Feasibility Study of X-Band Micro Sar for Space-Bornemission

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Abstract: The utilization of frequency spectrum in the microwave range is one of the imaging methods of the surface or underground layers. Due to the unique characteristics of this frequency range and considering advantages providing by this imaging methodsuch as sensing capabilities in all weather conditions, Imaging without the sunlight requirement, Sensitivity to the dielectric properties of materials, penetration in ground depth and accurate determination of terrain height differences, hence the importance of active imaging as imaging payload for satellite designers with a synthetic aperture radar payload increases. Since the SAR satellite design parameters are numerous and highly associated with each other, Designing a remote sensing satellite with synthetic aperture (SAR) requires a high number of compromises between the parameters. Achieving general information of the essential parameters such as the dimensions of antenna, resolution, pulse repetition frequency and the relationship and also compromise between these parameters, requires analysis and evaluation of specific requirements in the designing. In this paper the principal requirements of designing and analysis of a SAR sensor is investigated. It also provides a compromise between the requirements and the parametersand finally a typical satellite is proposed according to considered requirements.

Key words: Feasibility · X-Band · Micro Sar for Space-Bornemission

INTRODUCTION

After World War II, plans for the use of SAR payload was presented by Goodyear airline. Researches’ conducted in this regard lead to side looking airborne radar (SLAR) construction in order to search military purposes and also military zones detection. Such radars with left and right antenna in flight path were able to provide more accurate segmentation of given targets. With respect to the development of synthetic aperture radar technology SLAR systems in 1950, an effective step was taken in order to create high quality images.

Military and industrial developments carried out using airborne platforms, were continued by Goodyear, Hughes and Westinghouse companies. Then The Jet Propulsion Laboratory, Biological Research Institute of Michigan University began research in this field. Extensive studies began in 1974 and finally in 1990, the satisfaction improvement of a SAR mission leads to launch five SAR satellites into space. Today's advanced space SAR radar has functionality in different modes of imaging in L, C and X frequency bands [1-4].

Synthetic aperture radar is a coherent system that can be adjusted to produce a high resolution. This type of radar use signal process in order to produce images. The mentioned sensor can be installed and used on a variety of carrier. Satellites with synthetic aperture radar payload are applicable in the lower orbits to have universal coverage and also require lower average power in comparison with higher orbits. Since the beginning use of synthetic aperture radar (SAR) up to now, many satellites have been designed and utilized. Some of these satellites are now imaging from different parts of the world. Satellite SEASAT was the first satellite to measure the oceans and seas using synthetic aperture radar payloads [2, 5, 6].

Investigations reveal some differences between synthetic aperture radar design for airborne and spaceborne applications as follows:
Fig. 1: Spatial SAR payload imaging structure.

**Difference in Pulse Repetition Frequency (PRF):**
The required frequencies for spaceborne applications are more accurate and considerable and become one of the principal constraints in the system design. Effective factors on pulse repetition are as follows: carrier velocity, antenna length, imaging bar width, incidence angle, transmitted pulse length, satellite height, and wavelength. For more information see [7-10].

**Required Average Power:** Average power in spaceborne applications is much greater than the average power in airborne applications. An accurate compromise must be made due to the productivity power of system as one of the space limitation and bottlenecks of design. It should be noted that batteries and solar cells on satellites have limitations because productivity power can have a significant effect on the productive resolution [11, 12].

**Antenna:** Antenna design for the spaceborne applications is face with complexity. Spatial antennas have larger dimensions and must transmit higher power [13, 14].

Other cases, such as reliability, atmospheric losses, integration time events, test etc are considered as bottlenecks components design which are not mentioned in this section.

**Requirements of the Designing a SAR sensor**

**Satellite (Elevation) Height:** Satellite height selection is the first requirement in designing, because as the satellite height reduced the required power for satellite payload and atmospheric attenuation decreased. It should be mentioned that power loss can lead to energy substructure weight loss and ultimately will reduce the size of the satellite. Satellite movement velocity or in other words the antenna movement rapidity of payload can be determined by satellite height determination as an important parameter in designing.

\[ V_s = \sqrt{\frac{GM}{R + h}} \]  

(1)

Here G is earth’s gravitational constant, M, weight of earth, R, Radius of earth and h, the satellite height. Averaging in 500km height a velocity about 7km/s can be obtained.

