Precise spaceborne SAR image formation technique based on the analysis of critical errors using the spaceborne SAR simulator

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ABSTRACT

This paper proposes the precise spaceborne synthetic aperture radar (SAR) image formation technique based on the analysis of critical error factors that severely degrade the SAR image quality. These are error factors related to the antenna beam pointing, the effective velocity, and the Doppler centroid. We newly developed the spaceborne SAR system simulator which is able to analyze effects that critical errors of the user-designed spaceborne SAR induce on a focused image. Using it, effects of critical errors are analyzed for spaceborne SAR image formation. Analysis results show that these cause phase distortion of raw data, distort the symmetry of the azimuth impulse response function (IRF) of point targets in the focused image, and defocus the SAR image. To resolve these problems, we suggest to make use of the phase gradient algorithm (PGA) to compensate phase distortion induced by antenna beam pointing errors. Also, the effective velocity of the illuminated beam and the Doppler centroid of spaceborne SAR raw data are exactly calculated by proposed methods using both orbit state vectors and the raw data acquisition geometry based on the newly defined two-way slant range equation model. Furthermore, azimuth block processing is used to reduce signal level of ambiguities produced by side lobes of antenna beam. The experimental results on the simulated SAR data show that proposed methods are able to reduce error effects as well as improve the focused SAR image quality greatly.

Keywords: SAR image formation, Error effect analysis, Spaceborne SAR simulator

1. INTRODUCTION

The spaceborne SAR system is the all weather-imaging active sensor that can acquire ground images of the earth day and night. Nowadays, most of spaceborne SAR systems require high-resolution image with a resolution below 1m. Therefore, very accurate SAR data processing techniques are needed to make high quality SAR images without errors.

Especially, effects of critical factors that may induce errors in the SAR image have to be analyzed precisely and processed properly for precise SAR data focusing. These factors are mainly related to the antenna beam pointing, the effective velocity of the SAR sensor, and the Doppler centroid. Inaccurate analyses of them induce degradation of the focused SAR image quality such as resolution loss, geometric distortion, contrast loss, and spurious targets.

In order to research and develop the precise spaceborne SAR processing technique, we have newly developed the spaceborne SAR system simulator which is able to analysis error effects of main factors related to the spaceborne SAR system. It is the software tool conceived to simulate and generate raw data acquired by the spaceborne SAR system. In particular, it provides simulated raw data produced by multi point targets taking into account different SAR acquisition modes (Stripmap, Spotlight and ScanSAR), and reproduces main SAR functionalities without considering system hardware choices. Furthermore, it is able to be used for the design of the real satellite SAR sensor, and to improve the scientific understanding of the complex radar backscattering behavior.

Main contribution in our work is also to develop the spaceborne SAR processing technique that can reduce error effects arising from inherent characteristics of the spaceborne SAR system used to achieve raw data, so retain reasonable quality at the same time. In our SAR focusing process, the technique to compensate phase error due to the antenna beam pointing is used. Next, the effective velocity and the Doppler centroid calculation methods using the two-way slant range equation model are suggested. Also, azimuth block processing is proposed to reduce signal level of ambiguities due to side lobes of antenna beam. These are based on simulations and analyses using the developed spaceborne SAR system simulator. The particular approaches used in our SAR focusing technique produce excellent results on focused SAR images.

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The rest of this paper is organized as follows. Section 2 introduces the developed spaceborne SAR system simulator. Section 3 and 4 describes error effect analyses and proposed processing methods related to the antenna beam pointing, the effective velocity of the spaceborne SAR sensor, and the Doppler centroid. Section 5 explains experimental results and performance analyses of proposed methods through computer simulations. Finally, Section 6 concludes this paper.

2. SPACEBORNE SAR SYSTEM SIMULATOR

2.1 Overall concept

For the precise SAR data focusing, we focus our attention on main error factors related to the antenna beam pointing, the effective velocity, and the Doppler centroid in case of the satellite SAR system. To analyze their effects that affect SAR focusing and focused images and get the accurate spaceborne SAR focusing algorithm, the end-to-end simulator of the spaceborne SAR system has been developed considering operations of the real spaceborne SAR system. In particular, it consists of mathematical models based on operation environment and system parameters of the real spaceborne SAR sensor. And it is able to generate simulated rawdata of point targets on the earth that is acquired from the satellite SAR system. Furthermore, because critical error factors of the spaceborne SAR system are modeled mathematically in the developed simulator, the performance of SAR image formation methods using generated rawdata is able to be tested and evaluated efficiently. And it can analyze various effects related to data processing to get a high quality SAR image. Also, through this, it can evaluate the overall performance of the user-designed satellite SAR system.

