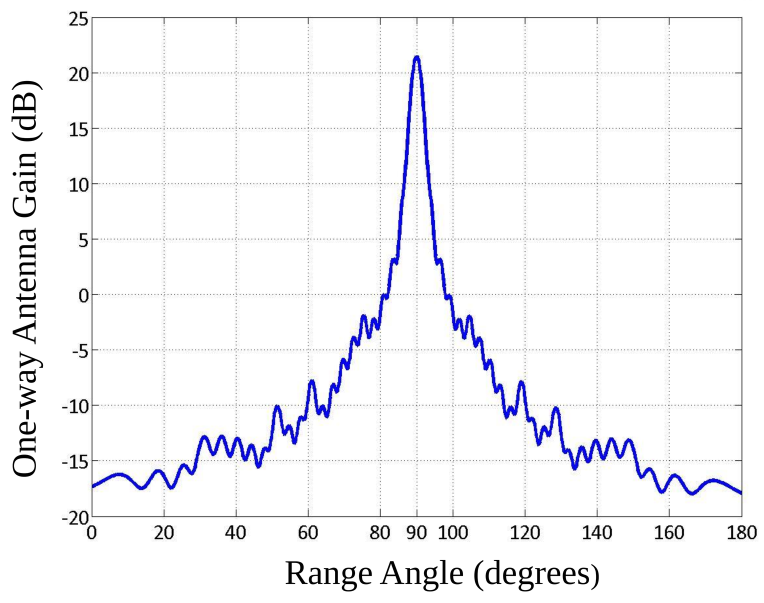
Micro-XSAR System

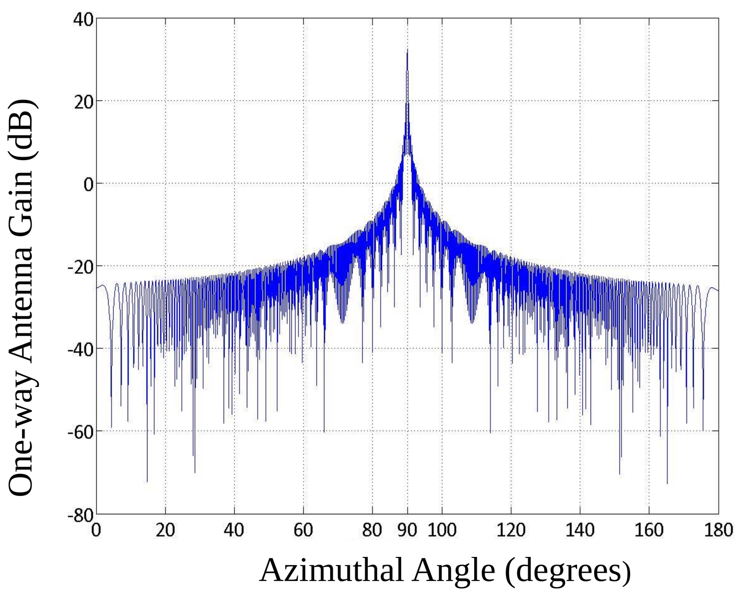


Center frequency	9.65 GHz (X-band)
Chirp Band-width	upto 130 MHz
Antenna Size	4.6 meters (azimuth) X 0.7 meters (range)
Antenna Aperture Efficiency	60%
Satellite Altitude	618 km
Data rate	upto 370 Mbps
Peak RF power	600 kW
SAR Image Resolution	upto 3 meters
Nadir Offset Angle	20 degrees to 50 degrees
Swath-width (Strip-map Mode)	> 28 km

