ANALYSIS OF SAR MAIN PARAMETERS FOR SAR SENSOR DESIGN ON LSA

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Abstract. LAPAN plans to conduct a flight test of LSA (LAPAN Surveillance Aircraft). LSA STEMME-S15 is capable of carrying sensor payloads up to 160 kg that are mounted on both sides of the wings with altitude between 400-2000 m. LSA can be designed to perform imaging by using optical sensors and SAR (Synthetic Aperture Radar). Compared to imaging using optical sensors, SAR sensor has advantages such as it can operate all day and night, able to penetrate clouds, and able to see objects from side looking, while optical sensors generally see the object perpendicular to the ground. Therefore the use of SAR imaging technology can complement optical imaging technology. To design SAR system imagers on LSA, it is necessary to simulate the primary parameters SAR i.e. altitude and look angle of sensor, speed of LSA, SAR frequency and signals power shot to object to calculate the resolution of azimuth and ground range values that can be obtained. This SAR parameters simulation used MATLAB which have been designed with two approaches; the first approach where the SAR sensor is ideal and in which all the fundamental parameters (such as polarization, frequency, etc.) are used to generate the desired sensitivity and resolution of azimuth and ground range, and the second approach is where SAR sensor is designed in a limited antenna size (constraint case), with the assumption that the dimensions of the antenna and the average available power are fixed. The data used in this simulation is a pseudo-data obtained from LSA technical spesification and SAR sensor. The simulation results with the first approach shows that if LSA is flying at an altitude of 1000 m, with speed of 36.11 m/s, and SAR frequency of 5.3 GHz, then to get resolution of azimuth, slant range and ground range of 1 m, 1.2 m and 3 m, it is necessary to design the length and width of SAR antenna at 2 m and 13.5 cm, with look angle of 23.5 degrees. While the result of second approach simulation is that if LSA is flying on the same altitude and speed, on the same look angle and SAR frequency, with a particular design of antenna length and width of 2 m and 13.5 cm, then azimuth, slant range and ground range resolution of 1 m, 1.87 and 4.79 m will be obtained. Form both simulations, it can be concluded that limited SAR system on LSA, especially on the technical aspects of mounting and space as in the simulation with the second approach, will produce slightly lower slant range and ground range resolution when compared with SAR system in the first simulation. This shows that space limitation on LSA will affect decrease the value of spatial ground range resolution. The simulation results are expected to be inputs on designing SAR imaging system on LSA.

Keywords: Synthetic Aperture Radar (SAR), LAPAN Surveillance Aircraft (LSA), SAR parameters

1 INTRODUCTION

Synthetic Aperture Radar (SAR) technology has been proven to be a reliable tool in observing the Earth and providing data and information of high-resolution imagery for object and surface target through a moving aircraft. Unlike optical sensors and infra-red, the SAR has the ability to operate day and night regardless of the weather and solar lighting (Skolnik, 2001; Skolnik, 2008). The main reason many parties use SAR technology is, unlike optic sensor, the quality of the imagery is not dependent on the weather or availability of light. In this case, SAR imaging system is considered to have advantages over optical imaging system (Musawwar, *et al.*, 2008).

Airborne platforms are more flexible than satellite missions for developing and testing data fusion at fine spatial (1 to 10 m) and spectral resolutions, which have prompted a new generation of LiDAR, SAR and imaging spectrometer instrument packages (Asner, 2012; Kampe, 2010). Airborne platforms offer specific advantages for the study of terrestrial ecosystem, including targeted acquisitions of seasonal and diurnal processes (e.g., wetland inundation, plant phenology, drought and fire impacts) and coordinated field and remote sensing data collection needed to scale process-level understanding to the scale of airborne and satellite remote sensing observations (Chambers, 2007).

Technology and method of SAR data using have been developed for many applications in Indonesia, such as forest monitoring to support the Indonesian National Carbon Accounting System (INCAS) program and other emergency missions (such as tsunami, floods, landslides early warning systems, etc.). Potential applications of SAR data for forest monitoring is very high, especially for observing forest destruction and degradation. SAR data specifications needed for forest monitoring is SAR data of C-band frequency, HH, VH, and VV polarization with spatial resolution ranges between 15~30 m and 1~3m (Tjahjaningsih, *et al.*, 2009). Stages of SAR data processing include image processing, geometry conversion and processing of related applications.

LAPAN and TU-Berlin are developing LAPAN Surveillance Aircraft (LSA) STEMME S15 that can be flown with a load weighing 70 kg on each wing at an altitude of 400-2000 m that can be applied to optical remote sensing or SAR (Hakim, *et al.* 2012). One important part in designing SAR sensor on LSA is determining the main parameters associated with the spatial resolution (ground), the resolution of azimuth and range, the speed and altitude of spacecraft, incident angle and so on. These parameters should be clearly defined prior to design a SAR sensor system on LSA. This article intends to describe the analysis of the main parameters in designing a SAR sensor on LSA. This analysis is expected to be inputs in designing the SAR sensor placed on LSA spacecraft.