![Figure 1. Overall concept of the developed spaceborne SAR simulator](image)

Figure 1 shows the overall concept of the developed spaceborne SAR simulator which includes main characteristics of the real satellite SAR system. As shown in Figure 1, the developed simulator consists of several models such as the sensor dynamics/attitude model, the target observation model, the antenna beam pattern model, the antenna beam pointing model, the rawdata generation model, the image formation processing model, and the performance analysis model. In particular, when the SAR illuminates a beam on targets to get rawdata, various effects such as two-way antenna beam pattern, beam pointing errors and Doppler effects are reflected on generated rawdata. Also, it is able to simulate the dynamics/attitude operation on the orbit similar to the real spaceborne SAR sensor.

2.2 Developed spaceborne SAR simulation models

To develop and test the spaceborne SAR focusing algorithm, the developed simulator has various models that simulate main characteristics and operation mechanism of the real spaceborne SAR system. In this section, we describe briefly
main models of the developed simulator that have an effect on the performance of the spaceborne SAR focusing
algorithm.

1) Sensor dynamics/attitude model

This model defines the slow time vector to define radar timing according to the SAR acquisition mode. The Keplerian
orbital elements (orbit semi-major axis $a$, orbit eccentricity $e$, true anomaly $\nu$, orbit inclination $\alpha$, longitude of the
ascending node $\Omega$, and argument of perigee $\omega$) are used to define the sensor trajectory in the development of the SAR
system simulator, as shown in Figure 2. As orbital quantities, this model provides the sensor position and velocity
vectors in the Earth Centered Earth Fixed (ECEF) Cartesian coordinate. Also, the sensor geodetic pointing attitude in
terms of pitch and roll angles is modeled, and satellite SAR operations are conducted on the Kepler orbit.

2) Antenna beam pattern model

Using antenna excitation coefficients for both transmission and receiving and coefficients of the polynomial steering law,
the antenna beam pattern is modeled as shown in Figure 3, which is the same as the real satellite SAR sensor.
Furthermore, by calculating elevation and azimuth target observation angles, and evaluating azimuth steering angles for
the whole data acquisition time, transmission and receiving antenna radiation patterns are reflected on targets. Therefore,
effects related to the antenna beam pattern of the real spaceborne SAR are inherent in simulated raw data.

3) Antenna beam pointing error model

The developed simulator has the model to generate pointing errors in terms of roll, pitch and yaw angular coordinates
during data acquisition time. Drift and jitter pointing errors are taken into account in this model. For each axis (roll, pitch
and yaw), pointing errors are modeled as the superimposition of two terms; (a) the drift term that represents the linear
error contribution, (b) the jitter term that represents the random error contribution. The graphical representations of these
errors are showed in Figure 4. In Section 3, mathematical models of antenna beam pointing errors are described in detail.

4) Target observation model

The data acquisition geometry of a spaceborne SAR is modeled for target observation. Point targets are positioned on the
WGS-84 ellipsoid, and their reflectivity can be set. For the whole acquisition, this model provides target coordinates,$R_{T,ECEF}$ in the ECEF frame and $R_{T,SP}$ in the sensor pointing frame using orbital quantities, dynamics vectors and attitude
parameters evaluated by the sensor dynamics/attitude model. Also, it gives the elevation and azimuth observation angles,
evaluated in the sensor pointing frame, under which each target has been viewed from the SAR sensor.
5) SAR rawdata generation model

This model has in charge to define and generate the received signal of the SAR sensor. In other words, it simulates to
generate rawdata of the user-designed spaceborne SAR system. In particular, the received signal is simulated as the
function of the significant instants time. Such instants represent all transmission and receiving instants during the whole
data acquisition. It describes the received signal using radar parameters, antenna radiation patterns, target and sensor
positioning, and beam pointing errors. The mathematical model of this received signal, $S_{Rx}$ is defined as Eq. 1, and the
received signal is provided in its Complex components.