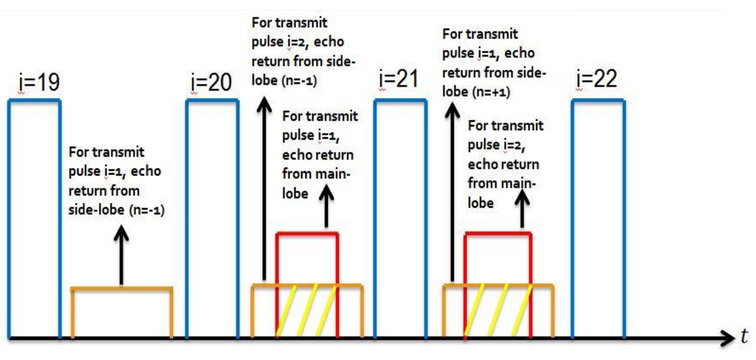


Antenna Design by Genetic Algorithm

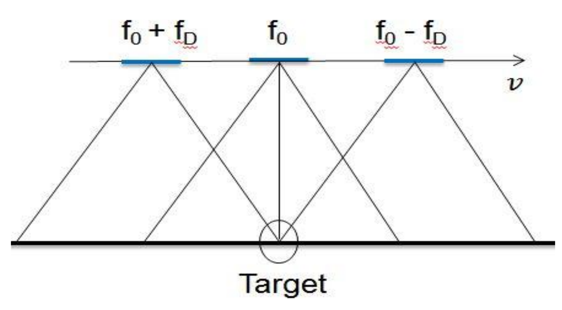




SAR Ambiguity Calculation



Range Ambiguity



Azimuthal Ambiguity

Range Ambiguity arises primarily from the undesired preceding and succeeding pulse echoes from the side-lobes arriving at the antenna simultaneously with the desired echo from the main-lobe. It is measured as the Range Ambiguity to Signal Ratio (RASR). In the fig, n= -1 implies echo return from the preceding pulse and n= +1 denotes echo return from the succeeding pulse.

$RASR = \sum_{i=1}^{N} Sa_i / \sum_{i=1}^{N} S_i$ where

$S_i = \sigma_{i0}^0 G_{i0}^2 / R_{i0}^3 \sin(\eta_{i0})$ for $j=0$

$S_{ai} = \sum_{j=-nh}^{nh} \sigma_{ij}^0 G_{ij}^2 / R_{ij}^3 \sin(\eta_{ij})$ for $j \neq 0$

$S_i = \sigma_{i0}^0 G_{i0}^2 / R_{i0}^3 \sin(\eta_{i0})$ for $j=0$

$S_{ai} = \sum_{j=-nh}^{nh} \sigma_{ij}^0 G_{ij}^2 / R_{ij}^3 \sin(\eta_{ij})$ for $j \neq 0$

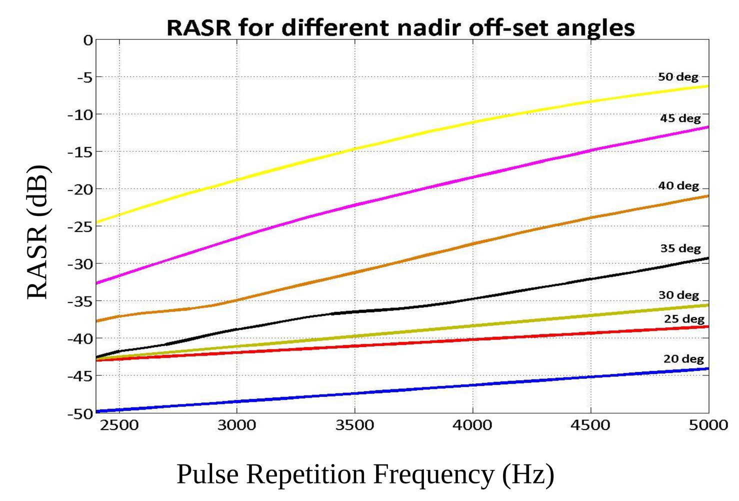
j is the pulse number
i is the time interval index of the data record window
η_{ij} is the incidence angle
R_{ij} is the Range distance
n_h is number of pulses to horizon
G_{ij} is the range antenna gain
N is total number of time intervals
σ_{ij}^0 is the normalized backscatter coefficient at given η_{ij}
ΣS_{ai} is the total ambiguous signal power from adjacent pulses while ΣS_i is the total desired signal power.