2 SAR IMAGING SYSTEM ON LSA

2.1 SAR Geometry on LSA

Figure 2-1 illustrates the simple geometry of a side-looking LSA SAR geometry showing the relationship between altitude (h), incident angle (θ_i) and beam width (γ). The radar mounted on a LSA platform moves at velocity (v), with a near circular orbit on constant altitude. Radar beam leading up to the object is perpendicular to the orbit and the flat surface of the earth below it (Soleh, *et al.*, 2014). In this case, the LSA SAR STEMME-S15 is simulated to be flying at an altitude of 400-2000 m with a speed of 36.11 m/s.

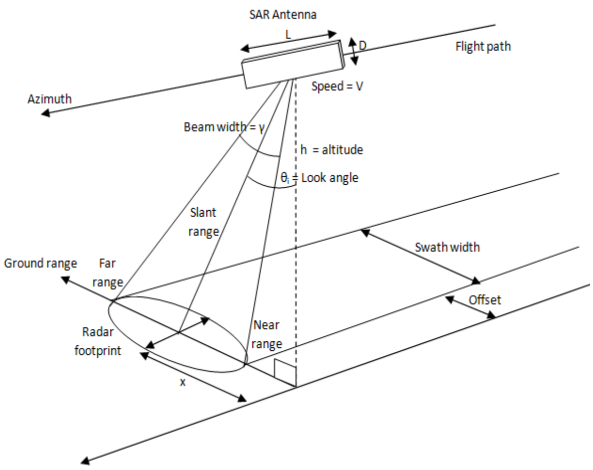


Figure 2-1: The simple geometry of the side looking SAR system

Look angle or incident angle is the angle between radar beam and normal to the surface of the earth at a certain point. This angle is important because it affects the radar cross section hitting the target area (in general, a smaller incident angle produces a larger backscatter power) but reduces ground range resolution and swath width (which will increase with greater incident angle). In the radar beam area between γ_{near} and γ_{far}, the system must be able to reach the area in question. Note that by enlarging the incident angle, it can lead to reduced system access time to the desired area. Thus, the initial value of incident angle is set between 20° - 30°. And then we can calculate the slant range distance.

2.2 Resolution Range

One of the starting points for any radar design is the radar range equation, which relates the signal to noise (SNR) at the receiver with the target's radar cross section, its distance to the radar and a number of system parameters. For a SAR system, a useful expression is the single look signal to noise (Ulaby *et al.*, 1982).

On a SAR system, ground range resolution is expressed as $\delta_r = c/2B \sin \theta_i$ where c is the speed of light, B is the band width of radar pulse and θ_i is the incident angle. Due to technological limitations, the range resolution can be enlarged by increasing the bandwidth of the radar pulse but it also reduces the sensitivity. Range resolution is also affected by the size of incident angle, but a too large incident angle tends to reduce the radar cross section in normal direction. The relationship between the slant range and ground range is illustrated in Figure 2-1. The center of slant range can be found with $R_c = h^2 + x^2$ equation where h is the height and x is the distance from nadir to the center of footprint, and the size of beam width range can be found with $a_r = \lambda/D$ equation where λ is the wavelength of the C-band radar, and D is the diameter of the SAR antenna.

2.3 Azimuth Resolution

The magnitude of the azimuth resolution from SAR system is approached with $\delta_a = L/2$ equation or half of the length Lof SAR antenna. This equation also produces azimuth beam width value of $a_a = \lambda/L$ where λ is the wavelength of the C-band radar and L is the length of the SAR antenna.

2.4 Synthetic Antennas

In the SAR system, the length of synthetic antenna depends on the size of azimuth beam width multiplied by the slant range distance. In this case, the length of synthetic antenna can be found with $L_{sa} = \delta_a \cdot R$ where δ_a is the azimuth beam width and R is the slant range distance. Because of $\delta_a = \lambda/L$, then we can state that $L_{sa} = \lambda R/L$ where λ is the wavelength of the C-band radar, R is the slant range distance and L is the length of the SAR antenna.

Once the sensor and the main parameters of SAR are designed on LSA, the next step is to simulate the SAR system parameters which will be calculated. Basically, the input parameters are divided into three types; parameter of SAR geometry, parameter of SAR sensor configuration and parameter of SAR imagery quality. The first parameter is the geometry of SAR, including the length and width of the antenna, altitude and speed of the platform, incident angle, azimuth and range beam width, the total distance of azimuth, distance of slant range, minimum and maximum of slant range, ground swath and the length of synthetic antenna. The second parameter is the configuration of the SAR sensor including frequency of carrier signal (carrier), baseband bandwidth, width of chirp signal, PRF (pulse repetition frequency), peak power output, the antenna gain (gain), wavelength, desired sigma 0, signal power, noise power, SNR (signal to noise) per signal. The third parameter is the quality of SAR imagery including the slant range, azimuth and ground range resolution and imagery size (Soleh, *et al.*, 2014).

2.5 LSA Polarimetric SAR

LSA polarimetric SAR is designed to operate in C-band frequency with quad-polarimetric capabilities (HH, HV, VH and VV) that is placed on LSA-STEMMES15. LSA is a light aircraft with a maximum of two passengers that can be loaded with remote sensing sensor to observe the Earth's surface. LSA is equipped with mounting for placing payload (sensors) of remote sensing under the body and two pieces under the right and left wings (Hakim *et al.*, 2012). Specifications of complete LSA SAR polarimetric can be seen in Table 2-1.

