Evaluation of TerraSAR-X Spotlight Processing Accuracy based on a New Spotlight Raw Data Simulator

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***Abstract*— This paper evaluates the Spotlight processing accuracy for TerraSAR-X. It describes the developed Spotlight raw data simulator. Approximations in the Sliding Spotlight processing are calculated and verified by using this simulator. Based on a worst case scenario raw data were simulated and processed with an Extended Chirp Scaling algorithm for Sliding Spotlight. The simulation results demonstrate the applicability of the processing algorithm for TerraSAR-X.**

I. Introduction

Te rraSAR-X is the German Synthetic Aperture Radar (SAR) satellite mission with scientific and commercial applications, which will be launched in 2005. It is a public-private partnership between the German Aerospace Center DLR and Astrium GmbH [6]. It employs a high-resolution X-band SAR based on active phased array technology, which allows operation in Stripmap, ScanSAR and Spotlight modes in different polarizations.

For TerraSAR-X Sliding Spotlight data processing, a new formulation of the Extended Chirp Scaling Algorithm [3] for Spotlight [5] has been derived. This algorithm is based on chirp and azimuth scaling, SPECAN and subaperture processing. In order to verify and evaluate the quality of the TerraSAR-X Spotlight processing, a Spotlight raw data simulator was developed. It uses an orbit calculation based on Keplerian elements and an ellipsoidal Earth reference model, accoring to WGS84 [1,4].

The Spotlight Mode of TerraSAR-X will have a comparatively high resolution, a large synthetic aperture time, but on contrary a small swath width. Due to these particularities, the approximations included in the chirp scaling algorithm [2,3] have been investigated. Approximations in the processing algorithm as well as in the raw data generation are investigated by point target analysis with respect to the image quality.

TABLE I
Operational Spotlight Modes for TerraSAR-X

	High Resolution Spotlight Mode	*Spotlight Mode*
scene extension ground rg	10 km	10 km
scene sxtension az	5 km	10 km
ρ_{rg}	1 m	1 m
ρ_{az}	1 m	2 m

Two operational Spotlight modes are planned for TerraSAR-X. The defined scene extensions and resolutions are summarized in Tab.1. These scene sizes in combination with the azimuth antenna beam width of $0.33°$ and a full performance incidence angle range from $20°$ to $55°$ require both Spotlight modes of TerraSAR-X to be in sliding geometry [5].

II. Spotlight Raw Data Simulator

The developed TerraSAR-X Spotlight raw data simulator generates Steering or Sliding Spotlight point target raw data. The simulation starts with a TerraSAR-X orbit calculation based on Keplerian elements. The point targets are positioned within a sliding spotlight scene on the WGS84 Earth reference ellipsoid. Depending on the point target position the illumination times are calculated for each target individually. Using the saltellite orbit and the point target position the slant range history is *exactly* calculated. This is the basis for the two-dimensional chirp generation. Finally, the raw data signals of all targets are stored in a single raw data array.

During raw data generation, a flat Earth approximation is made for the scene area with a maximum extension of 10 km. Fig.1 shows this approximation, which influences only the calculation of the illumination start and end times of the targets. Here a small error is introduced, which is the difference between the Earth ellipsoid and the assumed flat Earth. The maximum error occurs at the corners of the scene and is less than 4 m in height. This is in the order of houses and thus can be neglected.

