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Frequency analysis of SAR system design for small satellite

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Frequency analysis of SAR system design for small satellite

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Abstract. Great interest is given in recent years to the small satellites as their main advantages are the low development cost and the reduced deployment time, which give attention to develop payloads that can be mounted on the platform of these satellite. the platform of small satellites imposes constraints on the sensor design to fit in the size, mass and power limitations, which leads to necessary trade-offs between the design parameters of the sensor. The selection of the operating frequency is dependent mainly on the mission requirements as each frequency band gives different information about the scene and has different penetration capabilities. However, the SAR sensors used on small satellites come with limitations, so other parameters should be considered during the design. After going through the SAR design process, a frequency analysis is presented at L, C and X bands, which is used to evaluate the effect on the size of the antenna (length and width) and the average power consumption that suit the constraints of small satellite.

1. Introduction

SAR sensor design process for small satellites comes with limitation in compactness, power consumption and mass to fit within these platforms, which affects the design parameters selection of the sensor system specially the operating frequency. However, the operating frequency selection is dependent mainly on the mission requirements like the satellite application, the required resolution and the technological aspects [1], [2].

A design analysis between three operating frequencies at L, C and X band and their effect on the other satellite system parameters like dimensions and mass is discussed. Higher frequencies – higher than X-band- has been excluded from this study because of the technological issues that come with them, also the lower frequencies -lower than L-band- have large dimensions for the antenna which make them out of small satellite scope.

From mission perspective the L-band, suits the missions that require a higher degree of penetration as it has longer wavelength [3,4]. on the other hand, for higher resolution the X-band is preferred due to wide available band widths and the technology maturity of the components, while for a compromise between the two bands the C-band provides a rational performance between the surface penetration and resolution [5], [6].

SAR system Design parameters equations including the minimum antenna area required, PRF selection, the ambiguity and the average transmitted power is presented is section 2. The design methodology used for evaluating the design parameters is given is section 3. The design methodology validation is in section 4. The frequency analysis is given in section 5. The results of the different frequencies on the design parameters are provided in section 6. The last section is the conclusion.

2. SAR parameters

2.1. Minimum antenna area

A typical antenna of SAR is one antenna with high gain used for both transmission and reception. One of the design parameters of SAR system is the dimensions of the antenna, and it is constraint by the antenna minimum area constraint for usable design. It is for the treatment of a special SAR design case, which has the design goals of achieving the widest possible swath and the best possible resolution [7]. Thus, SAR system should every time transmit when it advances a $L_{az}/2$ distance, at least one pulse, therefore the PRF minimum is:

$$PRF_{min} = \frac{2.V_{st}}{L_{az}} \quad (1)$$

So, to avoided the Doppler spectrum of azimuth from being overlapped with each other, the antenna length Laz should achieve:

$$L_{az} > \frac{2.V_{st}}{PRF} \quad (2)$$

The maximum swath Wg_{max} is the projection on the ground of the unambiguous slant-range swath determined by the minimum PRF:

$$Wg_{max} = \frac{c}{2.PRF_{min}.\sin\theta_i} = \frac{c.L_{az}}{4.V_{st}.\sin\theta_i} \quad (3)$$

To avoid echoes in range from being overlapped, the antenna pattern is used to suppress them in elevation direction. So, the antenna footprint in elevation must be narrower than the maximum width of swath Wg_{max}.

$$\text{footprint}_{elevation} = \theta_e.R = \frac{\lambda.R}{W_a} < Wg_{max} \quad (4)$$

Therefore, the width of the antenna Wa should be:

$$W_a > \frac{2.\lambda.R.PRF.\tan\theta_i}{c} \quad (5)$$

Using the equations (2) and (5), the minimum area of antenna that fits the ambiguity limitation is:

$$A_{min} = \frac{4.\lambda.R.V_{st}.\tan\theta_i}{c} \quad (6)$$

But at the case of SAR system designing which doesn't require simultaneously the possible wider swath width and the possible best resolution, a smaller antenna can be selected to achieve these goals [8].

PRF for a spaceborne SAR is an important design parameter, as it influences most of the other system parameters. PRF value affects many system parameters like peak transmitter power, raw data rate and pulse duty factor. while, its availability is affected by many factors including SAR altitude, incidence angle, swath width, transmitter pulse length and antenna length [9].