Table 2-1: Specifications LSA SAR Polarimetric STEMME S15

Specification	Unit
Total Length	8.52 m
Total height	2.45m
Wing span	18m
Max Payload Weight under each wing	70kg
Max baggage weight	20kg
Velocity	36.11 m/s
Operating altitude	400m – 2000m
Max. Range	1300km

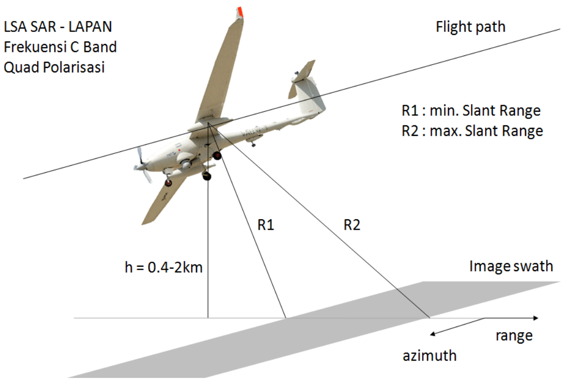


Figure 2-2: Geometry of LSA polarimetric SAR

Operation mode of SAR stripmap is capable of producing high-resolution wide image with a relatively small antenna by moving the antenna to move target/object with constant velocity. A smaller aperture will produce beam to a target at long distances. An antenna platform that moves in x direction ath height from target, will affect the number of beams that can be sent received by the antenna (see Figure 2-2).

Monitoring Earth with side looking SAR system on LSA can be operated in stripmap mode with look angle of 25 - 60° at an altitude of 400-2000 mdpl. Technically this look angle can be operated more than 60°. SAR system uses a Linear Frequency Modulated (LFM) wave called chirp signal. The radar transmits a lot of waves with separated frequency bandwidth of 100 MHz in Pulse Repetition Interval (PRI) or as an inverse of the PRI called Pulse Repetition Frequency (PRF). Range resolution is determined by the 100 MHz band width system. It means that the SAR system can generate the highest range resolution of 1.5 m. While the azimuth resolution obtained is 0.35 m which is the half of the length of the antenna of 0.7 m.

During the signal reception duration, the antenna is waiting to receive radar signals reflected from the target in the form of a one-dimensional range pieces echo as a function of speed of time. Radar signal received in the form of raw SAR data is assumed to be a baseband signal after quadrature demodulation by eliminating the carrier frequency signal. Quadrature demodulation triggers imaginary signals and has quadrature phase and magnitude.

2.6 Design of SAR Sensor on LSA

SAR LSA system consists of two subsystems: antenna subsystem and SAR signal acquisition module. SAR acquisition signal subsystem consists of radar electronic and data acquisition modules. Figure 2-3 illustrates the interconnection module of SAR system on LSA.

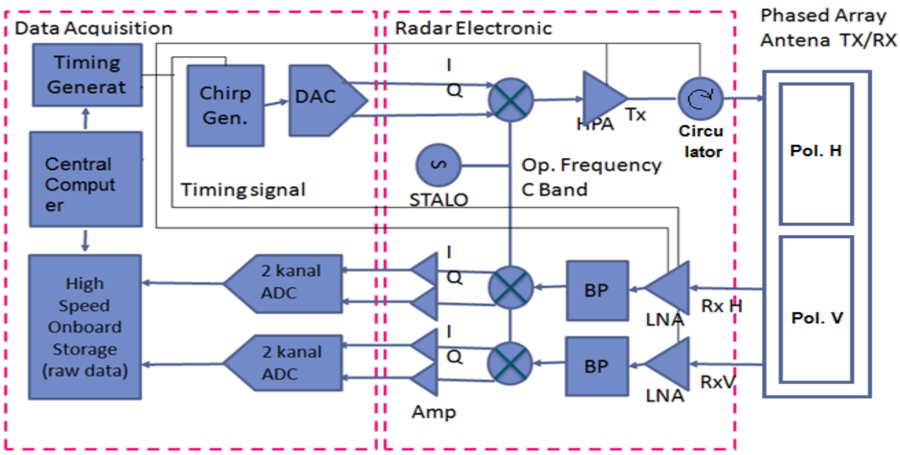


Figure 2-3: Hardware architecture of LSA polarimetric SAR

Antenna design used in this system is phased array with quad-polarimetric capabilities. The signal is transmitted in H or V linear polarization. Backscattered signals are received by an antenna with horizontal and vertical polarization and videos are digitized with high-speed 4-channel ADC for every polarization, each divided into two signals; in phase (I) signal and quadrature (Q). Furthermore, the SAR raw data from each polarization of H and V is stored in the navigation data with high speed data storage.

Table 2-2: Characteristics of LSA SAR

SAR Parameters	Unit
Operating Frequency	5.3 GHz
Chirp/Baseband Bandwidth	80 MHz
PRF	600Hz
Azimuth resolution	1 m
Range resolution	1.2 m
Ground Range Resolution	3 m
Look angle	23:57 deg
Width	510 m (altitude of 1000m)
Sampling	4 channels, 250Msps, 12bit

Multi-polarization SAR phased array antenna is placed on a certain mounting (pod) located under the left wing of LSA STEMME-S15 aircraft (see Figure 2-4). SAR antenna is placed outside the pod. The advantage of this design is the freedom in operating the antenna with certain look angle and the ease in changing the antenna configuration. The SAR acquisition system is placed inside the pod. The LSA SAR operating system with stripmap mode has several characteristics that can be seen in Table 2-2.

