SAR RETURN SIGNAL SYNTHESIS IN TIME-SPATIAL DOMAIN

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ABSTRACT:

This paper describes a time-spatial domain model for simulating raw data acquisition of space-borne SAR system. The position, velocity and attitude information of the platform at a certain time instance is used for deriving sensor-target model. Ground target is modelled by a set of point scatters with reflectivity and two-dimensional ground coordinates. The signal received by SAR is calculated for each slow and fast time instance by integrating the reflectivity and phase values from all target point scatters. Different from frequency domain simulation algorithms, the proposed time domain algorithm can provide fully physical modelling of SAR raw data simulation without any assumptions or approximations.

KEY WORDS: SAR, Time Domain, Raw Data Simulation

1. INTRODUCTION

The interest on SAR instrumentation and data processing has recently been growing in Korea as KOMPSAT-5 program has been started. Huge budget is invested to the satellite/payload development program and the satellite/payload cannot be repaired after the launch of the satellite. In this sense, very careful and thorough test and validation works are required for verifying the successful operation of the space-borne payload in orbit. During the test and validation processes, the tools so called simulators are used in order to simulate anticipated in-orbit operational environments. The SAR simulator can be used for several purposes such as follows.

- Mission analysis and optimal system design
- Performance test of data processor or estimator
- Pre-flight performance test of SAR payload
- Pre-trials required for correcting in-flight malfunctioning
- System operation training
- Demonstration

This paper concerns only the simulation of return signal from ground targets which can be used mission analysis, macro-scale system design verification and testing SAR data processor algorithms.

Figure 1 shows the inverse relationship between a SAR simulator and a processor. Backscattering characteristics of ground targets are translated to slant-range reflectivity map according to local incident angles between the transmitted signal and target faces. The SAR system transfer function simulates the signal acquisition model of SAR sensor in order to convert the slant-range reflectivity to raw data. A SAR data processor applies the inverse system transfer function to convert the raw data back to the slant-range reflectivity map, which are ultimately used for many different applications in order to extract the geophysical information of interest.

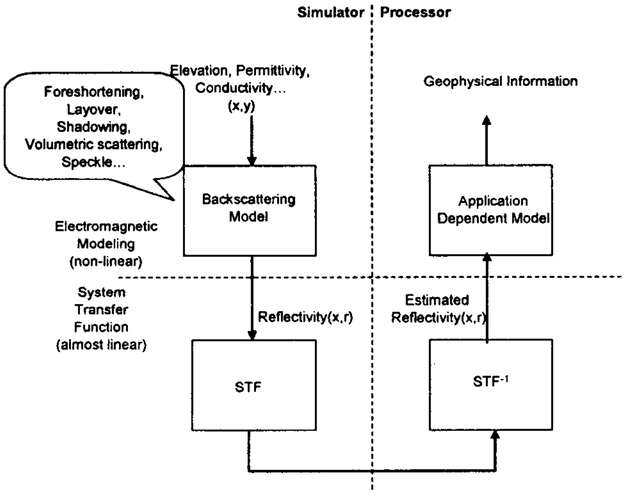

Figure 1. Simulation and processing.

The system transfer function implicates a frequency domain filter which requires a linear time domain impulse response. Most of the currently operational SAR focusing processors use frequency domain algorithms (inverse system transfer function) by virtue of their computational efficiency in order to process wide area scenes (Carrara et al., 1995; Curlander & McDonough, 1991; Franceschetti & Lanari, 1999). The real response of SAR sensor model is not absolutely linear so that all frequency domain algorithms are based on certain assumptions, limitations, and approximations such as straight flight path, constant velocity of sensor, high-order contribution tailoring, and so on, which may degrade the quality of focused images. The simulation algorithm must be based on approximation-free and fully-physical modelling of SAR system in order to apply various characteristics of SAR system and its operational environment, and therefore, to analyze their ultimate effects precisely and accurately.

This paper describes the time-spatial domain model for simulating raw data acquisition of SAR system.

2. DATA COLLECTION GEOMETRY

The celestial reference system (ECI : Earth Centered of Inertia) is selected as a reference coordinate system in order to apply full physical modelling of satellite orbit. A ground target is defined in UTM domain with height, so that the coordinates of each target scatterer can be transformed to geographic latitude/longitude (Snyder, 1987), to the terrestrial reference system (ECEF : Earth Centered of Earth Fixed), and to the celestial reference system successively. Whole astronomical dynamics including precession, nutation, Earth rotation (DUT1) and polar motion are applied for the coordinate conversion between ECI and ECEF (McCarthy & Petit, 2004).