$$s_{Rx}(\tau_h, t_n) = A_{\text{error}}(t_n) \cdot e^{j \Phi_{\text{error}}(t_n)} \cdot \sum_{i=1}^{N_T} r_{T,i} \cdot G_{Ts} \cdot G_{Rs} \cdot \text{rect}_f \left( \tau_h + n_a T - \frac{T_p}{2} - t_{d,i}(t_n) \right) \cdot e^{j \left( t_s \cdot t_n + \frac{T_p}{2} - t_{i,i}(t_n) \right)}$$

(1)

where $A_{\text{error}}(\cdot)$ is the amplitude error, $\Phi_{\text{error}}(\cdot)$ is the phase error, $r_T$ is the reflectivity of targets, $N_T$ is the number of
targets, $G_{Ts}$ is the transmission antenna radiation pattern, $G_{Rs}$ is the reception antenna radiation pattern, $n_a$ is the
ambiguity number, $T$ is the pulse repetition interval, $T_p$ is the chirp duration, $t_n$ is the azimuth time instant of the
transmitted signal, $\gamma$ is the chirp rate, and $f_c$ is the carrier frequency. $t_{d,i}$ represents the two-way delay generated by the
propagation of the signal between transmission and reception. $t_s$ is the $h$-th range time instant within the sampling
window of the receiving signal, and it is defined according to the following equation.

$$\tau_h = swst + \left( h - 1 \right) \frac{f_s}{j}, \quad h = 1..n_s$$

(2)

where $n_s$ is the number of range time samples, $swst$ is the sampling window start time, and $f_s$ is the sampling frequency.

The used SAR data focusing algorithm is explained in Section 5 and its performance analysis is based on IRF quality of
point targets on the focused image. The performance of the developed spaceborne SAR system simulator has verified
through our several test and evaluation [2]. In the following sections, error effect analyses of key factors for spaceborne
SAR image formation are performed, and its results are utilized for precise spaceborne SAR data focusing.

3. ANTENNA BEAM POINTING

3.1 Mathematical models of antenna beam pointing errors

Unstable antenna beam pointing generates errors such as drift and jitter. They induce phase errors on rawdata, and the
degradation of the SAR image quality. In particular, antenna beam pointing variations induce shifts of the Doppler
centroid. Inaccurate Doppler centroid produces azimuth resolution loss, signal to noise ratio loss, signal to Doppler
ambiguity ratio loss, and swath localization error. Antenna beam pointing errors and phase errors induced by them are
able to be defined mathematically, and analyzed their effects. Figure 6 shows the graphical geometry for movements of
antenna beam pointing angles (roll $\gamma$, pitch $\alpha$, and yaw $\beta$) of the spaceborne SAR. In this figure, $\hat{r}_{in}$ is the ideal antenna

![Figure 5. Target observation geometry](image-url)
beam pointing vector. The beam pointing vector $\vec{r}_0$ is converted to $\vec{r}_1$ due to roll $\gamma$, and $\vec{r}_1$ is moved to $\vec{r}_2$ by pitch $\alpha$. Finally, $\vec{r}_2$ is moved to $\vec{r}_3$ by yaw $\beta$.

The Doppler frequency that corresponds to angles of antenna beam pointing is expressed mathematically as Eq. 3.

$$f_d = \frac{2\nu}{\lambda} \vec{v} \cdot \vec{r}$$

$$= \frac{2\nu}{\lambda} \left( \tan^2(\alpha) + \frac{\tan(\theta + \gamma)}{\cos^2(\alpha)} \right) \cdot \sin \left( \beta + \frac{\sin(\alpha)}{\tan(\theta + \gamma)} \right)$$

where $\vec{v}$ is the satellite velocity vector, $\lambda$ is the wavelength, $\vec{r}$ is the antenna beam pointing vector, and the symbol $\cdot$ is the Scalar product of vectors. Drift that represents the linear error contribution is defined as Eq. 4.

$$e_d = A_{d,pp} \cdot t_n, \quad t_{\text{start}} \leq t_n \leq t_{\text{end}}$$

where $A_{d,pp}$ is the peak-to-peak variation rate of pitch, yaw, and roll. Jitter that represents the random error contribution is defined as Eq. 5.

$$e_j = \sum_{m=1}^{M} A_{j,pp,\phi_m} \sin(2\pi f_m t_n + \phi_m), \quad t_{\text{start}} \leq t_n \leq t_{\text{end}}$$

where $A_{j,pp}$ is the peak-to-peak amplitude of jitter for pitch, yaw, and roll. $f_m$ is the jitter frequency, which has $m$ sampling frequencies, and $\phi_m$ is the random initial phase of jitter. The phase error due to pointing errors is able to be expressed as Eq. 6. It is based on the theory that the derivative of the phase is the frequency; $d\phi/dt = 2\pi f$.

$$\phi_e(n) = \phi_e(n-1) + f_d(n) \cdot \frac{2\pi}{\text{PRF}}$$

where $\phi_e(n)$ is the phase error of $n$-th pulse, and $f_d(n)$ is the Doppler frequency of $n$-th pulse, which is calculated using Eq. 3. Based on these models, rawdata that antenna beam pointing errors are reflected on are generated in our simulations.