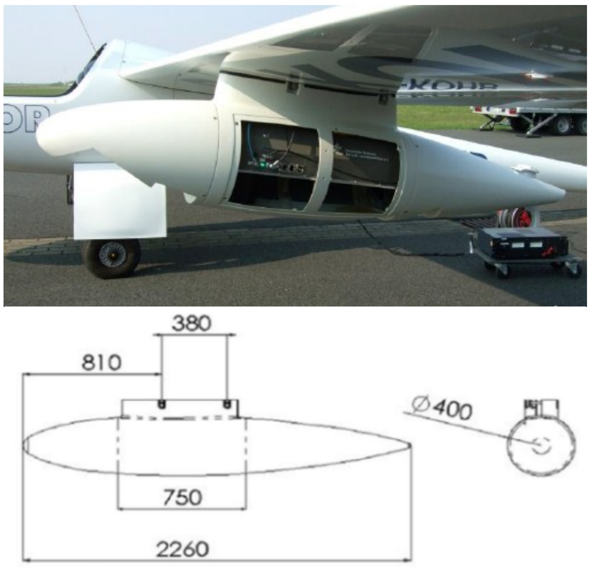


Figure 2-4: SAR Sensor Mounting on LSApod

There is only one computer in the acquisition of SAR data which controls the radar signal generator (chirp), receives radar signals from the backscattered target with a high-speed ADC and sets time synchronization for transmission and reception of SAR signals. In each of the SAR system, time synchronization has a very important role because it controls everything that happens in the system before sending and receiving chirp signals. This synchronization is repeated on each time interval (PRI=1/PRF). Chirp signal is transmitted in a horizontal polarization and then received by both multi-polarization antennas with time delay of τ_D.

$$\tau_D = \frac{2R}{c} \quad (2\text{-}1)$$

If bandwith chirp (B) is 80 MHz, then the range resolution can be calculated by

$$\delta_r = \frac{c}{2B} = 120 \text{ cm} \quad (2\text{-}2)$$

Azimuth resolution, can be expressed as

$$\delta_a \geq L_a/2 \quad (2\text{-}3)$$

WhereL_a is the length of the antenna. Before the chirp signal is transmitted, the signal is amplified in advance by High Power Amplifier (HPA) in the radar electronic module. It is necessary to obtain adequate signal for strengthening the signal to noise ratio (SNR) at the receiver antenna.

3 METHOD

3.1 Tools, Materials, and Data

In this research, the tools used to perform simulations are computer hardware and programming simulator using MATLAB. The data used for simulation is a pseudo-data in the form of values as shown in Tables 1 and 2. Considering the trade-off among SAR parameters as mentioned above, in this case we have produced a SAR mission design simulation that will be orbited. This design simulation is in accordance with the standard of strip map SAR operating mode. Because of the limited scope, this new study is only done for first order optimization.

3.2 Simulation Approachment

In this study, two possibilities have been considered with two assumptions:

- LSA SAR sensors under ideal case, assuming all input parameters are in the form of a number of fundamental parameters (such as polarization, frequency, etc.), are used to generate the desired sensitivity and resolution of azimuth and ground range. The main focus of this first approach is setting the azimuth and ground range resolution in early stages as the main parameter indetermining the design of SAR sensor system to be built in the form of dimension/sizeof SAR antenna required to obtain resolution as mentioned above.
- LSA SAR sensor under constraint case, assuming the antenna dimensions and available average power has been fixed. This procedure is useful for testing the mission carried on the process that might be done. It is considered to be more realistic for planning a mission in limited circumstances. The main focus of this second approach is establishing the dimension/size of SAR antenna (length x width) in accordance with the specifications of LSA aircraft, which is determined from early stages as the main parameter for obtaining optimum values of azimuth and range ground resolution.

Both approaches are done to see the effects of both simulations on SAR sensor system design prior to production, in this case the advantages and disadvantages of each simulation when applied to the SAR sensor system on an actual LSA.

4 SIMULATION RESULTS

On ideal cases as in the first approach, the desired fixed resolution of the azimuth and ground range direction can be obtained as shown in Figure 3-1. The simulation result of the first approach suggests that if LSA is flown at an altitude of 1000 m at a speed of 36.11 m/s, and 5.3 Ghz of SAR frequency, chirp pulse width of 10 µs and PRF (Pulse Repetition Frequency) of 600 Hz, peak output power of 20 Watts, then to obtain the resolutions of azimuth, slant range and ground range that are fixed respectively at 1m, 1.2m and 3m it is necessary to design the length and width of the SAR antenna respectively to 2m and 13.5cm with a look angle of 23.5 degrees, azimuth beam width of 1.6 degrees and a baseband bandwidth of 125 MHz.