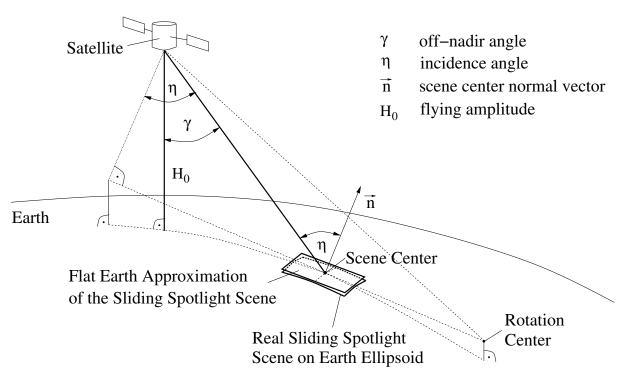
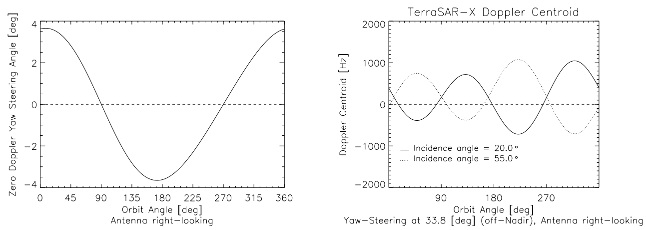


Fig. 1. Flat Earth approximation arround scene area during raw data generation

During raw data generation, also the TerraSAR-X Yaw-steering is considered. The simulator calculates the Yaw-steering law for the mechanical antenna offset angle of $33.8°$ off-Nadir. The required Yaw-steering angle over one orbit is illustrated in Fig.2a) and varies between $\pm 3.65°$. The simulator can handle two different Yaw-steering laws:
1) The z-axis of the satellite points perpendicular to the surface of the Earth reference ellipsoid.

2) The z-axis of the satellite points to the center of the Earth in Nadir direction.
For incidence angles away from the one used for the steering calculation residual Doppler centroids arise. The worst case residual Doppler centroid of 1.1 kHz occurs for steering the z-axis of steering law 1), and is considered as the worst case in the following.



(a) Zero Doppler Yaw-steering angle vs orbit angle

(b) Residual Doppler centroid vs orbit angle

Fig. 2. Zero Doppler Yaw-steering angle and residual Doppler Centroid over one orbit for steering the satellites z-axis perpendicular to the surface of the Earth reference ellipsoid

The Doppler centroid variation over one orbit is shown in Fig.2b) for a maximum pointing error of $0.015°$ in roll, pitch and yaw. The two curves in Fig.2b) correspond to the borders of the full performance incidence angle range, which varies between $20°$ and $55°$.

III. Definition of a TerraSAR-X Test Scenario

The following worst case scenario was defined for the investigation of the processing accuracy:

mode	*High Resolution Spotlight*
scene size	10 km (ground rg) x 5 km (az)
Doppler centroid f_{DC}	1.1 kHz
incidence angle η	55°
synthetic aperture time	1.1 s
assumed maximum total az scene bandwidth	B_{az} = 15 kHz
maximum az frequency	$f_{max} = B_{az}/2 + f_{DC}$ = 8 kHz

Fig.3 shows the location of the targets, which are used in the raw data simulation. The results presented within this paper are for the target in the upper right corner of the scene.

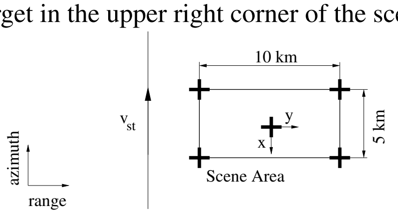


Fig. 3. Scene area with targets

IV. Spotlight Processing Algorithm and its Approximations

A new formulation of the Extended Chirp Scaling Algorithm for Spotlight has been derived for Sliding Spotlight geometry [5]. The designed Spotlight algorithm enables a global processor concept, since its basic processing functions are identical in the Extended Chirp Scaling formulations of the other imaging modes, like Stripmap and ScanSAR mode, which will also be operated by TerraSAR-X.

The following approximations are made in a chirp scaling algorithm and are investigated with respect to the reference scenario.