**3.2 Compensation of phase errors due to antenna beam pointing errors**

In order to compensate phase distortion induced by antenna beam pointing errors, we use the PGA [5] that is the representative autofocus technique. In particular, we suggest combining it with the extended chirp scaling (ECS) algorithm [4] for SAR data focusing. In processes of the ECS algorithm, azimuth chirp signals are able to be deramped. In other words, azimuth chirp signals are converted to sine wave signals, and then deramped azimuth signals are compressed to IRF by doing Fourier transform. In this process, the PGA is able to be applied to the azimuth deramped signal. Therefore, azimuth signal phase errors produced by antenna beam pointing errors can be estimated and compensated. These overall processes are showed in detail in Figure 10 of Section 5.2.
4. EFFECTIVE VELOCITY & DOPPLER CENTROID

4.1 Error effect analysis

For spaceborne SAR data focusing, the effective velocity, $V_r$, of the illuminated beam on a ground is the very important parameter from which the Range Cell Migration (RCM) factor is calculated. It is different from the flight velocity of a satellite SAR, and its incorrect value is enough to cause serious degradations of the focused SAR image. Also, the Doppler centroid, $f_{DC}$ is the key parameter to calculate the azimuth frequency of rawdata.

In the ECS algorithm [4], the RCM factor, $\beta$ is expressed as Eq. 7, which is the key factor for the exact Range Cell Migration Correction (RCMC).

$$\beta(f_a) = \sqrt{1 - \left(\frac{f_a \cdot 2}{2 \cdot V_r}\right)^2}$$ (7)

where $f_a$ is the azimuth frequency. As seen from Eq. 7, the RCM factor $\beta$ is dependent on $f_a$ and $V_r$. Therefore, $V_r$ and $f_{DC}$ have to be calculated correctly to get the accurate $\beta$.

Error effects of the effective velocity and the Doppler centroid on spaceborne SAR processing have analyzed through spaceborne SAR simulations. As seen in Figure 7, the analysis results show that these errors cause severe defocusing on the focused image. Considering these results, calculation methods of the effective velocity and the Doppler centroid for precise SAR processing are suggested in the following sections.

![Figure 7. Error effects of $V_r$ and $f_{DC}$ on the azimuth IRF: (a) Defocusing due to error, (b) No error](image)

4.2 Calculation of the effective velocity

Spaceborne SAR data processing depends critically on the accurate model of the imaging geometry as it evolves through time. The geometry from the spaceborne SAR presents an interesting problem because both the satellite and the earth’s surface move with time. That is, to compute the accurate effective velocity is not easy due to the earth’s curvature and rotation. However, it is able to be calculated by the hyperbolic slant range equation using additional information such as state vectors of the spaceborne SAR and scene center coordinates [1]. In case of the real satellite SAR system, these are provided as attributes of acquired rawdata.

![Figure 8. Rawdata acquisition geometry.](image)

The rawdata acquisition geometry of the satellite SAR system is showed approximately in Figure 8. In this figure, $R$ is the slant range from the SAR to the scene center, $R_0$ is the closest slant range from the SAR to the scene center, and $t_0$ is the azimuth time at $R_0$. Based on the rawdata acquisition geometry of Figure 8, the hyperbolic slant range equation model is defined as Eq. 8, and it is able to be expressed as Eq. 9.
\[ R_\text{eff}(t_n) = R_0^2 + V_r^2 (t_n - t_0)^2 \]  \hspace{1cm} (8)

\[ V_r = \sqrt{\frac{R^2(t_n) - R_0^2}{(t_n - t_0)^2}} \]  \hspace{1cm} (9)

To calculate exactly the effective velocity defined in Eq. 9, we use orbital data of the spaceborne SAR such as orbit state vectors and time data as defined in Table 1. However, most of satellite SAR systems are not capable of measuring their orbital and attitude data at the pulse repetition frequency (PRF), so only provide them at an interval of specific time during the raw data acquisition.