2.1.1 PRF constraints. For acquiring a high azimuth resolution, SAR sends a pulse for every time SAR platform travels half of the length of the antenna in azimuth direction, to achieve the azimuth beam width Nyquist sampling. The following condition presents the lower bound of the PRF:

$$PRF_{min} = \frac{2.V_{st}}{L_{az}} \qquad (7)$$

Thus, for improving azimuth resolution, the antenna length in the direction of motion is critical which require faster pulsing from the SAR. Which reduces the inter-pulse period that is used to collect data in the range direction. Unfortunately, for given SAR frequency if there is more than one pulse exist in the scan area simultaneously produces the range-ambiguity, i.e., the PRF maximum is defined by reception of sequential pulses.
The upper limit for the PRF is related to the swath width by the following condition:

$$PRF_{max} = \frac{c}{2.Wg} \qquad (8)$$

Using the equations (7) and (8) the usable PRF range can be defined as:

$$\frac{2.V_{st}}{L_{az}} < PRF < \frac{c}{2.Wg} \qquad (9)$$

2.1.2 *Eclipsing Avoidance (Blind ranges).* Unfortunately, the range of PRFs values between the lower and upper limits of PRFmin and PRFmax is not all available. The receiver becomes blind during transmission because of the inherent in SAR systems isolation problems. The signal received is said to be eclipsed, when the echo returned from the scene coincides with a transmit event. So, avoiding PRFs that results in eclipsing is necessary by achieve the inequality*:*

$$\frac{(N-1)}{(\tau_{near} - \tau_p)} < PRF < \frac{N}{(\tau_{far} + \tau_p)} \qquad (10)$$

Where:

- N Whole numbers (1,2,3,..) representing pulses.
- τ_p Transmitted pulse width.
- τ_{near} Delay time between transmission and reception of the pulse to the near edge of the swath.
- τ_{far} Delay time between transmission and reception of the pulse to the far edge of the swath.

$$\tau_{near} = \frac{2.R_n}{c} \qquad (11)$$

$$\tau_{far} = \frac{2.R_f}{c} \qquad (12)$$

Where:

- R_n Slant range from the antenna to the near edge of the swath.
- R_f Slant range from the antenna to the far edge of the swath.

PRFs which causes eclipsing depends on the transmitted pulse-width and slant range from the antenna to the swath far and near edges [10].

2.1.3 Avoiding Nadir Returns. If PRF value is very large, the returns will be overlapped of Nadir (near range) and far range. These happens at a time τ_{nadir} from the transmit-pulse start:

$$\tau_{near} = \frac{2.H}{c} \qquad (13)$$

Where:

- H SAR height over the nadir point

The echoes that come from near range are much stronger than that come from far range as the small incidence angles has large backscattering coefficient. The echo duration is equal to the width of the transmit pulse at least and will become longer for the terrain at near range [16].

One approach to overcome this limitation is to avoid PRFs that causes the echo from near range to reach the receiver with the echo of far range simultaneously. Like in the case of the far range echo transmitter-pulse eclipsing. The PRFs values which make the avoidance of collapsing of echoes from near range with that of the far range are expressed by the following inequality:

$$\frac{(M-1)}{(\tau_{near}-\tau_p-\tau_{nadir})} < PRF < \frac{M}{(\tau_{far}+\tau_p-\tau_{nadir})} \quad (14)$$

Where:

M Whole numbers (1,2,3,...) corresponding to pulses

During calculating the minimum antenna area, a zero-order ambiguity analysis is presented. For the rejection of out of swath target ambiguous radar echoes, the footprint on the ground of the antenna pattern must be larger than the swath. This footprint is given by the one-way 3 dB beam width.
Ambiguous targets which are located at the edges of the footprint would only have 6 dB suppression capability. The big dynamic-range of σ0, makes this insufficient for the suppression. The range-ambiguities resulting from side-lobes of the antenna elevation pattern are illustrated in Figure 1.
The azimuth direction antenna beam-width is used to determine the Doppler bandwidth. As, the minimum PRF which is used to sample the azimuth Doppler spectrum with at the least the Nyquist rate. the Nyquist rate of the 6 dB Doppler bandwidth, which allow antenna pattern side-lobes spectral components to fold back into the spectrum main area, resulting in azimuth ambiguities, which is illustrated in Figure 2 [11].