However, LSA is designed for a limited antenna size due to consideration of mounting techniques and available space. Therefore, this situation led us to simulate the design with the second approach (for cases with constarint circumstances). The simulation with this second approach suggests that if LSA is to be flown at the same altitude and speed, with same view point and SAR frequency, same chirp pulse width, PRF (Pulse Repetition Frequency), and peak output power , with length and width of the antenna that has been fixed respectively at 2m and 13.5cm, it will obtain a resolution of azimuth, slant range and ground range of 1 m, 1.87 m and 4.79 m with an azimuth beam width of 1.6 degrees and a baseband bandwidth of 80 MHz as shown in Figure 3-2.

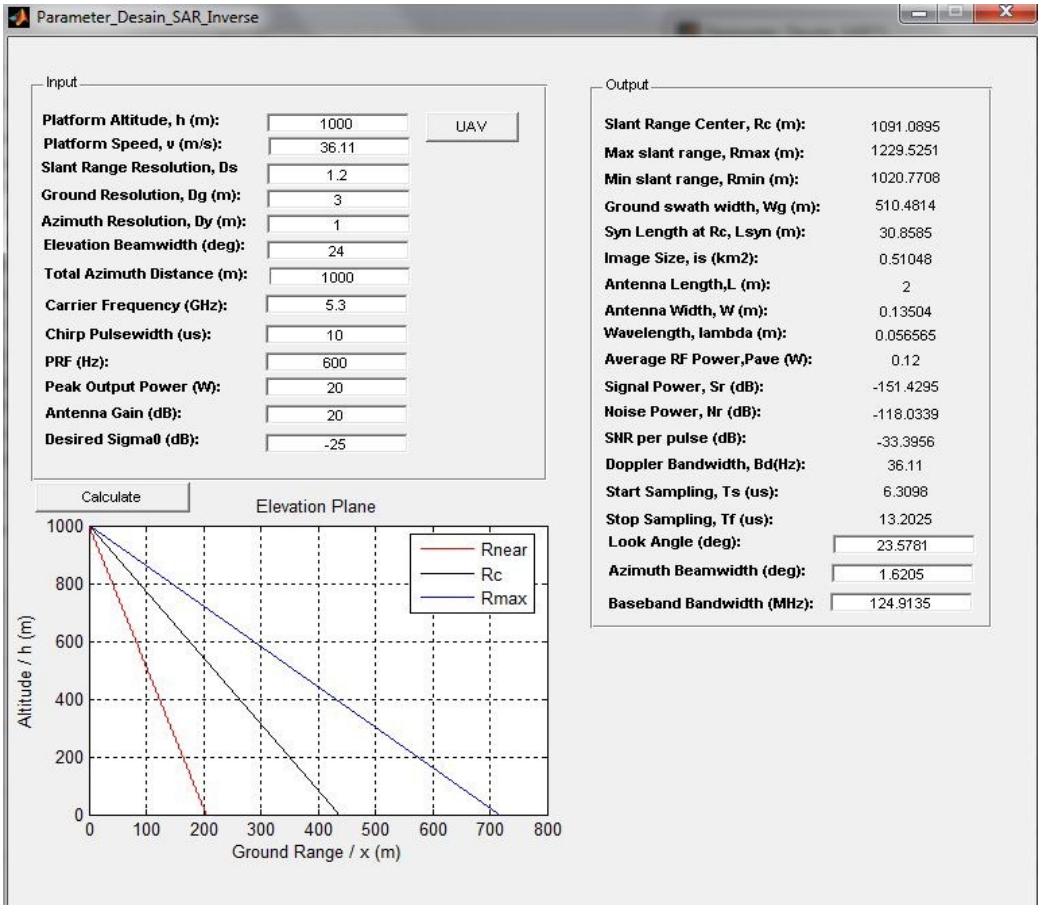


Figure 3-1: SAR parameters system simulation that is designed to obtain a fixed resolution