These data are not enough to compute the precise effective velocity. That is, SAR image formation requires interpolation of these sparse data points to the PRF. In order to increase samples of orbital data, we use the simple interpolation technique that makes use of Hermite polynomials. This approach is precise, but only as accurate as the input state vectors used, and its detail procedures are described in [10].

**Table 1.** Orbital data of the satellite SAR system

<table>
<thead>
<tr>
<th>Data</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital Time</td>
<td>Array of times at which the satellite orbital data are supplied in seconds</td>
</tr>
<tr>
<td>ECEF Position - X/Y/Z [m]</td>
<td>Satellite SAR position on the orbit in ECEF Cartesian coordinates corresponding to the orbital times</td>
</tr>
<tr>
<td>ECEF Velocity - X/Y/Z [m/s]</td>
<td>Satellite SAR velocity on the orbit in ECEF Cartesian coordinates corresponding to the orbital times</td>
</tr>
</tbody>
</table>

Furthermore, to enhance the accuracy of the calculated effective velocity, we propose the method that uses the two-way slant range equation model. In particular, in case of the satellite SAR system, there is the difference between positions at pulse transmission and at pulse reception because the distance between the SAR sensor and ground targets is very far. In other words, there is the ambiguity number, \( n_a \) that takes into account the time interval between the transmission and the reception in terms of pulse repetition intervals. Therefore, \( R(t_n) \) in Eq. 9 has to be defined as Eq. 10, where \( R_Y(t_n) \) and \( R_R(t_n) \) are slant ranges from the SAR to the scene center at pulse transmission and pulse reception. To calculate \( R_Y(t_n) \) and \( R_R(t_n) \), scene center coordinates in the ECEF frame that are provided in the attribute value of rawdata are able to used, and the minimum value of \( R(t) \) becomes \( R_0 \) of Eq. 9.

\[ R(t_n) = \frac{R_Y(t_n) + R_R(t_n + n_a \cdot \text{PRI})}{2} \]  \hspace{1cm} for all range sample bins \hspace{1cm} (10)

In order to get the accurate two-dimensional (2-D) RCM factor, \( V_r \) has to be calculated for all range sample bins as shown in Figure 9.

**Figure 9.** Effective velocity for range sample bins.

To calculate \( V_r \) for all range sample bins, the index of the center range sample bin has to be computed, and is calculated as the following equation.
where \( R_{\text{ref}} \) is the slant range for the scene center. Next, to compute local coordinates of all range sample bins, the ground range, \( \Delta R_g \), and the slant range, \( \Delta R_s \), for one range sampling interval are computed using Eq. 12. The local coordinate is defined as the Cartesian coordinate that the origin is the scene center coordinate. In the local coordinate, X-axis, Y-axis, and Z-axis represent the azimuth direction, the range direction, and the height.

\[
\Delta R_g = \frac{R_s}{a \cdot \sin(\Delta \theta + \theta_0)} \cdot \Delta \theta, \quad \Delta R_s = \frac{c}{2f_s}
\]

For all range sample bins in one range line that the scene center exists, local coordinates, \((0, Y, 0)\) are calculated using the equation; \( \Delta R_g \times (id_{RgBin} - id_{RgBinCenter}) \), where \( id_{RgBin} \) is the index of each range sample bin. These local coordinates of range sample bins are able to be converted to ECEF coordinates. Therefore, for all range sample bins, \( R(t_n) \) and \( R_0 \) can be computed using the above suggested method. Finally, \( V_r \) is also calculated exactly for each range sample bin, so the accurate 2D RCM factor, \( \beta \) is acquired for precise spaceborne SAR image formation.

### 4.3 Calculation of the Doppler centroid

The Doppler frequency is able to be calculated using position and velocity vectors of the SAR sensor and the target. Particularly, the following equation model is utilized to compute the Doppler frequency, \( f_d \).

\[
f_d = \frac{2}{\lambda} \left( \overrightarrow{P_S} - \overrightarrow{P_T} \right) \cdot \left( \overrightarrow{V_T} - \overrightarrow{V_s} \right) / R_{ST}
\]

where \( \overrightarrow{P_S} \) is the position vector of the SAR sensor in ECEF frame, \( \overrightarrow{P_T} \) is the position vector of the target in ECEF frame, \( \overrightarrow{V_s} \) is the velocity vector of the SAR sensor in ECEF frame, \( \overrightarrow{V_T} \) is the velocity vector of the target in ECEF frame, and \( R_{ST} \) is the slant range from the SAR sensor to the target.