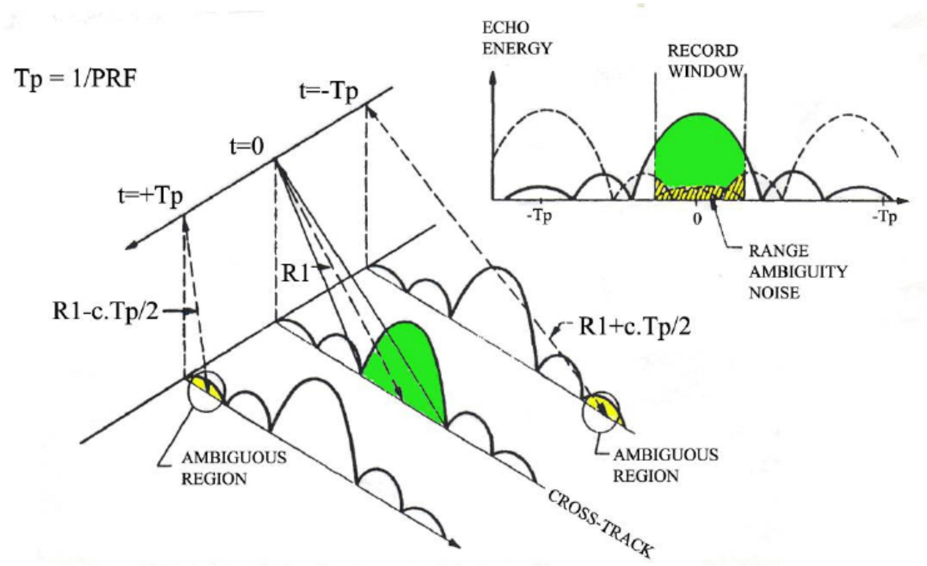

Figure 1. Illustration of SAR range ambiguities

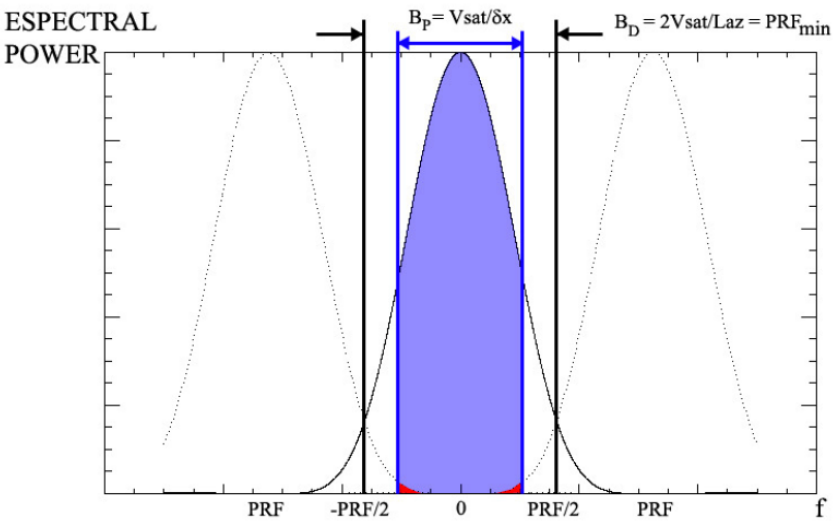

Figure 2. Doppler spectrum spectral folding for PRF=B_D

For a given antenna pattern in azimuth and range, the PRF value is chosen so the whole ambiguity noise relative to the signal is very small. On the other hand, for certain PRF value or group of values, the antenna dimensions must achieve the ASR specification.
The ambiguous signal power at certain Doppler frequency f0 and sometime delay τ0 is expressed as:

$$S_a(f_0,\tau_0) = \sum_{m,n\neq 0} G^2(f_0 + mPRF, \tau_0 + n/PRF).\sigma_0(f_0 + mPRF, \tau_0\, n/PRF) \tag{15}$$

Where

m	Whole numbers (1,2,3,...) corresponding to pulses
n	Whole numbers (1,2,3,...) corresponding to pulses
$G^2(f,\tau)$	Two-way far field antenna power pattern
σ_0	Radar reflectivity