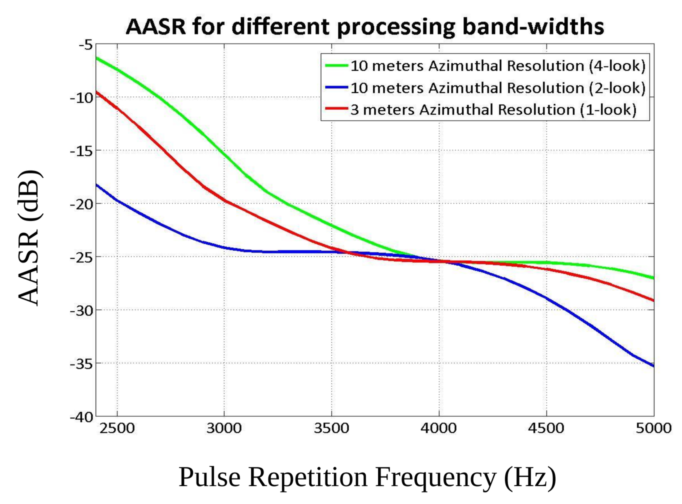
Azimuth ambiguitiy arises from finite sampling of azimuth frequency spectrum at the Pulse Repetition Frequency (PRF). It is measured as the Azimuthal Ambiguity to Signal Ratio (AASR).

In the fig, f_0 is the center frequency of the transmitted pulse and f_D is the Doppler frequency shift of the echo return.

$$AASR = \frac{\sum_{m=-\infty}^{\infty} \int_{-Bp/2}^{Bp/2} G^2(f+mfp)df}{\int_{-Bp/2}^{Bp/2} G^2(f)df} \quad m \neq 0$$

where
f_p is the PRF
(f) is the cross-range pattern at an azimuthal angle corresponding to Doppler frequency f.
We fold the spectrum at ± $f_p/2$ and consider the spectral overlap in the azimuth processing band-width ± $B_p/2$.





Pulse Repetition Frequency (PRF) Selection Constraints

TX Interference Constraint	Nadir Interference Constraint	Signal Processing Constraint
$\frac{k-1+Dp+Dgf}{\frac{2Rn}{c}} < f_P < \frac{k-Dp-Dgr}{\frac{2Rf}{c}}$	$\frac{fp}{k} < \frac{1-Dp}{\frac{2Rf}{c} - \frac{2H}{c}}$ or $\frac{fp}{k} > \frac{1}{\frac{2Rn}{c} - \frac{2H}{c} - \tau N}$	$f_P < \frac{1}{TRx+2\tau p+Tsw}$

R_n is the Near Range, R_f is the Far Range, H is the satellite altitude, D_p is theDuty cycle, $t_{gr(gf)}$ is the Rise(Fall) time, τ_N is theNadir echo duration, τ_P is the Pulse width duration, T_{Rx} is the Receiving window, T_{Sw} is the Switching time, $D_{gr(gf)} = t_{gr(gf)}$/PRT where PRT is the Pulse Repetition Time, c is the Speed of light in vacuum, V is the radar-satellite radial velocity, L is the antenna length in azimuth, and k is any Positive Integer.

SAR Image Resolutions

Ground-range Resolution

Applying the Pulse Compression Technique, the ground-range resolution is given by:

$$\delta_{gr} = \frac{c}{2B\sin\theta i} \text{ where}$$

c is the velocity of light in free space
B is the chirp-signal band-width
θi is the Incidence angle.
Higher the band-width better the ground-range resolution.

Azimuthal Resolution

For Synthetic Aperture Radar, using 100% of the azimuthal processing band-width, the azimuthal resolution is given by:

$$\delta_{az} = \frac{L}{2} \text{ where}$$

L is the length of the antenna in azimuth.

Signal to Noise Ratio (SNR)

SNR of a SAR Image is expressed in terms of Noise Equivalent Sigma Zero which is defined as the radar cross section which produces a received power equal to the thermal noise power, i.e. SNR of unity. It is given by:

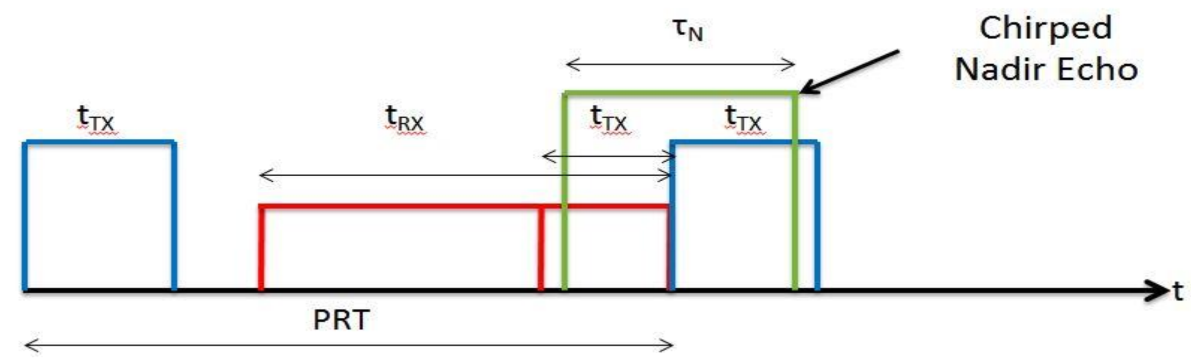
$$\sigma_{NEZ0} = \frac{16\pi R^3 \lambda BkTFv\sin\theta}{(Pt)(Lr)^2(Laz)^2(€ap)^2 cD} \text{ where}$$

R is the slant-range, Pt is the Peak RF Power λ: is the radar center wavelength, F is the Noise Figure, k is the Boltzmann's constant, T is the System Noise Temperature, Lr is the Antenna Length in elevation, Laz is the Antenna Length in Azimuth, c is the velocity of Light in vacuum, €ap: is the Antenna aperture efficiency, θis the Off-nadir angle, D is the Duty Cycle of TX pulse, and B is the Chirp Signal Band-width.

High chirp band-width is necessary for good ground-range resolution. However, this degrades the SNR. As compensation, we have to use higher duty cycle to improve SNR. But using high duty cycle severely restricts the PRF selection due to interference with TX and Nadir echo interference!

Nadir Echo Allocation by ECMPR Scheme

I. Make the nadir echo overlap with a future transmitted pulse (as in conventional method).
II. Make the nadir echo overlap with the replica of the transmitted pulse in the receiving window just before a future transmitted pulse. (Nadir echo interfering in this region will fall outside the receiving window after range compression), assuming the nadir echo does not saturate the LNA receiver.



Nadir Echo Allocation Scheme

ECMPR Modified Nadir Interference Constraint:

➢The rising edge of the nadir echo must occur after the rising edge of the replica of the transmitted pulse in the receiving window. Thus,

$$\frac{2H}{c} \geq \frac{k}{fp} - \tau_P$$

➢The falling edge of the nadir echo must occur before the falling edge of the next transmitted pulse. Thus,

$$\frac{2H}{c} + \tau_N \leq \frac{k}{fp} + \tau_P$$

Combining, we get,

$$\frac{k-D}{\frac{2H}{c}} \leq f_p \leq \frac{k+D}{\frac{2H}{c}+\tau_N} \;\forall\; D > D_{cr}, \quad D_{cr} = k * \frac{\tau N}{\frac{4H}{c}+\tau N} \text{ where}$$

D_{cr} is the Critical Duty Cycle, D is the Duty Cycle, H is the Satellite Altitude, k is any positive Integer, τ_N is the Nadir Echo Duration, τ_P is the Pulse width Duration, and c is the velocity of light in vacuum

The permissible time-zone in RX window is increased by t_{TX} thereby increasing swath-width . Thus from this perspective,