**Incidence Angle:** Incidence angle is the angle between the antenna beam and the normal to the earth surface of the target area. Figure 1 illustrates the incidence angle of a typical satellite. This parameter is highly considerable due to the influence on the radar cross-sectional area (RCS) and range resolution on the ground and also imaging strip width. Generally angle extenuating can cause return increase form target and transmitted power reduction to the target. Incidence angle is obtained from the following equation [2].

\[ \eta = \sin^{-1} \left( \frac{h + R_{\text{air}} \sin \gamma}{R_t} \right) \]  

(2)

\( \eta \) and \( \gamma \) represent the incidence angle and antenna beam point incident angle respectively.
Sensitivity: Another starting point for designing synthetic aperture radar is radar equation that is associated with signal-to-noise at the receiver, radar cross sectional area and other parameters. Radar equation can be expressed as follows [4].

\[
\text{SNR} = \frac{\eta_{\text{ant}} P_{\text{avg}} G_j^2 \lambda_0^3 \delta R_g \sigma_0}{2(4\pi)^3 R^3 (k_B T_{\text{sys}} V_s) }
\]  

(3)

Sensitivity is usually expressed in an expression of equivalent noise caused by SNR=1 in equation (3) and yields equation (4) [4]:

\[
\sigma_{0, \text{one}} = \frac{2(4\pi)^3 R^3 (k_B T_{\text{sys}} V_s) }{\eta_{\text{ant}} P_{\text{avg}} G_j^2 \lambda_0^3 \delta R_g }
\]

(4)

Sensitivity can be improved by using methods:

- Increasing the averaged power with the increase in peak power which is associated with technical constraints, or increasing the pulse width...
- Reducing the distance to the target, leading to a reduction in satellite height and the use of low orbits.
- Increasing antenna gain which causes enhancement in the physical length of the antenna and also range resolution and image strip width deterioration.
- Reduce the necessary resolution.
- System noise reduction (receiver noise and quantization noise) which is usually 300 k for SAR systems.
- System waste reduction using antenna feed system improvement or the placement of modules T/R in order to improve the system gain, which increases the cost of power.

Range Resolution: For a SAR system, the range resolution (resolution in the direction perpendicular to the payload movement direction) is presented as follows [5]:

\[
\delta R_g = \frac{c}{2B_R \sin \eta}
\]

(5)

B_R and \( \eta \) indicate the radar pulse width and incidence angle respectively.

Resolution in range direction is determined by transmitter and receiver. Making pulses narrower as possible is the main limitation of resolution in range direction. In other words, the constraint of resolution reduction is in the making transmitted pulses narrower.

Azimuth Resolution: Typically the resolution of a system is defined to be the following [6]:

\[
\delta_s = \frac{L_{\text{uz}}}{2}
\]

(6)

L_{uz} is a marker as the antenna length in the azimuth direction. The term is derived from the equation \( \theta_H = \frac{\lambda}{L_{\text{uz}}} \) to estimate the beam width.

It is necessary to decrease the antenna length in the payload movement direction (azimuth) in order to improve the resolution in the azimuth direction.

Antenna Dimension: One of the primary limitations on the antenna area requirements arise from the initial analysis of the ambiguities in the range and azimuth.

In order to prevent ambiguities caused by targets returns and covered area composition in the range and azimuth direction we can conclude to express minimum antenna dimension as follows:

\[
A_{\text{eff}} \geq \frac{4V_s \lambda \tan \theta}{C}
\]

(7)

where \( V_s \) correspond to the satellite velocity, \( \lambda \) is wavelength, \( C \), \( \theta \) and \( A_{\text{eff}} \) correspond to light velocity, incident angle and minimum antenna dimension respectively.

Mentioned equation indicates that wavelength, incident angle and satellite velocity are highly effective in the determination of the minimum antenna dimension. Note that the minimum dimension is independent of other parameters, such as resolution or sensitivity.

Ambiguities in Range and Azimuth Direction: SAR radar is designed to be able to transmit the successive pulses and obtain return signals. This continuous frequency sampling is called pulse repetition frequency (PRF). Since sample data from the Doppler by SAR must be such that there are no adverse effects on the image, therefore the radar needs to satisfy the Nyquist sampling and hence we have:

\[
\text{PRF}_{\text{min}} = \frac{2V_s}{L_{\text{uz}}}
\]

(8)