Hence, the integrated ambiguity to signal ratio (ASR) is given by

$$ASR(\tau) = \frac{\sum_{m,n\neq 0}\int_{-B_p/2}^{B_p/2} G^2(f_0 + mPRF, \tau_0 + n/PRF).\sigma_0(f_0 + mPRF, \tau_0\, n/PRF)df}{\int_{-B_p/2}^{B_p/2} G^2(f_0,\tau_0).\sigma_0(f_0,\tau_0)df} \tag{16}$$

Where

B_p Processing bandwidth

The PRF is upper bounding this processing bandwidth. However, abortion from this bandwidth can be used to exclude a fragment of the folded Doppler spectrum into the main Nyquist window, so in the processor, the ambiguity ratio can be enhanced at the price of azimuth resolution worsen.
The ASR is expressed with dependence on τ, which indicates the place at cross-track in the image. Knowledge of the antenna two-dimensional pattern is required by this ASR expression, and the time delay and the Doppler frequency are used to formulate the reflectivity of the target. Also, these quantities derivation from the data measured requires relations. Typically, using local incidence angle antenna pattern can be given. The separation of the range and the azimuth components for design purposes becomes more practical [11].

2.1.4 *Range ambiguity to signal ratio (RASR).* Ambiguities appear in Range results from previous and following echoes received simultaneously at the antenna with the desired echo. For airborne SAR data this phenomenon is typically not significant, since the echo spread is relatively small to the interpulse period. Spaceborne SARs contrary, between transmitting and receiving a pulse several inter-pulse periods are elapsed, which make range ambiguities to become significant. to deduce the exact value of RASR, at a certain time (t_i) in the window of data record, ambiguous signals came from the succeeding ranges [12]:

$$R_{i,j} = \frac{c}{2}\left(t_i + \frac{j}{PRF}\right) \tag{17}$$

Where

j number is positive for preceding interfering pulses (j=0 for the desired pulse), and negative for succeeding ones

After that the integrated RASR is calculated by taking the sum of all signal components that come from preceding and succeeding echoes in the data window to the wanted pulse integrated signal ratio. The ambiguous signals power in any given resolution cell, is given by:

$$S_{i,a} = \sum_{j\neq 0} \frac{\sigma_{i,j} G_{i,j}^2}{R_{i,j}^3 \sin(\theta_{i,j})} \tag{18}$$

Where

$\sigma_{i,j}$ Normalized backscatter coefficient at a given incidence angle
$\theta_{i,j}$ A cross-track antenna pattern at that incidence angle
$G_{i,j}$ A cross-track antenna gain at that incidence angle
σ_0 Radar reflectivity

The desired signal is given by:

$$S_i = \frac{\sigma_{i,0} G_{i,0}^2}{R_{i,0}^3 \sin(\theta_{i,0})} \tag{19}$$

Finally, the RASR is given by:

$$RASR = \frac{\sum_i S_i}{\sum_i S_{i,a}} \tag{20}$$

Representing the ratio between useful signal and ambiguous signal levels average [17].

2.1.5 *Azimuth ambiguity to signal ratio (AASR).* It is commonly referred to the ratio of the ambiguous signal to the wanted signal, within the azimuth processing bandwidth of the SAR correlator and it can be calculated using the following equation:

$$AASR = \frac{\sum_{m\neq 0} \int_{-B_p/2}^{B_p/2} G^2(f_0 + mPRF)df}{\int_{-B_p/2}^{B_p/2} G^2(f)df} \tag{21}$$

Assuming a uniform target reflectivity across the scene in azimuth and in range and separating the two-dimensional pattern of the antenna as the product of the elevation and azimuth patterns, which to most significant side-lobes is a reasonable approximation. The typical range of AASR is about -20dB. Nevertheless, even at this value high bright targets next to dark targets can have ambiguous signals observed in images [13].

The radar range equation is the initial start point for any radar design process, as it connects a number of system parameters with the receiver signal to noise (SNR) and the target's radar cross-section and its distance to the radar. The radar range equation can be altered in a number of forms and used in many ways. In a SAR system, a useful form is the single look signal to noise [14].
The sensitivity of the system is usually expressed by the noise equivalent σ_0 (NESZ), which results from setting SNR=1, so:

$$P_{avg} = \frac{2.(4.\pi)^3 R^3.K.F.T_s.V_{st}.a_w.L_{tot}}{NESZ.\lambda^3.G^2.\rho_{rg}} \quad (22)$$

3. Design methodology

The target application has a significant effect on the design process of the SAR system. Which determines the desired specification that the design should achieve and include Desired swath width, Ground azimuth and Range resolution, Incidence angle, Frequency, Polarization, Radiometric accuracy, SNR and Sensitivity represented by NESZ.

