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Synthetic Aperture Radar for Small Satellite

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Abstract*: Small satellites are growing because they have shorter development cycles, lower cost, new technologies, and more frequent access to space. Sensors for Small satellites come with trade-offs to allow them fit within the mass, size, power and weight constraints imposed by the platform, these trade-offs between sensor system parameters can affect the mission requirements. Considering traditional SAR mission, each frequency band has different capability of penetration and special image characteristics, so the final SAR application will determine the appropriate bands needed. Small satellites come with constraints on the SAR sensor, so an analysis of SAR sensor system parameters (antenna length, antenna width and average transmitted power) at L, C and X band given a determined performance parameters is presented to analyze the effect of these frequency change on the system parameters and to determine the frequency band that is more suitable to fit within the small satellite SAR sensors constraints.

***Keywords* : SAR design , Frequency band, Small satellite, parameters trade-off.**

I. INTRODUCTION

Synthetic Aperture Radar (SAR) is a type of radar which is used in different weather conditions (clouds, fog or precipitation etc) and at different times (image can be acquired during day as well as night) to acquire a high resolution aerial and space based imaging of a terrain. The main reason to choose the SAR image instead the optical imaging devices (e.g. a camera) is the SAR ability to acquire the image of the terrain surface in all weather conditions and all times at day or night. On the other hand the optical devices work only in the day time and cannot work in bad weather conditions. There are two main types of platform; the satellites and the aircrafts. Sensors carried on the satellites have the ability to reach each point on the Earth's surface and offers a repetitive and systematic image collection. It needs high power requirements which lead to a high cost. Satellite sensors are restricted to a certain part of the earth and certain time dedicated by their orbits. On the other hand the sensors carried on the air crafts has the facility to monitor any part of the earth at each time and have low power requirements but have a restriction on the swath on the covered area. Satellite orbits are selected based on the capability and objective of the sensor or sensors they carry.

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Orbit selection means choosing the orbit parameters like altitude and inclination and rotation direction relative to the Earth which serve the mission objectives. New technologies help in developing new system concepts, also the technologies affect the design choices which are affecting the technological trends. Based on the applied technique and technology, the system design changes. The Categorization of spaceborne SAR sensors according to their operational flexibility can be within four generations. The on/off sensors are the first-generation sensors that have a one fixed operational mode (fixed beam, bandwidth, incidence angle, etc.), sensors operating in many modes such as Strip-Map, Scan-SAR or Spot-Light are the Second generation with restrictions on the commanding which is macro-based used for a specific mode choosing without the flexibility of changing or altering the instrument individual settings. However, the inability of producing wide coverage and high-resolution image simultaneously known as the ―fundamental limitation of SAR sensors‖, these current sensors don't offer a satisfactory solution to it; instead, they offer the choosing and compromising flexibility between high-resolution and wide-coverage [1]. Third generation which are the current SAR sensors (for example TERRASAR-X) provides a better flexibility in controlling approximately each of the instrument individual parameter, through the usage of the main instrument construction blocks to generate the wanted mode of operation with the needed instrument setting. Currently a concentrated research is performed for producing a fourth generation called Smart-Multi-Aperture-Radar-Techniques (SMART) explained in [2], [3] which are the systems that use different forms of Digital Beam forming (DBF), like SCan-On-REceive (SCORE), transmit phase centre variations, and multi-receive channels of azimuth direction which are combined called SMART. Multiple channels in elevation and/or azimuth with DBF capability usage considered the main feature of this SAR systems future generation. Which allows for synthesizing several or dynamic-digital-receiver beams? These SMART modes of operation generate many digital receiver beams, enabling each beam to illuminate on ground an unambiguous range part. By utilizing SMART sensors DBF property, which provides the capability of generating or forming the receiver beams from the echo signal recorded without analog beam forming (ABF) needing. These formed beams are used also in the elevation direction for scanning by following the echo on the ground SCORE, which provides the possibility for designs of SAR sensors that can produce wide-swath with high-resolution using small antennas [2]. Robustness, weight, compactness and power consumption are the main contains to design SAR sensors carried by a small satellite. The centre frequency of the system is a key parameter in the system design which detects the needed resolution, the technological aspects and the system application.