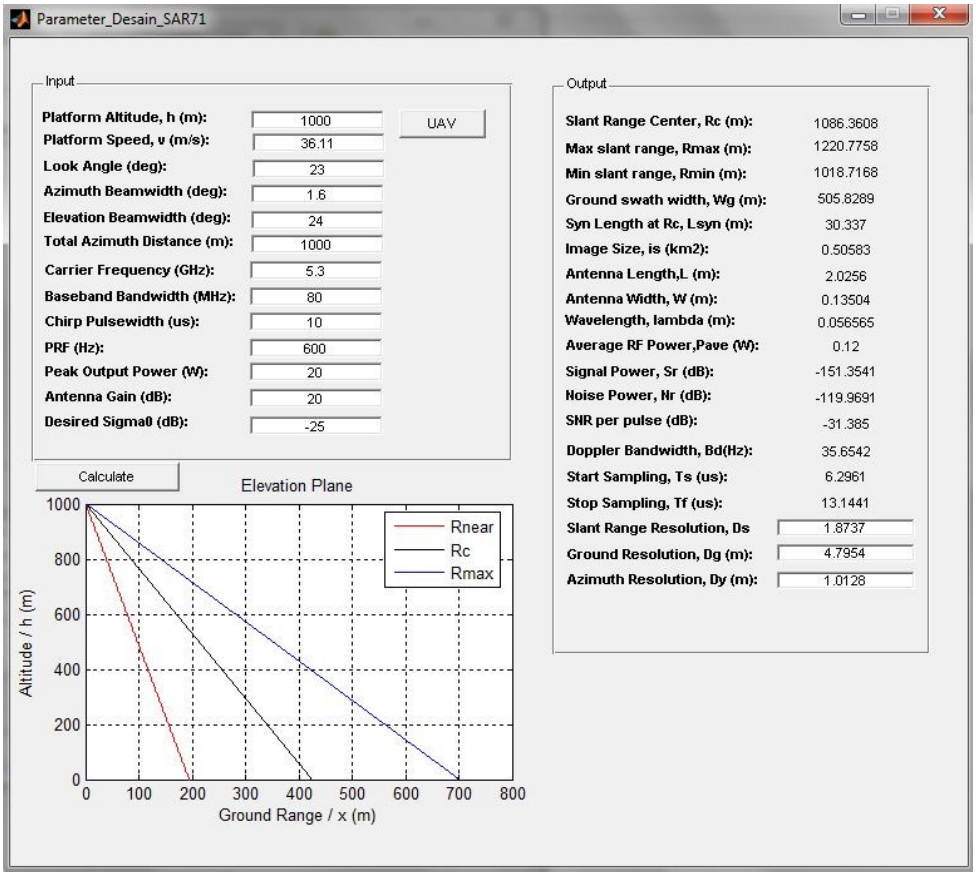


Figure 3-2: SAR system parameters simulation that is designed for limited antenna size

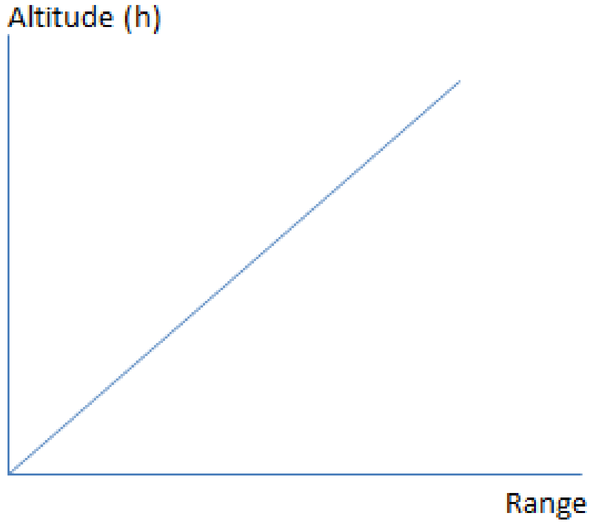
5 ANALYSIS AND DISCUSSION

As explained above, the parameters of SAR has been simulated with two possible models, the SAR parameter system design with desired fixed resolution and SAR parameter system design for limited antenna size. The first system is an ideal case which was designed withfixed resolution of azimuth and range to determine the look angle (deg), beam width azimuth (deg) and baseband beam width (MHz) on a SAR sensor. The second system is a case of limited antenna size (due to limited mounting on the wing of LSA) to determine the resolution of azimuth (m), slant range (m) and ground range (m). The simulation results of the first model for SAR design parameters with desired fixed resolution are shown in Figure 3-1 and the second simulation results for SAR design parameters with limited antenna size are shown in Figure 3-2.

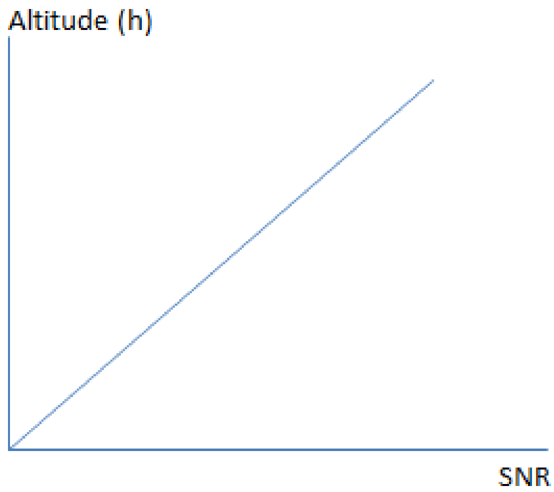
Of the two simulation approaches, itcan be concluded that SAR system limited to LSA, especially to the technical aspects of mounting and space as in the simulation with the second approach, will produce are solution of slant range and ground range which are slightly lower compared to the SAR system in first simulation. It shows that limited space availability in LSA lowers the spatial resolution value of slant range and ground range direction. The simulation results are expected to give useful inputs in designing SAR imaging system on LSA.

The results of main parameters simulation of SAR on LSA produced some initial conclusions that can be analyzed and give inputs in designing a SAR sensor system. Here are some important parameters analyzed in this simulation:

- The height *h* of flying LSA spacecraft strongly influences the range and SNR value. The greater the value of *h*, it will enlarge the range, but reduces the ratio of signal to noise or SNR as shown on the graph in Figure 4-1. Because the value of SNR is proportional to $1/R^4$, where R is the distance of sensor to the surface of the earth. In this case, to make SNR value acceptable, the antenna gain G must be increased or the magnitude of the transmitted power signal P_t should increase in accordance with $SNR = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4 k T_o B_n F}$ equation, where P_t is radar signal power, G is the antenna gain, λ is the radar wavelength, σ is the radar cross section, R is the distance of sensor to the surface of the earth, k is the Boltzmann constant 1.380658 x 10-23 JK^{-1}, T_o is the antenna temperature, and B_n is the bandwidth of the radar pulse and F is noise figure.