Here \( V_s \) is the satellite velocity. Continuous sampling of artificially effect imposes ambiguities in range and azimuth on the SAR. For SAR carrier spacecraft, PRF is high(>1000). Note that rapid movement of spacecraft in
LEO orbit (about 7km/s), leads to high height, large illumination area on the ground and many simultaneous transmitted pulses in the air. Therefore, there is a possibility of collision between multiple pulses. Return echoes from different pixels of the ground, reach the SAR antenna simultaneously. This artificial effect in SAR caused ambiguities in range direction. Regarding the confidence of avoiding ambiguity in range direction due to the half-power beam width, PRF should satisfy the following conditions:

$$PRF_{max} = \frac{cW}{2\rho_m \lambda \tan \theta}$$  \hspace{1cm} (9)

W is antenna width, \( \lambda \) wavelength, \( c \) light speed, \( \theta \) incidence angle, \( \rho_m \) slant range, between SAR antenmean and middle point of narrow strip. When the above conditions are satisfied, ambiguities of signal in the range direction related to returned signals will be less.

**Minimum Power:** Another condition is that the signal received by the SAR antenna must be able to supply enough power to possess reasonable SNR. Accordingly the received power by the receiver expressed as

$$P_r = \frac{P_t G_r}{2\pi R^2} \sigma \frac{1}{2\pi R^2} G_r \frac{\lambda^2}{4\pi}$$  \hspace{1cm} (10)

where \( P_t \) is radar receiver power, \( P_t \) is radar transmitter power, \( G_t \) is transmitter power gain, \( R \) is transmitter slant range to the target, \( R \) is slant range between target to receiver, \( \sigma \) is reflector radar cross section and \( G_r \) is receiver power gain.

Precise look at above equation reveals the critical role of radar distance from target or \( R \). As you can see, in this equation the power received by the receiver has inverse relationship with \( R \) biquadrate. Contrary to the direct path communication (When the transmitter and receiver are placed opposite each other) that received power has inverse relationship with \( R \) square. It can be seen that the received power level at the receiver, to what extent can be less. Another consequential parameter in the above equation is the direct relation of recursive power level from target with radar cross section or its \( \sigma \).

Hence comparing the above equation with respect to any of the direct path signal can be concluded that, there is only two way for having detectable power in the receiver (providing fixed distance traveled by the signal and fixed frequency carrier signal), first increasing radar cross section targets and second enhancement of transmitter and receiver antennas gain. As you know, targets radar cross sections are not in the designer hands and depending to their applications are imposed. So the only way left is to use antennas with high gain. Therefore, no trace of the SAR satellites can be considered in simple and small antennas with low gains in SAR system.

**Frequency Band Selection:** Selecting central frequency of the system is one of the essential parameters. This selection is based on usage, required resolution and available technology. Most satellites carrying SAR sensors based on the extent of user area use L, C and X frequency bands. Although in some applications P frequency band is also used but it won’t have spatial use due to the long length of antenna needed in the high frequency band. The use of higher X frequency band to design and manufacture needs high technology which is one of the bottlenecks designing. In L frequency band the wavelength is large and causing higher wave penetration leading to use these images in forestry, geology application and etc. Increased permeability is in contrast to resolution therefore we won’t have low-resolution radars in this band. Higher resolution is achievable in X frequency band due to the more availability and bandwidth (for example TerraSAR-X uses bands higher than 300 MHz), technological Maturity in spatial domain, subsystems and elements designing in this frequency band. C frequency band is the band of frequency between two bands providing a moderate range in order to achieve resolution and penetration. This band has been the main choice for many of the SAR systems such as ERS-1, 2 and ENVISAT for 15 years [8].

**Polarization:** Polarization is an electromagnetic wave characteristic describing vector geometric location of the electric field as a function of time. If a wave is completely polarized, its locus could be limitedly in an elliptical or circular or linear form called elliptical, circular or linear polarization. Most image radar using the linear polarization, this kind of polarization can be divided into vertical and horizontal sections. Radar sensors are often designed in such way that has the ability to transmit and receive signals up to one of the two forms mentioned. In general, we consider four combinations of radar polarization:

- Horizontal transmission and horizontal reception (HH)
- Vertical transmission and vertical reception (VV)
- Horizontal transmission and vertical reception (HV)
- Vertical transmission and horizontal reception (VH)
Table 1: A SAR sensor design requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>3 x 10^6 m/s</td>
<td>Light rapidity</td>
</tr>
<tr>
<td>BW</td>
<td>100 MHz</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>( \dot{t} )</td>
<td>10 nsec</td>
<td>Pulse width</td>
</tr>
<tr>
<td>H</td>
<td>630 km</td>
<td>SARs satellite height</td>
</tr>
<tr>
<td>V</td>
<td>7.345 KMS</td>
<td>Satellite rapidity in orbit</td>
</tr>
<tr>
<td>SWATH</td>
<td>30 km</td>
<td>Satellite ground pass</td>
</tr>
<tr>
<td>FREQ. BAND</td>
<td>X</td>
<td>Frequency</td>
</tr>
<tr>
<td>RANGE RES/ AZIMUTH RES</td>
<td>5 meter 3 meter</td>
<td>Range and azimuth resolution</td>
</tr>
</tbody>
</table>