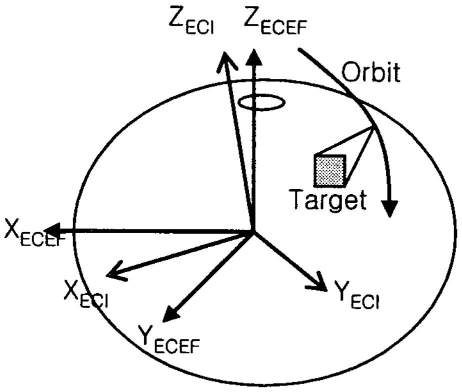

Figure 2. Data Collection Geometry.

3. SAR SIGNAL PHASE EQUATION

The radar transmits rectangular pulses with length of τ using a linear FM chirp signal with chirp rate *k*, interpulse period *T*, amd carrier frequency f_c.

$$s_t(n,t) = rect\left(\frac{t-nT}{\tau}\right)e^{j2\pi\left(f_c t+\frac{k}{2}(t-nT)^2\right)} \qquad (1)$$

Here, the quantity *n* is pulse number. The signal received from a single point target at pulse *n* is,

$$s_r(n,t) = rect\left(\frac{t-nT-t_d}{\tau}\right)e^{j2\pi\left(f_c(t-t_d)+\frac{k}{2}(t-nT-t_d)^2\right)} \qquad (2)$$

The time delay t_d includes motion between successive transmitted pulses, motion during transmission and reception of a pulse, and motion between transmission and reception of a pulse. The reference signal which is mixed to the received signal for demodulation is,

$$s_{ref}(n,t) = e^{j2\pi f_c(t-t_{dc})} \qquad (3)$$

where t_{dc} is the time delay between SAR and a reference point (normally scene center point). The demodulated IF (Intermediate Frequency) signal can be derived by mixing Equations (2) and (3) as follows.

$$s_{if}(n,t) = rect\left(\frac{t-nT-t_d}{\tau}\right)e^{j2\pi\left(f_c(t_{dc}-t_d)+\frac{k}{2}(t-nT-t_d)^2\right)} \qquad (4)$$

This signal is ingested to a sampling and digitization unit, and consequently digital in-phase and quadrature phase values are recorded.

4. SIMULATION ALGORITHM

The target is prepared by a rectangular raster data of which each grid point has a certain reflectivity value. The grid spacing of target raster data corresponds to geographical distance between each point scatter in UTM domain.

The satellite orbit is propagated during a certain time span (0~T_{max} seconds), so that the position and velocity in ECI coordinate system at any time of interest during the time span can be obtained by using a Lagrangian sample interpolator.

By using a nominal viewing angle of SAR (θ) and the simulation center time ($T_{max}/2$) the forward mapping is carried out to obtain the center target coordinates in UTM domain. This center target UTM coordinates are set to those of the center pixel of the target raster data. The UTM coordinates of each point scatterer of the target can then be calculated by using its column/row position and the specified grid spacing.

The range gate of early edge is calculated so that the target center corresponds to the center column of the sampled raw data. The positions of the satellite and the target center lead to two-way time delay t_{dc}, and

$$T_{rged} = t_{dc} - N_c/2/f_{sr} \qquad (5)$$

where N_c is the number of range bins and f_{sr} is range sampling frequency.

The simulation algorithm calculates the time of each pulse generation (slow time) during 0~T_{max} seconds by applying pulse repetition frequency, and time of each range sampling (fast time) during 0 ~ N_c by using range sampling frequency. For each fast time, the coordinates of all target point scatterers are converted to ECI and the instant ranges, and therefore, the time delay between the satellite and point scatters are calculated. The reflectivity of each target point scatterer is multiplied to the calculated phase value in Equation (4), and in-phase and quadrature-phase values are calculated. These complex values are summed for the responses of all point scatters. The algorithm has to be time-consuming due to four iteration loops (slow time, fast time and 2 dimensional point scatter distribution).

Figure 3 summarizes the steps of the proposed simulation algorithm.