During mission design the available platform resources imposes more constraints such as the allowable mass for the payload, available generated power, allowable size and dimensions, working altitude, attitude control, accuracy of attitude determination, downlink data rate, and so on. SAR system achievable performance is constraints by these limitations. After conflicting requirements trading, a final optimal design can be achieved.

The design flow shown in Figure 3, at the beginning converts the mission requirements (resolution, swath width, AASR, RASR, NESZ) into the required range and azimuth bandwidths. The required resolution in azimuth interprets to an antenna length (Laz). The minimum antenna width depends on the minimum antenna effective area (A_{eff}), but this minimum antenna dimension usually results in range ambiguities above the requirements. Therefore, an iterative design process is performed to optimize the antenna width and its illumination.

The minimum required PRF can be determined, when the azimuth dimension of the antenna is determined. After that, the valid PRF values map definition by applying the transmit interference and the nadir interference constraint.

Then the AASR and RASR can be calculated and also selection of the PRF value that optimizes the ASR at each incidence angle. If the optimized ASR does not meet the requirements, the antenna width is increased and the process is repeated.

After setting antenna parameters and the bandwidth, comes the determination of the power transmission necessary to satisfy the sensitivity requirement.

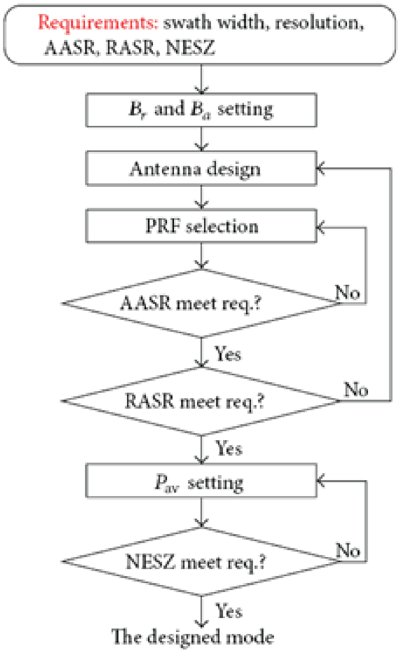

Figure 3. Flow chart of strip-map SAR system design

4. Design methodology validation

The validation is performed by deriving the system parameters from the mission requirements of a real system and comparing the obtained parameters. Therefore, for process validation, the TerraSAR-X main mission parameters have been set as constraints for obtaining the final mission specifications.
The main objective is to use the mission parameters of **TerraSAR-X** which are listed in the following table to derive the SAR system parameters using the suggested methodology and software tool and comparing the obtained results with that of the actual mission.

Table 1. TerraSAR-X mission parameters

Parameter	Value
Frequency f_0	9.65 GHz (X-band)
Orbital altitude	514 Km
Look angle	Between 20° and 45°
Resolutions	δR_g=1,7m δx=3m
Swath width	30Km
σ_0	-20 dB
ASR	20 dB
Mode	Strip-map

The variation of the minimum antenna area with the incidence angle is calculated and shown in Figure 1. As indicated at 20°, 45° incidence angles the minimum areas are 0.69 m^2 and 2.95 m^2 respectively. The lower bound for the required antenna area, is indicated by this figure without considering the ambiguity requirements [15].

optimum for this satellite. But the antenna length that TerraSAR-X satellite actually flown with is about 4,8m, which can be explained as despite decreasing the antenna length to improve the resolution the ambiguity requirements is still met. So, depending on this minimum antenna area restriction and this provided length the minimum antenna width should be no less than 0.5m.

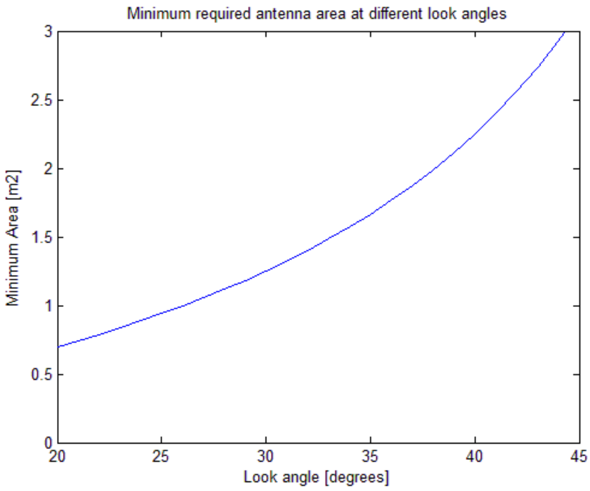

Figure 4. Minimum Antenna Area

After that the non-interference PRF values are calculated according to the design methodology and indicated as with areas in Figure 5.