For the applications that require penetration properties like the retrieval of biomass and minerals detection, The L band is preferable. The large antenna dimensions are the main limitation for that band. For high resolution application like the military applications, the X-band is required. The X- band has a lot of the technological restrictions. To compromise between the technological restriction of the X-band and the large antenna dimension of the L-band, the C-band presents a good performance in terms of the penetration and the resolution. The C-band is considered the best choice for the past years.

II. SAR PERFORMANCE PARAMETERS

The system parameters describe the instrument from two points of views. One of them is the operation parameters as the PRF and the other one is the quantities one as the antenna dimensions. The mission requirements detect the performance which is described as set of values related to the performance parameters. Figure 1 shows the performance parameters. Due to the performance studies, there are disagree between the desired parameters used in the SAR design. The performance bounds are the main condition to determine the various performance goals [1].

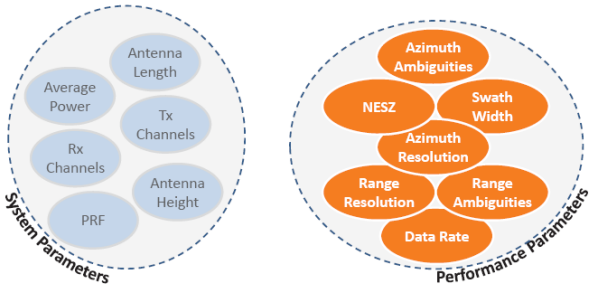

Fig. 1.Performance parameters

This paper will focus on the Minimum Antenna Area, PRF selection.

A. Minimum Antenna Area

The antenna beam pattern and the antenna gain are the main antenna parameters that affect the SAR performance. The antenna area is directly control the antenna gain. For uniform illumination the gain is:

$$A_e = \eta_{ap}.A_a \tag{1}$$

Where:

η_{ap} Aperture efficiency of the antenna
A_a Physical area of the antenna aperture

A typical SAR antenna is a single high gain antenna used for both transmitting and receiving. The swath width and the best resolution are the design goal , it is related directely to the minimum antenna gain.

For each distance of $L_{az}/2$, at least, one pulse should transmitted by the SAR system and the minimum PRF is, therefore:

$$PRF_{min} = \frac{2.V_{st}}{L_{az}} \tag{2}$$

Where:

PRF Pulse repetition frequency
V_{st} Satellite velocity
L_{az} Antenna dimension in azimuth direction

Therefore, to prevent overlapping azimuth Doppler spectra, the antenna length L_{az} must satisfy:

$$L_{az} > \frac{2.V_{st}}{PRF} \tag{3}$$

The a maximum swath Wg_{max} is inversely proportional to the minimum PRF :

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

To prevent overlapping echoes in range, the radiation pattern in elevation of the antenna should be suppress their signal. That means the maximum swath Wg_{max} should be larger than the footprint of the antenna.

$$\text{footprint}_{elevation} = \theta_e.R = \frac{\lambda.R}{W_a} < Wg_{max} \tag{5}$$

Therefore, the antenna width Wa must satisfy:

$$W_a > \frac{2.\lambda.R.PRF.\tan\theta_i}{c} \tag{6}$$

From Equations (3) and (6), the minimum antenna area satisfy the ambiguity constraints is:

$$A_{min} = \frac{4.\lambda.R.V_{st}.\tan\theta_i}{c} \tag{7}$$

In some cases of the SAR design there is no need to achieve the best swath width and the best resolution at the same time. To optimize the SAR design the smaller antenna is preferable to obtain a compact structure. It has a great effect on the design of multimode SAR's which reduces the system cost.

Not only the cost of the antenna is main target because the antenna size has an impact on the gain and then affect on the signal-to-noise ratio.