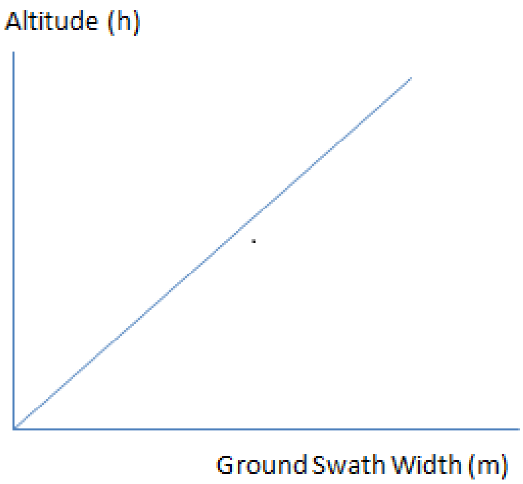
(a)



(b)

Figure 4-1: Comparison graph of altitude (h) to: (a) Range, (b) SNR

- Height h is proportional to the amount of ground swath width, but does not affect there solution amount of range and azimuth (Figure 4-2). The higher the LSA, the greater the value of ground swath width. However, the value of range and azimuth resolution will not change (fixed), this is because the value of range and azimuth resolution is only influenced by antenna length L and diameter D.
- The size of look angle or incident angle will affect the size of ground swath width and the resolution of ground range (Figure 4-3). The greater the incident angle, the greater the value of ground swath width and the resolution of ground range. The smaller the incident angle, the smaller the value of ground swath width and the resolution of ground range.



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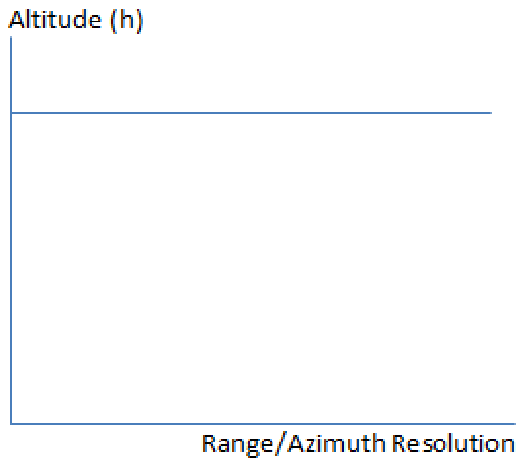
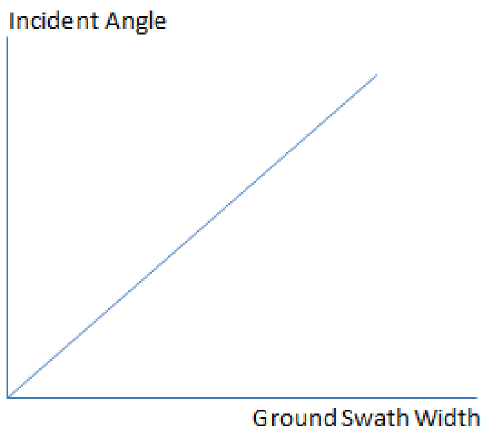
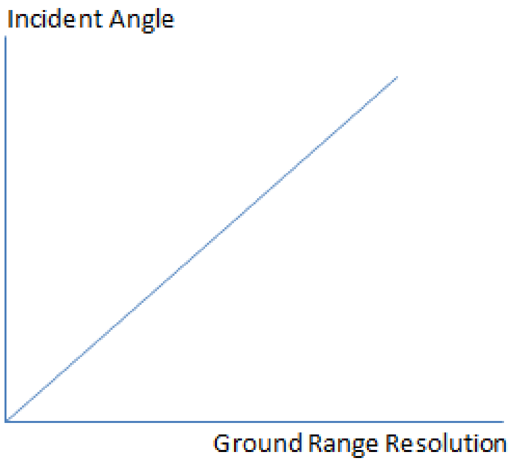


(b)

Figure 4-2: Comparison graph of altitude (h) to: (a) ground swath width, (b) range/ azimuth resolution



(a)



(b)

Figure 4-3: Comparison graph of incident angle to: (a) ground swath width, (b) resolution of ground range

- Range resolution is determined by the width of the transmitted signal's bandwidth. In this case, lowering the radar pulse bandwidth will reduce the value of the range resolution. And vice versa. But if the radar pulses bandwidth is increased, the effect is a reduction in sensitivity.
- Resolution of range and azimuth is affected by antenna length *L* and diameter *D*. Increasing the resolution of range and azimuth can be done by extending the size of the antenna, but other problems arise because it will increase the weight of the mounted antenna. For cases where space is limited, it should be avoided.
- The amount of frequency *f* and radar wavelength λ is determined by desired application and resolution and the availability/limitations of existing technology. In this case, desiringbetter signal penetration means that low *f* and long λ should be selected. Desiring a higher resolution means thathigh *f* and short λ should be selected. However, choosing a high *f* will complicate the technology.