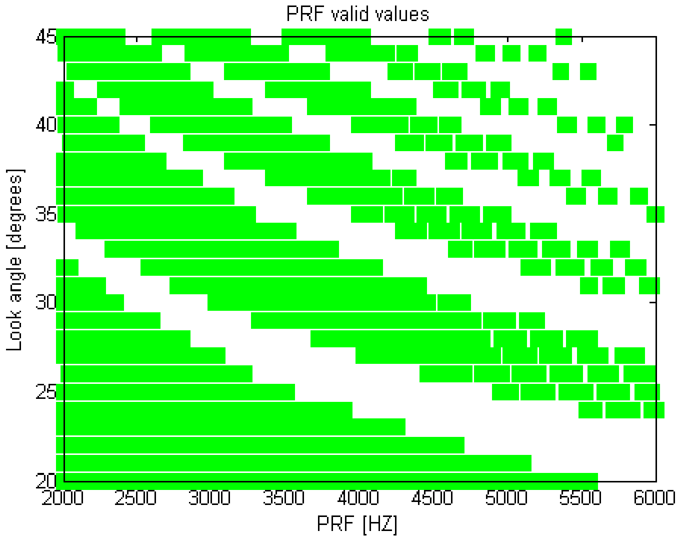

Figure 5. Non_interference PRF values

After that in the design methodology at every incidence angle in the required range of values a valid PRF value is chosen, such that the required ASR requirement is achieved at the required 30 Km swath. But if the ASR requirement cannot be achieved the process is repeated after increasing the antenna width. For the TerraSAR-X mission an antenna width of about 0.8 m fulfilled the ASR requirements at the all-incidence angles range of values. At each incidence angle the calculated ASR values fulfils the condition and are less than 20dB as shown in Figure 6. As indicated, all the values are less than 20dB.

A uniform antenna illumination pattern in azimuth assumption is used like in most orbital missions, for calculating the AASR. The AASR levels in practice are not enhanced by azimuth tapering which reduces the antenna gain. While, tapering in elevation pattern has a great impact on improving RASR. Which can be optimized for each system operating mode regarding SNR and ASR using Hanning tapering which is conventionally used in SAR systems.

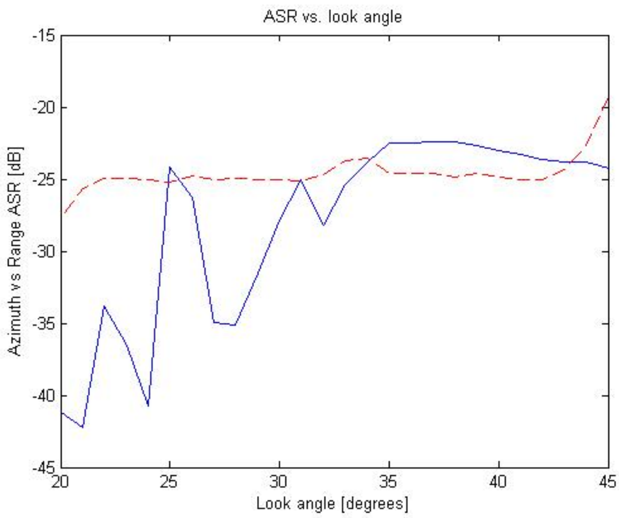

Figure 6. AASR and RASR levels with Hanning tapering in elevation

After that for achieving the required sensitivity the required average transmitted power is calculated as the last step, and it is calculated with the dependency on the range resolution for indicating the range resolution dramatic effect on it as shown in Figure 7. to achieve. For range resolution value of 1,7 m with -20 dB of NESZ requires a transmitted power around 300W.