The minimum antenna area works under three aspects:

- The processing bandwidth in azimuth is chosen by the SAR designer but it should be less than the PRF and at the same time achieves performance compatible with the data requirements [4].
- The nominal Doppler bandwidth is greater than the PRF. For a small processing bandwidth, to achieve reasonable azimuth ambiguity performance, the PRF cannot usually fall below about 75% of the nominal Doppler bandwidth.
- To incorporate into any SAR system design, the illuminated swath should be larger than the swath for which data is actually recorded.

Equation (8) present the constrains between the azimuth resolution and swath width. The speed of the platform really is the only parameter control the azimuth resolution.

$$\frac{W_g}{\tilde{n}_{az}} < \frac{c}{2.V_{st}.\sin ç} \quad (8)$$

B. PRF selection

PRF is considered as one of the most important parameter for a space borne SAR. The selected PRF influences many system parameters like raw data rate , peak transmitter power, and duty factor. On the other hand there are many factors that affect PRF availability as the transmitter pulse length, the swath width, the SAR velocity, the antenna length, the altitude and the incidence angle. Due to PRF [5] constraints, some combinations of antenna length and swath width may be incompatible as the ambiguity constraints may conflict and the Nyquist requirement.

To achieve the Nyquist sampling, each time the radar platform moves half of the long track antenna length, the radar sends a pulse. That will improve the azimuth resolution. Equation (2) presents the lower limit of the PRF.

According to the following condition the upper limit of the PRF is the swath width :

$$PRF_{max} = \frac{c}{2.Wg} \quad (9)$$

Therefore, from Equations (2) and (9) the available PRF range is:

$$\frac{2.V_{st}}{L_{az}} < PRF < \frac{c}{2.Wg} \quad (10)$$

Thus to improve the azimuth resolution, the azimuth antenna length is crucial and therefor the radar should pulse rabidly. To collect data in the range resolution, there is a less time between pulses. For a given radar frequency found at time in the target zone, the range ambiguity occurs if there are more than one pulse. In other word by continuous reception of back-to-back pulses, the maximum PRF would be determined.

Due to the isolation problems in radar systems, not all PRFs between PRF_{min} and PRF_{max} are available.The receiver is blind during the transmit event. When the returning scene echo coincides with a transmit event, the received signal is said to have been eclipsed. To avoid PRFs that will result in eclipsing , the PRF must satisfy the inequality:

$$\frac{(N-1)}{(\hat{o}_{near} - \hat{o}_p)} < PRF < \frac{N}{(\hat{o}_{far} + \hat{o}_p)} \quad (11)$$

Where

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

$\hat{o}_t$ Length of the transmitter pulse.

$\hat{o}_n$ Round trip propagation time to the near edge of the swath.

$\hat{o}_f$ Round trip propagation time to the far edge of the swath.

$$\hat{o}_{near} = \frac{2.R_n}{c} \quad (12)$$

$$\hat{o}_{far} = \frac{2.R_f}{c} \quad (13)$$

Where:

R_n Slant range to the near edge of the swath.

R_f Slant range to the far edge of the swath.

The returns from Nadir (near range) and far range will be overlapped when the PRF is too large. These hapen at a time τ_{nadir} from the beginning of the transmit pulse:

$$\hat{o}_{near} = \frac{2.H}{c} \quad (14)$$

Where:

H Altitude over the nadir point

Because the backscattering coefficient (σ) is larger for small incidence angles, the far range echo is significantly lower than the imaged near range. The duration of the near range echo is at least the length of the transmit pulse (τ_p) and for some terrain will last longer [6].

Only one solution to this approach is to avoid PRFs, which cause a near range echo to arrive at the receiver at the same time as the far range echo. Like the situation of the transmitter pulse eclipsing the far range echo. The PRFs, which avoid near range echoes coinciding with the far range are described by the inequality:

$$\frac{(M-1)}{(\hat{o}_{near} - \hat{o}_p - \hat{o}_{nadir})} < PRF < \frac{M}{(\hat{o}_{far} + \hat{o}_p - \hat{o}_{nadir})} \quad (15)$$

Where:

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

III. METHODOLOGY

The design objective is to obtain large swath width and at the same time small antenna width. To simplify the process the antenna width is chosen to be 5 m and the swath width is 30 KM and single polarization.From the analysis of the required minimum antenna area, figure 2 shows that the lower frequency bands require larger antenna size.