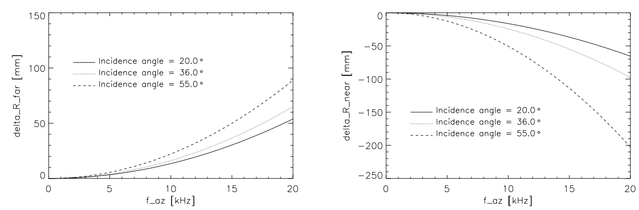
A. Range Cell Migration and Velocity-Parameter

During the Range Cell Migration Correction (RCMC) of the chirp scaling processing a range-constant velocity-parameter, called B-parameter is used. This is an approximation, since the B-parameter varies with range. This introduces an error into the RCMC. During the azimuth compression, the range-dependency of the B-parameter is accounted. The difference $\delta\Delta R(f_{max}, R)$, which occurs between the true RCM and the assumed RCM must be much less than one range resolution cell, to avoid image degradations. The RCMC error in far range can be expressed by:

$$\delta\Delta R_f(f_{max}, R_{far}) = \frac{R_{far}}{\sqrt{1-\frac{1}{B_{far}}\left(\frac{\lambda f_{max}}{2}\right)^2}} - \frac{R_{far}}{\sqrt{1-\frac{1}{B_{mid}}\left(\frac{\lambda f_{max}}{2}\right)^2}} \tag{1}$$

where R denotes the slant range and λ denotes the wavelength. The index $_{far}$ and $_{mid}$ implies the far range and the mid range, respectively.

In Fig.4, the dependence of the RCM approximation error as a function of azimuth frequency for far and near range is shown.



(a) RCM approximation error in far range

(b) RCM approximation error in near range

Fig. 4. RCM approximation error as a function of azimuth frequency for different incidence angles

Assuming the worst case maximum azimuth frequency of 8 kHz, an incidence angle of 55°, and a TerraSAR-X orbit, a maximum RCM approximation error of 33 mm occurs. This error is much less than a slant range resolution cell of 1 m.

B. Taylor Series Approximation

In the used formulation of the chirp scaling algorithm a quadratic Taylor series approximation in two-dimensional frequency domain is made. The resulting phase error, which shall be much less than $\pi/8$ = 22.5°, can be written as follows:

$$\phi_{e\_taylor}(f_{az}, f_{rg}) = \frac{-4\pi R_0}{\lambda}\left[\sqrt{\left(\frac{f_{rg}\lambda}{c_0}+1\right)^2 - \left(\frac{f_{az}\lambda}{2\cdot v_{st}}\right)^2} - \left(\beta(f_{az}, f_{rg}) + \frac{f_{rg}\lambda)}{c_0\cdot\beta(f_{az}, f_{rg})} + \frac{\beta(f_{az}, f_{rg})^2-1}{2\cdot\beta(f_{az}, f_{rg})^3}\cdot\frac{f_{rg}^2\cdot\lambda^2}{c_0^2}\right)\right] \tag{2}$$

where

$$\beta(f_{az}, frg) = \sqrt{1-\left(\frac{f_{az}\cdot\lambda}{2\cdot v_{st}}\right)^2} \tag{3}$$

the speed of light is denoted by c_0 and the velocity is $v_{st} = \sqrt{B_{mid}}$. For the analysis of the Taylor series error in Fig.5 the following parameters have been used:

carrier frequency f_c	9.65 GHz
range frequency f_{rg}	-75 MHz to 75 MHz
az frequency f_{az}	0 kHz to 20 kHz
incidence angle η	55°
velocity v_{st}	7400 m/s

Fig.5 shows a surface plot of the phase error due to the Taylor approximation as a function of the range frequency f_{rg} and azimuth frequency f_{az}. For the maximum azimuth frequency of ca. 8 kHz a maximum phase error of less than 1.4° occurs. Thus, the requirement of an introduced phase error less than $\pi/8$ is fulfilled.