In order to utilize above equation for spaceborne SAR data focusing, ECEF coordinates of the scene center is able to be used as \( \overrightarrow{P_S} \). Furthermore, \( \overrightarrow{V_s} \) is the cross product of \( \overrightarrow{P_S} \) and the vector \([0, 0, \omega_e]\), where \( \omega_e \) is the Earth’s rotation rate according to the WGS-84 Earth model, and its value is \( 7.2921151467 \times 10^{-5} \) [rad/sec].

As mentioned in Section 4.2, there is position variation of the SAR sensor on the orbit at pulse transmission and reception. Therefore, Eq. 13 has to be redefined as Eq. 14 for accurate spaceborne SAR data focusing.

\[
f_d = \frac{1}{\lambda} \left( \left[ \frac{\overrightarrow{P_{S,T_n}} - \overrightarrow{P_{T_n}}}{R_{ST,T_n}} \right] \cdot \left[ \frac{\overrightarrow{P_{T_n}} - \overrightarrow{P_{T_n,R_n}}}{R_{ST,R_n}} \right] + \left[ \frac{\overrightarrow{P_{S,R_n}} - \overrightarrow{P_{T_n,R_n}}}{R_{ST,R_n}} \right] \cdot \left[ \frac{\overrightarrow{P_{T_n,R_n}} - \overrightarrow{P_{T_n,R_n_n}}}{R_{ST,R_n_n}} \right] \right)
\]

where \( Tx \) and \( Rx \) means pulse transmission and pulse reception. In order to calculate \( f_d \) of Eq. 14, the position and velocity vector of the SAR sensor at each pulse is able to be computed using the interpolated orbital data as described in Section 4.2. Furthermore, to increase the capability of SAR focusing, the Doppler frequency of azimuth signal in each range bin is able to be calculated based on the equation using the range bin center coordinates calculation method suggested in Section 4.2. In conclusion, the mean value of calculated Doppler frequencies in each range bin is correctly calculated as the Doppler centroid, \( f_{DC} \).

### 5. EXPERIMENTS & RESULTS

#### 5.1 Spaceborne SAR rawdata generation

Experiments have performed to evaluate spaceborne SAR image formation techniques that are suggested in above sections. First, we have generated Stripmap rawdata that main characteristics of the satellite SAR sensor such as antenna beam pattern, beam pointing error, and beam illumination on the orbit are reflected on.
Table 2 shows values of spaceborne SAR system parameters and data acquisition geometry parameters used in the experiment of this paper. In Table 2, SWL is the sampling window length, B is the chirp bandwidth, and Taz is the azimuth synthetic aperture time.

Table 2. SAR system and processing parameters for simulation and verification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ω</td>
<td>0 [deg]</td>
<td>f_c</td>
<td>9.3 [GHz]</td>
</tr>
<tr>
<td>α_i</td>
<td>96 [deg]</td>
<td>PRF</td>
<td>3800 [Hz]</td>
</tr>
<tr>
<td>Ω</td>
<td>0 [deg]</td>
<td>T_p</td>
<td>30 [μs]</td>
</tr>
<tr>
<td>a</td>
<td>6937.854e3 [m]</td>
<td>swst</td>
<td>90e-6 [s]</td>
</tr>
<tr>
<td>e</td>
<td>0.0015</td>
<td>SWL</td>
<td>50e-6 [s]</td>
</tr>
<tr>
<td>t0</td>
<td>0 [deg]</td>
<td>B</td>
<td>83 [MHz]</td>
</tr>
<tr>
<td>Δθ</td>
<td>35 [deg]</td>
<td>f_s</td>
<td>100 [MHz]</td>
</tr>
<tr>
<td>δθ</td>
<td>7 [deg]</td>
<td>Taz</td>
<td>2.5 [sec]</td>
</tr>
</tbody>
</table>

In our experiments, antenna beam pointing errors are reflected on generated rawdata, and pointing errors are set as shown in Table 3. Particularly, drift is generated at 0.001 degree per second in pitch axis, and jitter is produced at two frequency bands in pitch, yaw, and roll axis.