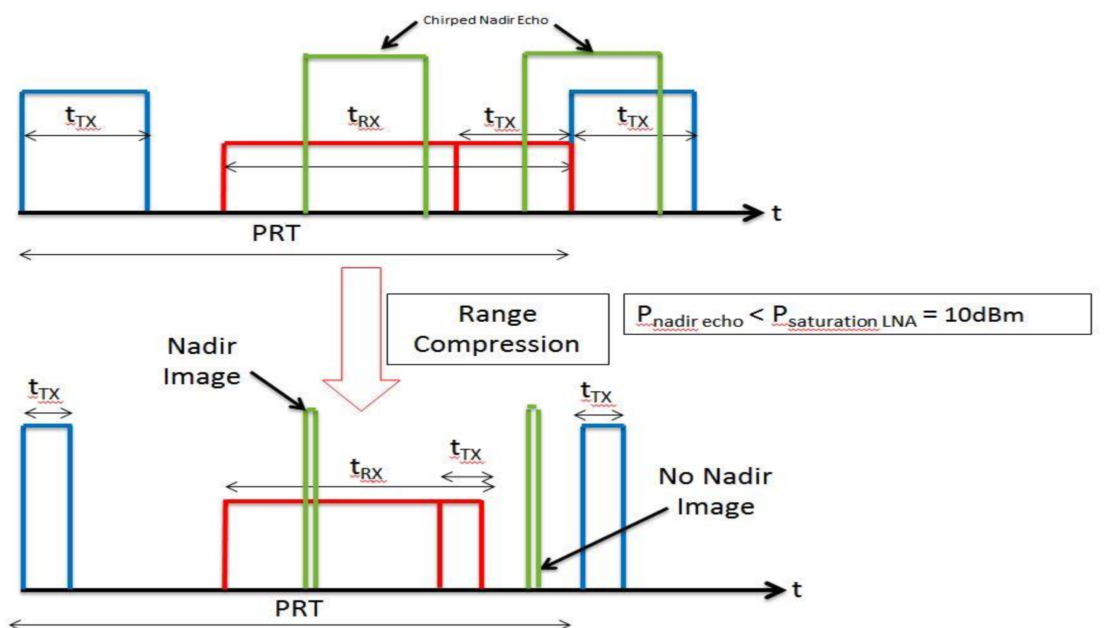
$$\textbf{ECMPSAR Gain} = \frac{t_{TX}}{t_{RX\,(conventional)}}$$

From the perspective of permissible time zone of occurrence of Nadir echo,

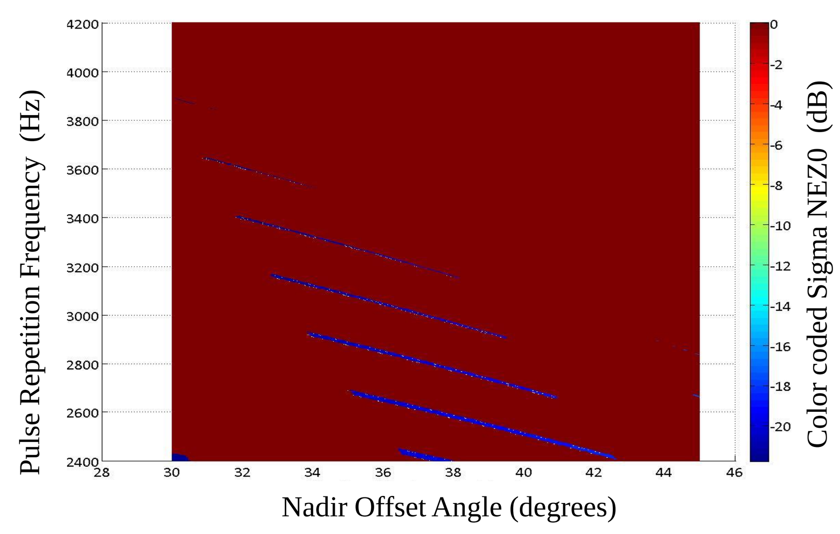
$$\textbf{ECMPSAR Improvement Index} = \frac{t_{TX}}{PRT - t_{RX}} \text{ where}$$