Figure 3 shows the transmitted power of L,C AND X band for the desired swath width 30 KM.

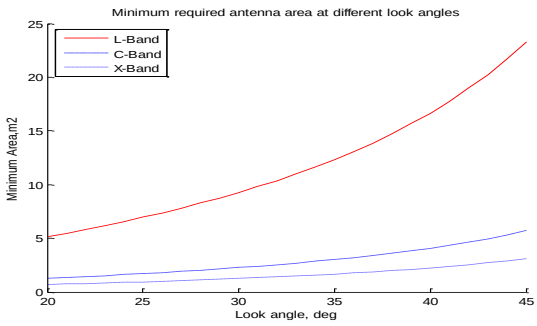

Fig. 2. L, C and X band initial antenna areas

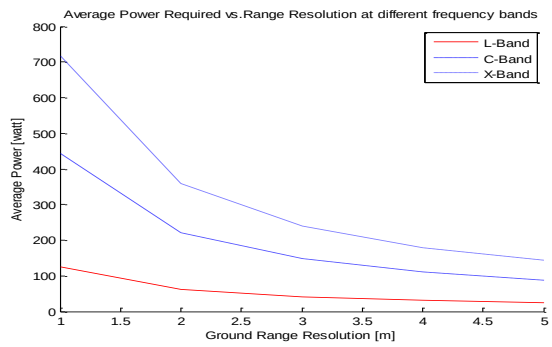

Fig. 3. Power transmitted at L, C and X bands

Table I illustrates the Results of the designed SAR configurations.

Table I Results of the designed SAR configurations

Parameter	L-Band	C-Band	X-Band
Frequency f_0 [GHz]	1.3	5.3	9.65
Altitude h [km]		510	
Look angle [º]		[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
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

30 km Swath width

An experienced end user detect the design parameters as the desired swath width, the Incidence angle, the azimuth resolution, the Ground range, the Polarization, the SNR, the Wavelength and the Sensitivity. These parameters are generally dependent on the SAR. Another constrains are imposed by the application as the platform altitude, the physical dimensions, the payload mass, the available power, the downlink data rate, the attitude control, the payload mass and the available plate form (airborne or satellite).

Figure 4 presents the Block diagram of the system design for strip-map SAR:

- The Azimuth ambiguity to signal ratio (AASR)
- The swath width
- The Range ambiguity to signal ratio (RASR)
- The Noise Equivalent Sigma Zero (NESZ)
- The resolution
- The antenna length (Laz)
- The minimum antenna effective area (Aeff) is used to determine the minimum antenna width (an iterative process is needed to optimize the illumination and the width of the antenna to avoid the range ambiguities)
- once the azimuth dimension of the antenna is set, the required PRF is determined (by applying the nadir interference constraint and the transmit interference constrains)
- For every incidence angle, the minimum value of PRF that will optimize the value of the ASR and the AASR and RASR are calculated
- In case the value of ASR does not achieve the requirements, the antenna is redesigned and repeat the process
- The system bandwidth and the antenna design are set.
- The final stage determine the transmit power to achieve sensitivity needs