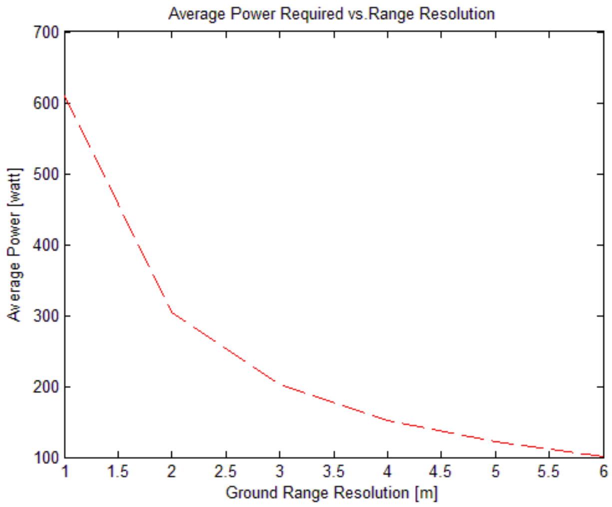

Figure 7. Average transmission power vs. Range Resolution

The results of the system design parameters values obtained achieving the mission requirements and that of TerraSAR-X are indicated in Table 2.

Table 2. TerraSAR design comparison

parameters	TerraSAR-X	Results
Antenna Length	4.8	4.8
Antenna Width	0.7	0.8
Average Transmit Power	360	359

So, based on the comparison results the design methodology produces valid and realistic results.

5. Frequency analysis

At this stage of the design of the system design process comes the frequency selection, which is mainly dependant on the application, but it has significant effect on other system parameters. A frequency analysis is presented at L, C and X frequency bands with the same mission parameters.

The required mission and quality parameters are listed in the following table with minimum acceptable sensor quality values of σ_{NE} and ASR values. The values stated in the table are from actual SAR missions like TerraSAR, RadarSAT or Envisat. Ambiguity problems can arise from the required lower values of ASR. For improving the sensitivity in case of more is required, decreasing the final range resolution is a choice.

Table 3. Quality and Mission Requirements

Quality requirements	
ASR_{min}	≈ 20dB
σ_{NE}	≈ -20dB
Ground Swath Width	30 km
Mission Requirements	
Frequency bands	9.65 GHz (X-band) 5.3 GHz (C-band) 1.3 GHz (L-band)
Altitude	510km
Look angle	20° to 45°
Polarization	single
Laz	≤ 5 m (if the quality requirements are not achieved it may be increased)

As a design objective, SAR antenna size is minimized as possible with considering the width of the swath to fit the required application. So, 5 m is the starting antenna length value of and it will be increased if the quality requirements are not met.

The application intended determines mainly the width of swath required, taking into consideration that small swaths are undesired for most application where the large swaths are not appropriate for small satellites because of the size of the antenna needed and for analysis simplification a 30 km swath is considered, also only a single polarization is considered.

At the different frequency bands the required minimum antenna area is illustrated in Figure 8, indicating that at the lower bands of frequency larger antenna sizes are needed.

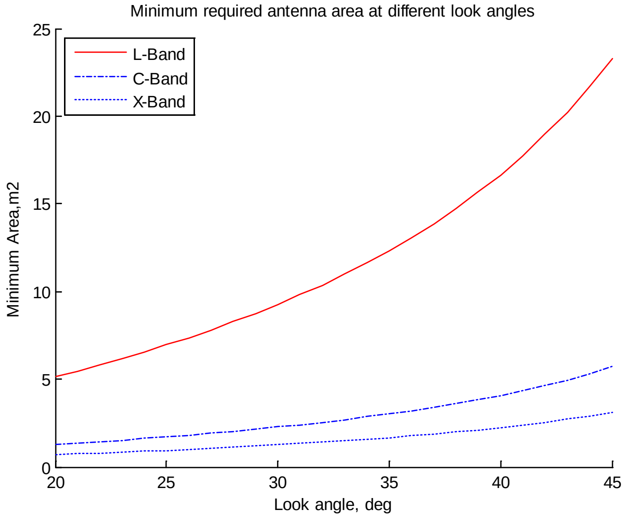

Figure 8. Initial antenna areas at L, C and X frequency bands

There is dependency between the required azimuth resolution and the needed antenna length, also long antenna lengths are required for the lower frequency bands but with the price of resolution reduction. Each frequency band is characterized by its penetration capability, but mainly frequency band selection is determined by the application.