Table 3. Antenna beam pointing error values

<table>
<thead>
<tr>
<th>Pointing error</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift</td>
<td>0.001°/sec (in p-axis)</td>
</tr>
<tr>
<td>Jitter</td>
<td>±0.001° (1~50 Hz)</td>
</tr>
<tr>
<td></td>
<td>±0.005° (50~100 Hz)</td>
</tr>
</tbody>
</table>

5.2 Overall spaceborne SAR focusing processes

- Spaceborne SAR Stripmap rawdata
  - Azi. Block Formation
  - Calculate f_DPC, V_r, f_a
  - Satellite Position/Velocity Data
  - Azi. FFT
  - Chirp Scaling
  - Range FFT
  - Range Compression, RCM Bulk Shift, SRC
  - Range IFFT
  - CS Phase Correction, Azimuth Scaling
  - Azi. IFFT
  - Azimuth Deramping
- Phase Error Estimation / Correction
  - Azi. FFT
  - Azi. Block Merging
  - Focused Image
  - Select range bin
  - Azimuth FFT
  - Windowing
  - jw
  - IFFT
  - Conjugate
  - Cal. Intensity
  - Im[]
  - Invert
  - Integrate over t
  - Phase error

Figure 10. SAR image formation: (a) Overall processing flow, (b) PGA processing flow
We used the well-known ECS algorithm as the fundamental SAR data focusing technique [4]. Using error effect analyses and processing methods described in Section 3 and 4, spaceborne SAR image formation has been executed precisely in our simulations. Overall processing flow of the proposed SAR image formation technique is showed in Figure 10.

As the key process of our spaceborne SAR image formation technique, azimuth deramping is added to use the PGA for phase error correction due to antenna beam pointing errors. Furthermore, the effective velocity and the Doppler centroid are calculated using orbital data and scene center coordinates based on the two-way slant range equation model. Also, to reduce the signal level of ambiguities due to sidelobes of the antenna beam pattern and to resolve memory limitation due to large scale Stripmap rawdata, azimuth block processing is proposed for spaceborne SAR data focusing.

![Azimuth block formation and processing](image)

Azimuth block processing is the SAR image formation technique to focus blocks of rawdata divided in the azimuth direction. In azimuth block processing, azimuth pulse data in the area that is larger than the mainlobe of the azimuth beam (3dB Doppler bandwidth) have to be compressed at the same time to get the full azimuth resolution. Therefore, one azimuth block consists of \( N_{p_w} \) pulses that are twice pulses of the antenna beam mainlobe, as shown in Figure 11. This block is compressed in azimuth at the same time, and then focused data for \( (N_{p_w} - N_{p_b}) \) pulses are discarded. That is, through one block processing, only \( N_{p,b} \) pulses azimuth data are compressed with the full Doppler bandwidth. To get all azimuth compressed data, this block processing has to be repeated for entire rawdata.

### 5.3 Simulation results and analyses

Phase errors that is estimated from azimuth deramped signal are showed in Figure 12. Linear component of phase errors is not estimated, but high order components of inserted phase errors are estimated similar to inserted phase errors.

![Results of phase error estimation due to antenna beam pointing errors](image)

As shown in Figure 13, the point target IRF in the focused image after estimating and compensating phase errors shows the ideal sinc pattern similar to the point target IRF which phase errors are not inserted in.
The point target image that is focused using suggested methods is showed in Figure 14. Furthermore, the quality of IRF has evaluated for the performance check of the proposed SAR focusing technique, and performance analysis results have described in Table 4. As seen it, error-free results are acquired, and the performance of our techniques is verified.

**6. CONCLUSION**

This paper has presented the precise spaceborne SAR processing technique based on the analysis of critical error factors. The error effects related to the antenna beam pointing, the effective velocity and the Doppler centroid of the spaceborne SAR have been analyzed using the developed spaceborne SAR system simulator. The analysis results have shown that these errors cause phase errors on rawdata, defocus the SAR image, and distort the symmetry of the azimuth IRF.

To solve these problems, several techniques have been suggested. In our experiments, suggested methods have compensated phase errors induced by antenna beam pointing errors. Also, the effective velocity and the Doppler centroid have calculated correctly by proposed methods based on the two-way slant range equation model. In conclusion, we have been able to confirm the good quality of the focused SAR image that error effects are eliminated by proposed methods. Therefore, these results make our techniques attractive for the precise spaceborne SAR image formation. As future works, effectiveness of proposed methods will be evaluated through focusing rawdata of the real spaceborne SAR system.
REFERENCES