Implementation and Simulation of a SAR Sensor: In this paper, methods of compromise between some technical requirements proposed and constraints on the design of a prototype SAR sensor in X band investigated. Then the best solution for our design can be expressed with respect to considered requirements. These diagrams are able to provide perfect view of fluctuations proceeding and compromise between them for a designer. Assumed requirements for designing and compromise between them are indicated in Table 1 as follows:

Imaging geometry of the SAR space radar is shown in Table 1. Physical aspects of SAR phased array antenna associated with width \( W_a \) and the length is related to \( \theta_v \) and \( \theta_h \), called vertical and horizontal tilt angles respectively. Equation 10 shows this relationship.

\[
\theta_v = \frac{\lambda}{W_a} \tag{11}
\]

\[
\theta_h = \frac{\lambda}{W_a} \tag{12}
\]

where \( \lambda \) is the wavelength of transmitted signal. According to equation (12) satellite land strip width expresses as follows:

\[
SWATH = \frac{\lambda R}{W_a \times \cos \theta} \tag{13}
\]

whereas \( \theta \) is incident angle of antenna transmitted wavelength radiation. Here \( R \) is incident range obtaining from following formula:

\[
R = \frac{h}{\cos \theta} \tag{14}
\]

His the satellite height. Substituting (13) in (14) equation (15) will obtain:

\[
W_a = \frac{\lambda h}{SWATH \times (\cos \theta)^2} \tag{15}
\]

Resolution range could be calculated considering equation (14):

\[
\delta R = \frac{c}{2B_R \sin \eta} \tag{16}
\]

\( B_a \) and \( C \) are pulse and light speed respectively.

Now we can calculate the amount of memory needed in order to determine the bit rate. According to (14) we have:

\[
Data Rate = 2 \times SWT \times PRF \tag{17}
\]

SWT compute as follows:

\[
SWT = \frac{2 \times SWATH \times \cos \psi}{C} \tag{18}
\]

where \( \psi \) corresponds to supplementary angle to \( \theta \). Therefore having 30 degree of tilt angle, \( \psi \) value will equal to 60 degree. Substituting corresponding values in equation (16), SWT will be 100 microsecond. With respect to equations (18) and (19), system PRF value will be calculated as:

\[
PRF_{\text{min}} = \frac{2 \times V}{La} \tag{19}
\]

\[
PRF_{\text{max}} = \frac{C \times Wa \times \cos \theta}{2 \times \lambda \times h \times \sin \theta} \tag{20}
\]

Hence we have PRFmin=2.515 kHz and PRFmax=10 kHz, substituting these values in (15), the bit rate will be obtained:

Data Rate\(_{\text{min}}\) = 251.5 Mbps

Data Rate\(_{\text{max}}\) = 1 Gbps

Therefore, image data storage rate of payload onboard memory can be determined. If we want to image from STRIPMAP imaging mode to 1000KM \times 30KM dimensions, then [9]:

\[
t = \frac{1000 km}{7.454 km/s} = 132.5 \text{sec} \tag{21}
\]

Required time for imaging of the strip is equal to 132.5 seconds. It is obvious that requisite satellite onboard memory value in order to store data of this strip is equal to 33.4 Gb and 132.5 Gb for PRF\(_{\text{min}}\)and PRF\(_{\text{max}}\) respectively. Regarding to desired height and satellite exposure average time in earth station view for 6 min, data transmission rate will calculated as follows[10]:

\[
\text{Data Rate} = 2 \times \text{SWT} \times \text{PRF} \tag{17}
\]
Figure 2 illustrates this increase and its rate with 3m constant resolution.

However, Figure 3 shows data transmission rate fluctuations while both azimuth and range resolution are increasing.