Within the technological limitations, increasing the pulse width increases the range resolution at the price of sensitivity reduction.

As the look angle is increased the available PRF values is decreased as illustrated in Figure 9.

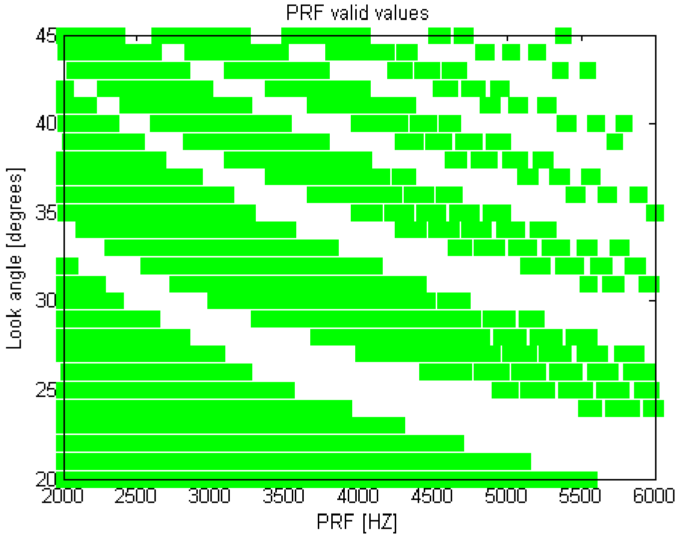

Figure 9. Noninterference PRF for 30 km swath width

Lower frequency bands need less power when scaling resolution with wavelength but requires large antenna sizes as illustrated in Figure 10 for 30 km swath.

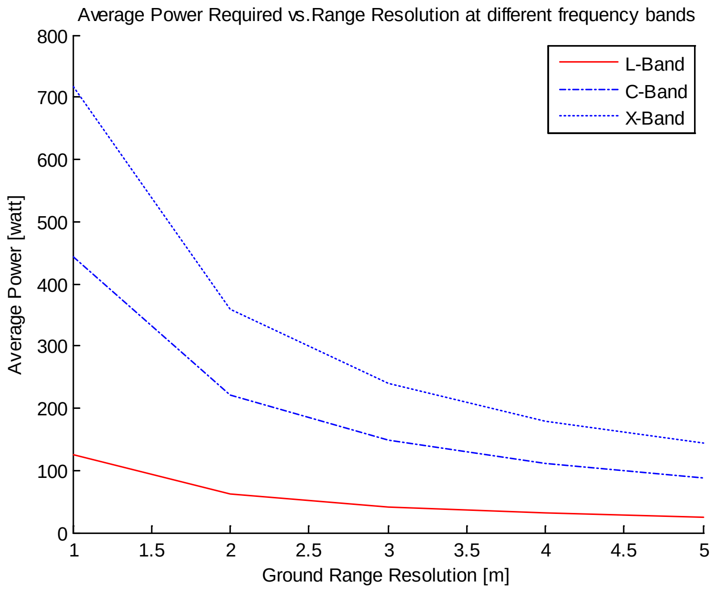

Figure 10. Transmission power at L, C and X bands

6. Results

The resulting values of the required system parameters are listed in Table 4 at the different frequency bands.

Table 4. SAR design configurations results

Parameter	L-Band	C-Band	X-Band	
Frequency f_0 [GHz]	1.3	5.3	9.65	
Altitude h [km]	510			
Look angle [°]	[20:45]			
Min antenna Area [m^2]	[5.14:23.8]	[1.26:5.71]	[0.69:3.14]	
Azimuth resolution δx [m]	3	2.5	2.5	30 km Swath width
Range resolution δR_g [m]	3			
Antenna length [m]	6	5	5	
Antenna width [m]	3.8	1.2	0.7	
Average power [w]	42	148	239	

7. Conclusion

In the SAR system design process, the operating frequency of the SAR system affects mainly the antenna dimensions and the average transmitted power with the same required mission parameters.

For more compact antenna size and dimensions the X-band is preferred, but it requires higher power transmission which requires heavier power supply system. On the other hand, for power transmission reduction and hence lighter power supply system the L-band is preferred, but the antenna dimensions are larger which requires more size. So, as a trade between the required antenna dimensions and power

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transmission for the same mission requirements the C-band is recommended as an operating frequency band.

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