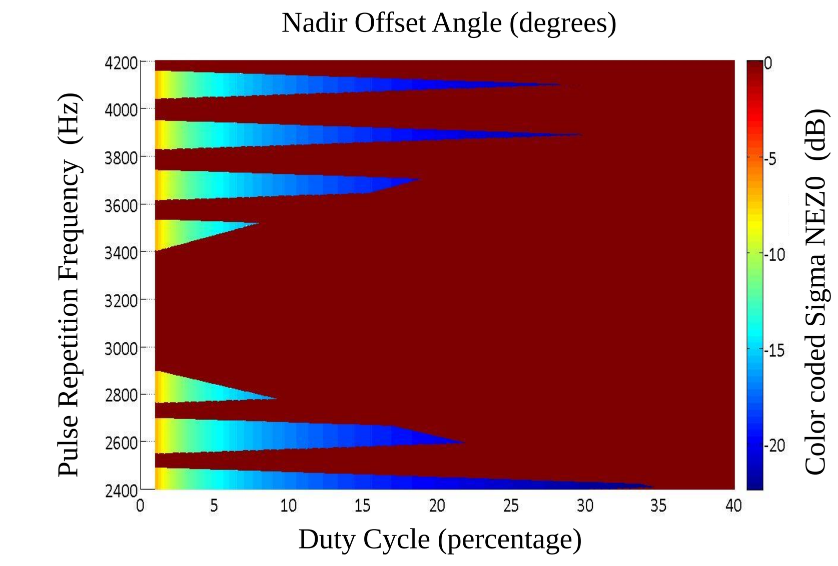
t_{TX} is the duration of the transmitted pulse, PRT is the Pulse Repetition Time, $t_{RX\,(conventional)}$ is the useful receiving window in the conventional method.