6 CONCLUSION

SAR system has been designed and the main parameter of SAR sensor on LSA has been simulated. In this paper, the designs of SAR are calculated with two models, the first model is the SAR parameter system design to generate desired fixed resolution. The first design is very considerate of antenna size and weight and the amount of required power, for limited space on LSA, this design is not recommended. While the second model is SAR parameters system design with limited antenna size. This second design is considerate of maximum resolution that can be generated and the amount of required power, so for LSA case,this design is more appropriate to apply. The first system has been designed with fixed range and azimuth resolution to get the incident angle (deg), the azimuth beamwidth (deg) and baseband beamwidth (MHz) on a SAR sensor. The second system has been designed by the limited size of the antenna by considering mounting aspect for the instalation of the payload sensor on the LSA wing and generates range (m), slant range (m) and the azimuth resolution (m) values.

The main parameters has been simulated and analyzed for the benefit of the initial design of the SAR sensor system on LSA. Height parameter of flying LSA spacecraft strongly influences the range and value of SNR. The height of flying is proportional to the amount of range gained, but is inversely proportional to the value of SNR, so to overcome it, antenna gain and greater signal power. The height of flying is also proportional to the amount of ground swath width, but does not affect the amount of range and azimuth resolutions, since both there solutions are only influenced by the length and diameter of the antenna SAR. The amount of the incident angle value is proportional to the acquisitioned amount of ground swath width and ground range resolution. The speed of aircraft will be inversely proportional to the value of the PRF (pulse repetition frequency) which will affect the rate of data sent and received by the SAR antenna. Range resolution is determined by the width of bandwidth whose signals are transmitted. Reducing the bandwidth of radar pulses will reduce the value of the range resolution and vice versa. Enlarging the range and azimuth resolution can be done by extending the size of the antenna, but other problems arise because it will increase the weight of the mounted antenna. The magnitude of frequency f and radar wavelength λ is determined by desired application and resolution and the availability/limitations of existing technology. Better signal penetration is enabled by selecting low f and longλ . When a higher resolution is desired, then high f and short λ should be selected. However, if a high f is chosen, this will lead to complicated technology.

From the two simulation approaches, it can be concluded that for SAR system limited to the LSA, especially from the technical aspects of mounting and space as in the simulation with the second approach, lower slant range and ground range resolution is produced, compared to the SAR system in first simulation. This shows that the availability of limited space in LSA impacts on lowering the value of spatial resolution of ground range direction. The simulation results are expected to give useful inputsin designing SAR imagers system on LSA.

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REFERENCES

Asner GP, Knapp DE, Boardman J., Green RO, Kennedy-Bowdoin T., Eastwood M., Martin RE, Anderson C., Field CB, (2012), Carnegie Airborne Observatory-2: Increasing science data dimensionality via high-fidelity multi-sensor fusion. Remote Sens. Environ. 124: 454–465.

Asner GP, Knapp DE, Kennedy-Bowdoin, Jones MO, Martin RE, Boardman J., Field CB, (2007), Carnegie Airborne Observatory: In-Flight fusion of hyperspectral imaging and waveform light detection and ranging (wLiDAR) for three dimensional studies of ecosystems. J. Appl. Remote Sens. 1(1) 013536.

Chambers JQ, Asner GP, Morton DC, Anderson LO, Saatchi SS, Espírito-Santo FDB, Palace M., Souza C., (2007), Regional ecosystem structure and function: Ecological insights from remote sensing of tropical forests. Trends Ecol. Evol. 22 (8): 414-423.doi:10.1016/j.tree.2007.05.001.

Cumming IG, Wong FHC, (2005), Digital Processing Of Synthetic Aperture Radar Data: Algorithms And Implementation. Artech House.

Hakim, Ichwanul TM, Wahyudi, Wirawan A., Panjaitan LK, Anggraeni D., Wandono FA, (2012), Top Level Specifications For A Light Surveillance Aircraft. TechnicalReport, LAPAN.

Kampe TU, Johnson BR, Kuester M., Keller M., (2010), NEON: The First continental-scale ecological observatory with airborne remote sensing of vegetation canopy biochemistry and structure. J. Appl. Remote Sens. 4: 043510.

Mondejar AG, Dekker PL, (2009), Feasibility Study on SAR Systems on Small Satellites: by Project Advisor Barcelona, 1-84.

Musawwar MA, Rasyid F., Ahmed F., Tahir U., (2008), Mir. Analysis and Design of a Synthetic Aperture Radar System.Final Year Project 2007-08, Department of Telecommunication Engineering National University of Computer and Emerging Sciences.

Skolnik MI, (2001), Introduction to radar systems, 3rd ed. McGraw-Hill.

Skolnik MI, (2008), Radar Handbook, 3rd ed. McGraw-Hill.

Soleh M., Arief R., (2014), Analisis Parameter-parameter Utama untuk Desain Sensor SAR pada LSA. Prosiding Sinas Inderaja 2014.

Tjahjaningsih A., Kustiyo, Trisakti B., Komarudin MR, Sambodo KA, (2009), Kajian Spesifikasi Dan Aplikasi Satelit SAR (Synthetic Aperture Radar). Technical report, LAPAN.

Ulaby, F.T., R.K. Moore and A.K. Fung (1982). Microwave Remote Sensing, Vol. 2, Addison Wesley, Reading, MA.