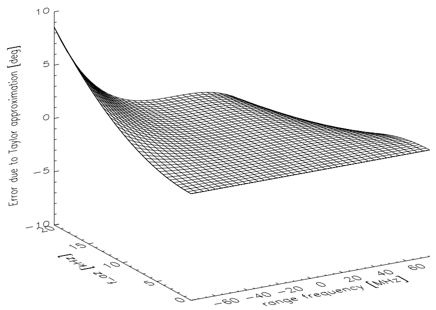


Fig. 5. Taylor approximation error in far range for 55° Incidence angle

C. Secondary Range Compression Term

The Secondary Range Compression in chirp scaling is corrected only for one reference range and not adjusted over the entire swath width. The resulting phase error is:

$$\Phi_{e\_SRC}(f_{az}, f_{rg}) = 2\pi \cdot \left(\frac{\beta(f_{az}, f_{rg})^2 - 1}{\beta(f_{az}, f_{rg})^3} \right) \cdot \frac{\lambda}{c_0^2} \cdot (R_{ref} - R_0) \cdot f_{rg}^2 \quad (4)$$

and shall be smaller than $\pi/8$ = 22.5°. Fig.6 shows a surface plot of the SRC phase error as a function of range and azimuth frequency.

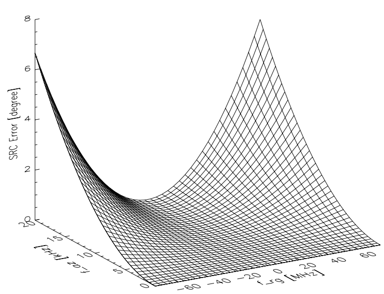


Fig. 6. SRC phase error in far range for 55° incidence angle vs. range frequency and azimuth frequency

For a maximum azimuth frequency of 8 kHz, an incidence angle of 55°, and a TerraSAR-X orbit, a maximum SRC approximation error of 1.1° occurs.

In summary all these approximation errors are negligible and thus the chirp scaling algorithm can be used for TerraSAR-X Sliding Spotlight processing.

V. Spotlight Simulation and Processing Results

Raw data of point targets as defined in Fig.3 were generated by using the spotlight raw data simulator and processed by the sliding spotlight processing algorithm. The resulting point target response function for the upper right target is shown in the contour plot of Fig.7.

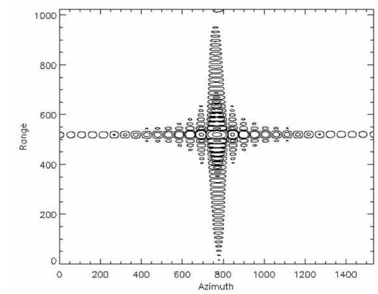


Fig. 7. Point target response function

The quality parameters of the point target response function are summarized in the table below:

TABLE II
Quality Parameters

	Azimuth	Range	Theory
PSLR	-13.182 dB	-13.253 dB	-13.2 dB
ISLR	-9.90 dB	-9.894 dB	-9.8 dB
resolution ρ	0.869 m	0.883 m	0.885 m

These results agree well with the theoretically values. This result of the point target processing is in accordance with the negligible processor approximations of the previouse section.

VI. Conclusion

A sliding spotlight raw data simulator was developed, based on Keplerian elements, an ellipsoidal Earth reference system and Yaw-steering. It is used to investigate and verify the Chirp Scaling algorithm used for Sliding Spotlight, which is the baseline for TerraSAR-X spotlight processing.

A worst case scenario has been set up and the various approximations have been analyzed with respect to this worst case scenario. All approximations are much smaller than the requirements for TerraSAR-X processing.

Finally, point target raw data have been generated for the worst case scenario and processed by the Extended Chirp Scaling algorithm for Sliding Spotlight. The results demonstrate a defraction limited focussing quality. Generally it can be stated that the higher requirements on the processing algorithm posed by the high resolution is relaxed by the small swath width. Not yet included are errors due to orbit inaccuracies, timing and instrument errors.

References

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