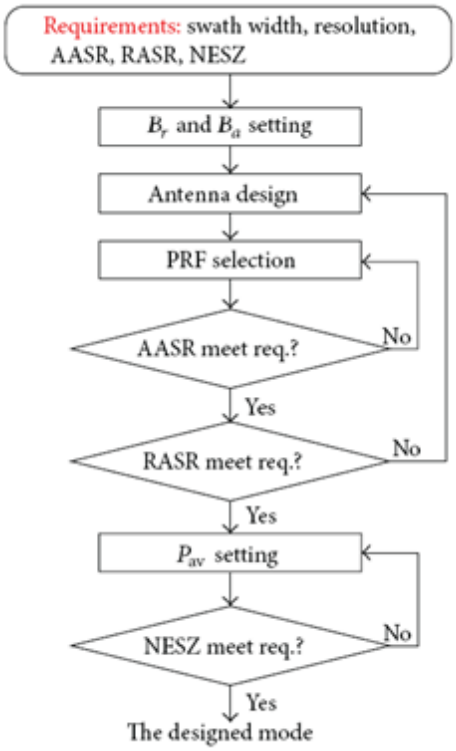

Fig. 4.Block diagram of the system design for strip-map SAR

IV. SAR SYSTEM DESIGN METHODOLOGY VALIDATION

For the validation of the design methodology, a test for the design flows and software tool is considered, to compare the results obtained with a system already operating. To validate the process in order to achieve the TerraSAR-X final specifications, set the main mission parameters as constraints. The target of the proposed process is to obtain similar system parameters as the actual TerraSAR-X . The mission parameters are presented in table II

Table II. TerraSAR-X mission parameters

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

Figure 5 shows the minimum antenna area at different look angles. For a 20º incidence angle the minimum antenna area is 0.69 m^2 and for a 45º incidence angle the minimum antenna area is 2.95 m^2 .

For TerraSAR-X, if antenna length is about 6m, azimuth resolution will be 3m. The actual antenna length of TerraSAR-X is around 4,8m, that means the azimuth resolution is increased as it still meet ASR requirements.

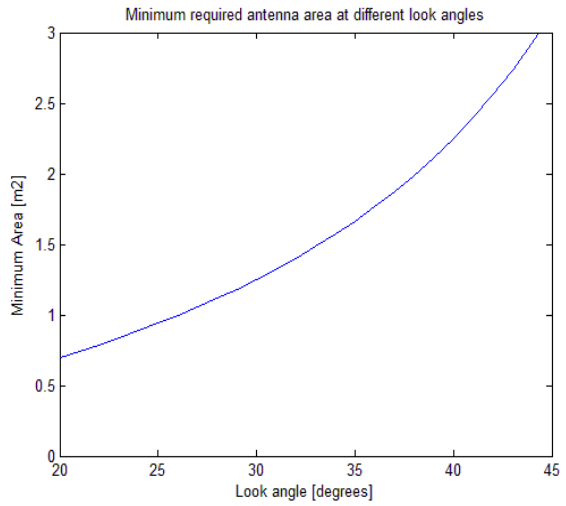

Fig. 5. Minimum Antenna Area

Figure 6 shows the valid PRF values with the different look angles.

The main objective gets the accurate value of ASR for the desired swath width 30 Km. So the PRF values are checked for each incident angle.

According to the proposed procedure if the PRF selection is failed the antenna width will be changed and repeat the process until reach the optimized value of the PRF according to the desired swath width.

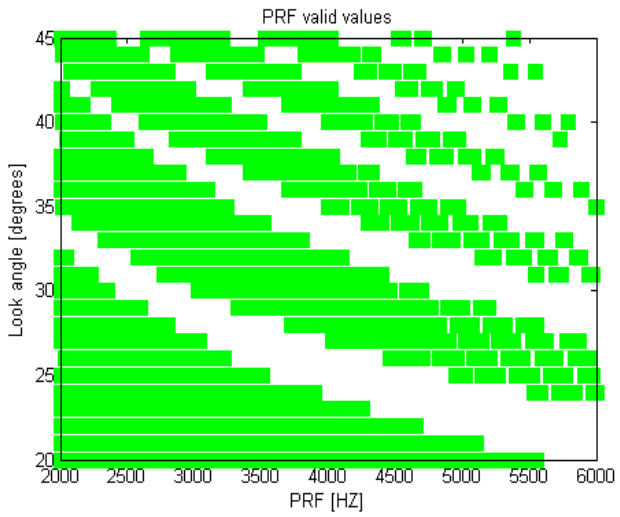

Fig. 6. Non interference PRF values

For an antenna width of 0.8, the ASR requirements are met for the entire range of incidence angles. Figure 7 shows final value of ASR. As specified, all values are less than 20dB.