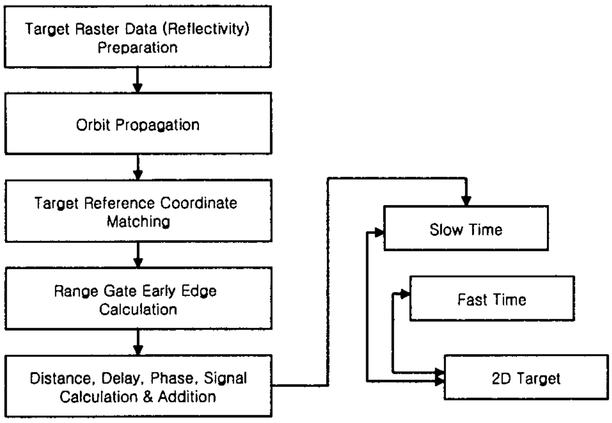

Figure 3. Proposed simulation algorithm.

5. EXPERIMENTS

The parameters used for the algorithm tests are based on ERS-2 orbit and SAR characteristics except modifications on a few parameters such as range gate and the number of range bins in order to reduce ground swath (Table 1).

Table 1. Experiment parameters

Parameter	Value	Unit
Carrier Frequency	5290.52	MHz
Nominal Look Angle	23.0	Degree
PRF	1679.95	Hz
Pulse Width	3.712E-5	Second
Sampling Rate	18.97	MHz
Chirp Bandwidth	15.55	MHz
No. Range Bins	1500	
Time Span	0.5	Second
Target Grid Spacing	30	Meter
Epoch Position	-2331.59	Km
(X,Y,Z)	-5468.10	
(ECEF)	3990.57	
Epoch Velocity	-3.235	Km/sec
(X,Y,Z)	-3.078	
(ECEF)	-6.090	

A point target is simulated at first in order to verify the simulation algorithm (Figure 4). A point target generated dispersed responses in the simulated raw data as shown in the top image of Figure 4. The application of 1-D matched filtering in range direction to the simulated raw data compressed the dispersed responses to a narrow line. The line shown in the range compressed image is not a straight vertical line due to the range skew. Yaw steering attitude mechanism was not applied in this case so that Earth rotation caused the range skew.

In this experiment, no range migration correction was applied. Therefore, the azimuth compressed image (the bottom image of Figure 4) shows spread-out point response. The Doppler centroid and rate were calculated purely by the satellite ephemeris data and Earth shape/rotation modelling. The absence of yaw steering mechanism resulted in a Doppler centroid of several Kilo-Hz, which exceeded the bandwidth of azimuth sampling (PRF). The repetition of spread-out point response in the azimuth compressed image was caused by the azimuth ambiguity due to the large Doppler centroid offset.

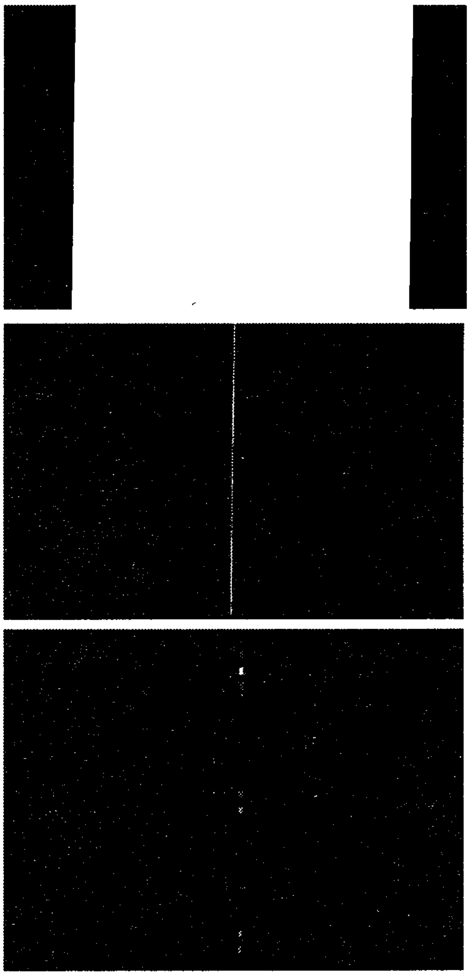

Figure 4. Point Target Test Result: Simulated Raw(top), Range Compressed(middle), Azimuth Compressed(bottom).