Simulations

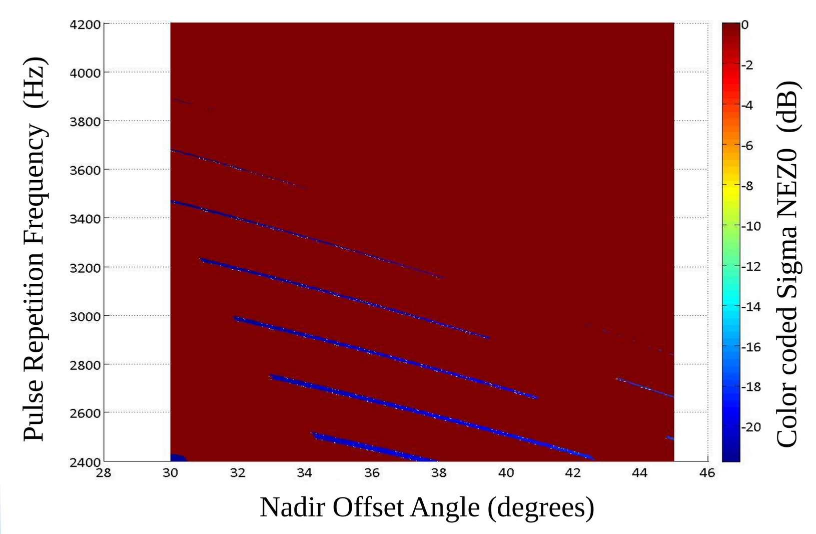


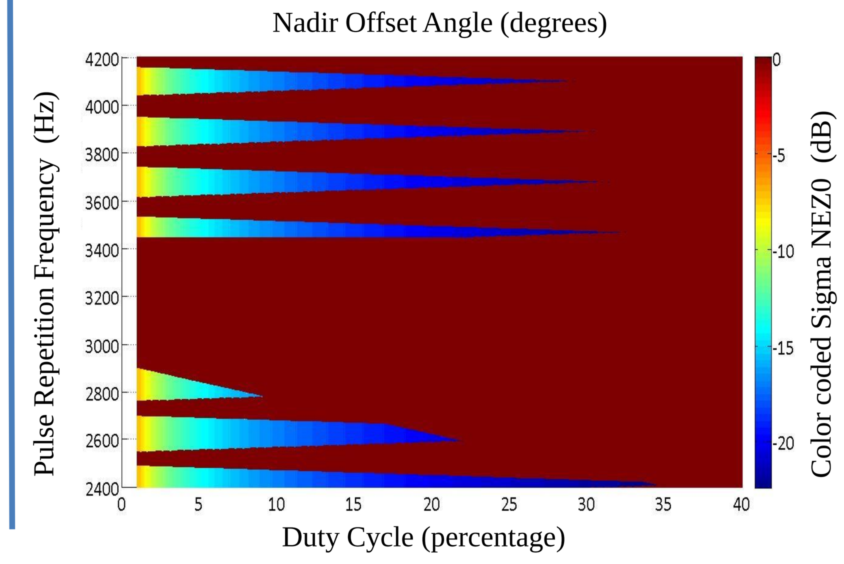
Conventional Method



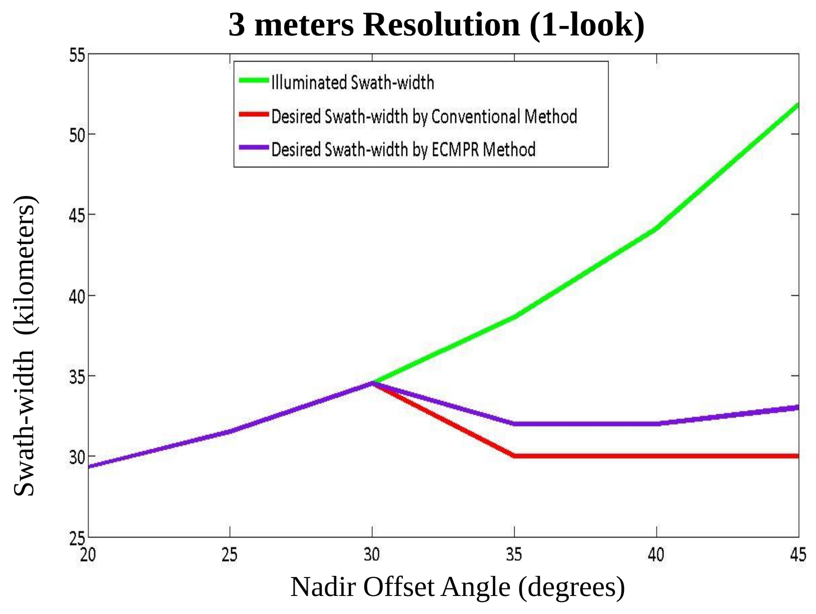


ECMPR Method

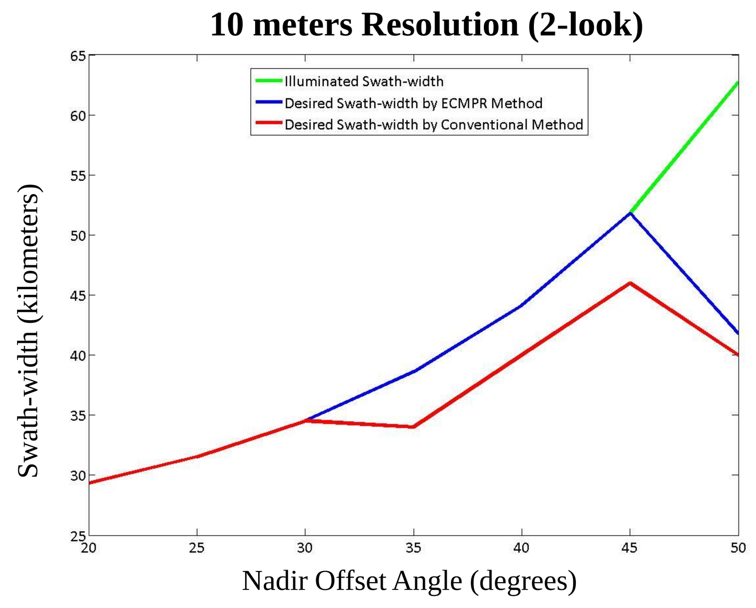




3 meters Resolution (1-look)



10 meters Resolution (2-look)



For comparison with the conventional method, we selected the PRF satisfying the following performance requirements: $\sigma_{NEZ0} \leq$ -15 dB, RASR ≤ -20 dB, AASR ≤ -17.5 dB

In the figures above, the bright strips denote the permissible PRFs and the dark regions denote non-usable PRFs due to interference with TX and Nadir Echo interference. As seen from the comparisons, the ECMPR scheme permits more permissible regions than conventional method.

Summary

- The ECMPR Method is beneficial for higher off-nadir angles greater than 30 degrees.
- At high nadir offset angles, for a given desired swath-width, we can use higher duty cycle if we employ the ECMPR Method.
- At high nadir offset angles, for a given duty cycle, we can get higher swath-width if we employ the ECMPR Method.