Then substituting equations (17), (18) and (20) in (16) equation (21) will acquire:

\[ B_R = \frac{c}{2 \delta_a \sin \theta} \]  

(21)
As proved there is no significant relationship between image data transmission rate with PRF\textsubscript{min} and antenna tilt angle (\(\theta\)). On the other hand substituting equations (17), (19) and (20) in equation (16) yield (22) and (23).

\[
\text{DataRate}(\text{PRF}_{\text{min}}) = \frac{4 \times N \times \text{swath} \times V_s}{\delta_a \times L_a}
\]

(22)

\[
\text{DataRate}(\text{PRF}_{\text{max}}) = \frac{N \times \text{swath} \times c \times W_a \times (\cos \theta)^2}{\delta_a \times \sin \theta \times h \times \lambda}
\]

(23)

In (23) image data transmission rate with PRF\textsubscript{max} is related to antenna tilt angle (\(\theta\)), this relationship is shown in Figure 4.

Figure 3 indicates that data storage rate highly reduced as tilt value increased. With respect to Figure 2, we will find that transmission data rate is decreased with azimuth resolution enhancement, so that concerning a resolution equal to 5 m, the data transmitting rate is at Gigabits per second(Gb/sec) and concerning a resolution equal to 50 this data transmitting rate will decrease to 10 Megabits per second. Figure 3 illustrate this point while both azimuth and range resolution is varying. Comparing Figure 2 and 3 reveals that data transmitting rate in higher in Figure 2 due to the constant azimuth resolution equal to 3m. but Figure 3 shows more reduction in data transmitting rate both azimuth and range resolution increase e.g. keeping 3m azimuth resolution and PRF\textsubscript{min} constant for 15m resolution, transmitted data rate will equal to 40 Megabits per second(Mb/sec) whereas this is reduced as both resolutions increase simultaneously according to Figure 3. Figure 4 shows the variation of data transmission rate against tilt angle. It is considerable in the figure that antenna tilt angle has great influence on data transmission rate and can also affect data transmission volume. In order to keep data transmission rate constant and designing satellite link budget, a mechanism should be adopted in case of PRF\textsubscript{max} use to leave no influence on data transmission with any increase or decrease in tilt angle. Available way to prevent this problem is PRF\textsubscript{max} use which is independent from antenna tilt angle according to equation (5) [11].

Regarding Figure 5, findings analysis unveil range resolution reduction as tilt angle increases and lead to better resolution (antenna orientation is correspondent to figure 1). This chart t is indicating that imagery at an angle less than about 15 Nadir degree is not applicable due to the worst resolution based on the resultant diagram. On the other hand for angles maximum over 15 degree no resolution decrease effect is see. This indicates that data rate over 75 degree has no efficacy and just leads to satellite power increase.

As noted above, one of the key points in the design of SAR satellite payload is antenna dimensions in order to satisfy minimum antenna dimension requirement to avoid ambiguities in range and azimuth direction. So the dimensions of the antenna to achieve determined resolution of the SAR radar payload design are quietly consequential, because by using those weight and dimensions of the payload can be estimated. Figure 6 enables system designers to achieve antenna width by take a look at three frequency band L, C and X. this figure represent that larger antenna should be used in L band than C and X.
Fig. 5: Range resolution against antenna tilt angle.

Fig. 6: Antenna width against tilt angle for three different bands.

Fig. 7: Relationship between antenna width, range and azimuth resolution according to tilt angle.
Figure 7 represents the relationship between antenna width, range and azimuth resolution for three-frequency bands X, C and L according to tilt angle (antenna orientation is correspondent to figure 1). Thus, the application of X-band antenna to use smaller size is more efficient. It should be mentioned that the use of X frequency band needs more power in comparison with L and C bands; hence a compromise should be done between antenna dimension and power in each frequency bands. Also, the rate of antenna length variation according to tilt angle demonstrates that smaller angles should be used in order to obtain more appropriate length of the antenna.

CONCLUSION

This paper presents the most principal requirements and constraints in designing and their effects of each and then the necessitous compromise between some of these is investigated in order to achieve the best design. After introducing the design requirements, a prototype SAR sensor was investigated. Analysis of findings reveals that data transmission rate with PRF\_m is independent from antenna tilt angle (\(\theta\)) but on the other hand it is dependent to PRF\_m, afterward its relationship was analyzed. Drawn diagrams approved presented design and calculations. Other substantial parameters in designing a SAR sensorsuch as antenna dimension, antenna tilt, range and azimuth resolution is achievable as considerable elements in systematic designing according to the result of present paper. With respect to represented graphs we can find out that antenna tilt angle should not be more than 15 up to 60 degree.

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