Figure 5 shows the result of extended target simulation and corresponding focusing. A sample drawing image of 100x100 pixels was used as a target and each point scatterer was modelled with 30m ground distance spacing. In this case, a yaw-steering attitude control mechanism was applied, and hence, approximately 300Hz Doppler centroid was obtained. This low Doppler centroid resulted in Earth rotation range skew less than the target resolution so that range skew correction was not necessary. However, range curvature due to parabolic iso-range intersection cannot be avoidable. The azimuth compression algorithm in this experiment did not apply any range curvature correction algorithm. Due to the descending right-looking and near-range-left illustration, the azimuth compressed image is reflected with a vertical axis. The vertical extension of the target feature is because the azimuth resolution is 4-5 times greater than the range/ground resolution in order for multi-look averaging.

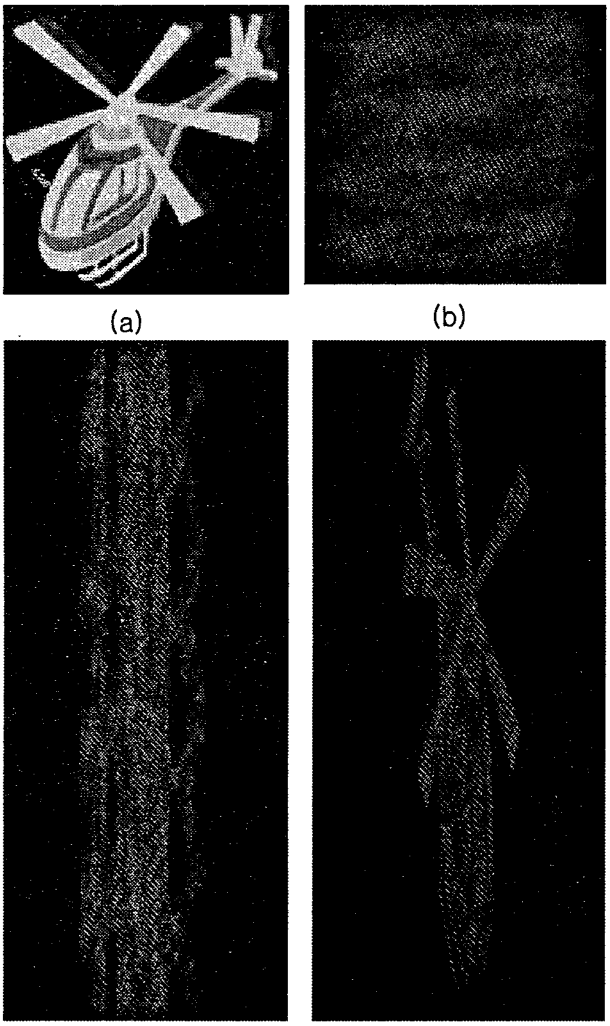
(a) (b)
(c) (d)

Figure 5. Extended Target Test Result: Target(a), Simulated Raw(b), Range Compressed(c), Azimuth Compressed (Single-Look Complex) (d).

6. CONCLUSION AND DISCUSSION

This paper described a time domain algorithm for simulating space-borne SAR, orbit, and ground target in order to generate SAR raw data. Considering the fact that the role of simulator is simulating instruments as well as expected real operational environment as close and accurate as possible, the proposed time domain SAR raw data simulation algorithm is highly required.

The proposed time domain algorithm can adapt any kind of characteristics such as attitude jittering, high frequency orbit perturbation, chirp wave oscillation and so on. The practical limit of the time domain algorithm is computational burden as expected. Since the swath reduction requires higher spatial resolution of target modelling, the simulation of extended target of full swath may take several days of processing. The elimination of stop-and-go approximation, which was not the case of the experiments performed in this paper, is the major time-consuming part. However, the simulator is not an operational tool but a test tool, and therefore, the proposed algorithm will be suitable for the applications which require very precise modelling of SAR system.

The following additional works are expected to be required in order to extend the application of the proposed algorithm.

- Precise antenna pattern modelling
- Facet modelling by using DEM (Digital Elevation Model)
- Automatic shadow detection by using ray tracing
- 3D CAD target modelling
- Multi-path reflection modelling
- Spolight and scan mode data simulation
- SAR component level noise characteristics modeling
- Inverse SAR target simulation

7. REFERENCES

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