Like in most orbital missions it is assumed that the illumination of the antenna is uniform in azimuth, in order to calculate the AASR. AASR levels in practice are not improve by azimuth tapering while causes reduction of the antenna gain. Due to the dependence of the RASR on the tapering in elevation of the antenna, for each operating mode of the system using Hanning tapering this tapering is optimized, in terms of SNR and ASR.

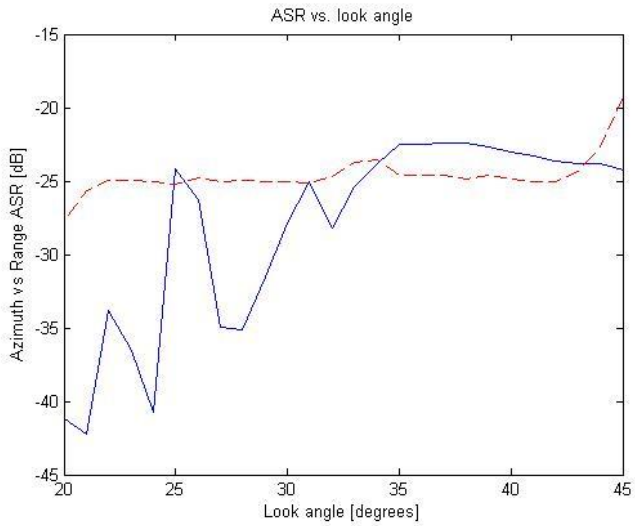

Fig. 7. AASR and RASR with Hanning tapering in elevation

The final step in the proposed process is the calculation of the average transmits power. Figure 8 illustrates the relation between the average transmitted power and the ground range resolutions. The required transmit power is around 300W for 1,7 m range resolution .

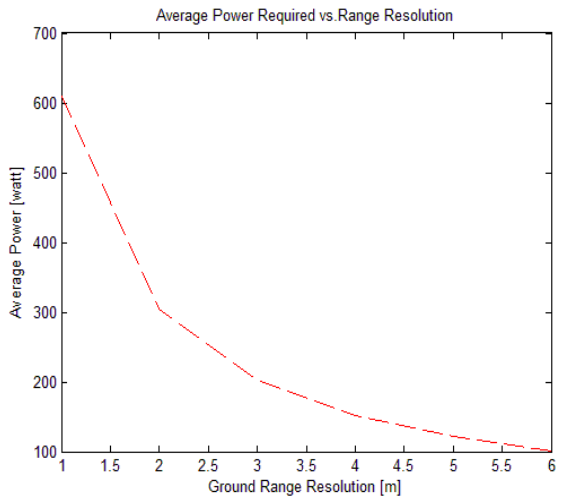

Fig. 8. Average power vs. Range Resolution

Table II illustrates the Extent of convergence between the actual mission parameters and the results of the proposed process

Table.II TerraSAR design comparison

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

It can be concluded that even though the design procedure used yields valid and realistic results.

V. CONCLUSION

The design of a spaceborne Synthetic Aperture Radar (SAR) sensor is the result of a number of trade-offs. Usually, the initial conceptual design phase is done through repeated trade-off study among different available design concepts and technologies.

SAR system performance is dependent on a multitude of parameters, many of which are interrelated in non-linear fashions. In this paper the most relevant parameters of a SAR system are discussed and the inter-relation between different parameters is explored.

Analysing the trade-offs between the SAR system parameters and performance parameters, to improve and optimize the performance of the system, described through the performance parameters.

The X band is more suitable for small satellite spaceborne SAR because of the small antenna dimensions but the power consumptions is higher.

From the point of view of antenna size the X band is more suitable for small satellite spaceborne SAR but from the power consumption point of view which intern means more mass the L-band is more suitable. If a trade is made between antenna size, power consumption and performance the C-band is the more appropriate

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