Estimation of the Phase−Error Function for Autofocussing of SAR Raw Data

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Abstract

An algorithm for estimating the phase−error function of SAR raw data is described, which exploits reflectors consisting of several neighbouring point targets. In a first step the azimuth signal of a reflector, which appears as highlight in its near environment, is extracted and used to estimate the reflected azimuth signal of a single point target. In the second step a local phase−error function is determined for each extracted reflector from the azimuth signal of the point target. The entire phase−error function of a SAR image strip is then constructed from the local phase−error functions using a weighted superposition technique. Compared to the phase−gradient algorithm the quality criterion for evaluating the sharpness of SAR images is improved by 15%. The standard deviation of coordinates−errors of objects in the SAR−image is reduced from 94 to 3.8 pel.

Introduction

For high resolution SAR images it is necessary to apply autofocussing techniques in addition to motion compensation to ensure the desired image resolution. Several autofocussing techniques have been proposed in the last years. The most advanced techniques are derived from the Phase−Gradient Algorithm (PGA) [1][2], which estimates the phase−error function from the raw data by evaluating the azimuth signals of reflectors. Having obtained the phase−error function the raw data can be corrected and azimuth focussing using the nominal azimuth reference function as a matched filter can be realized. For a precise estimation of the phase−error function point targets are required. Since such targets are not always available in the illuminated scene, the PGA algorithm uses so called strong reflectors instead, each of which consists of many joint point targets. Hence the phase−error function estimated by PGA is not accurate. Furthermore positional−errors of the used reflectors may cause an azimuth dependent coordinate error in the SAR image.

In order to avoid the faults of the Phase−Gradient Algorithm a refined algorithm for automatic focussing of SAR raw data is developed. The algorithm is embedded in a range Doppler processing of a side looking SAR in strip map mode and is also based on the evaluation of azimuth signals of reflectors in order to estimate the phase−error function. Therefore it is assumed that, range compression and motion compensation based on INS and GPS data are done in advance. The method used for the estimation of the phase−error function consists of two main steps.

Estimation of azimuth signals of point targets

In a first step the algorithm estimates azimuth signals of point targets. Therefore, reflectors, which appear as highlights in their near environment, are detected, their coordinates are assigned and their azimuth signals are extracted. For the detection of candidates of reflectors a low resolution SAR image is generated using a nominal azimuth reference function with reduced bandwidth. The watershed algorithm [3] is applied on the azimuth lines of the SAR image in order to locate the candidates of reflectors. However, only few azimuth lines are evaluated depending on their energy−content, which must be higher then the mean of the energy−content of the whole SAR image. A quality criterion G_u is assigned to each candidate, that describes the quotient of the amplitude and the local mean value in its near environment. The SAR Image strip is divided into several sections. The length of each section T_A is limited to the half of the length of the synthetic aperture T_L. In each section of the SAR image one reflector at least is selected.

In order to extract the azimuth signal of a reflector a Deramping processing followed by a Fourier transformation is applied on the range compressed data of the associated azimuth line. The reflector is extracted by use of a Hamming−Filter with the bandwidth B. The azimuth signal of the extracted reflector is finally obtained by carrying out the inverse Deramping operation and inverse Fourier transformation.

In order to obtain an azimuth signal of a point target a mathematical model for the parametric description of the azimuth signal of a selected reflector is applied. In this model the reflector is described by azimuth signals of several equidistantly distributed point targets. The number of the point targets M is determined as

$$M = INT\left\{ -\frac{f_p \cdot B}{2\pi \cdot f_R} \right\} + 1, \tag{1.1}$$

where f_R is the Doppler rate and f_p the pulse repetition frequency. Thus, the Azimuth signal $r(t_s)$ of the selected reflector can be described as

$$r(t_s) = \sum_{m=1}^{M} \left(A(t_s - T_m) \cdot \tau_p \cdot \sigma_m \cdot e^{j2\pi(-2R_{T_0}/\lambda + f_R(t_s - T_m)^2/2)} \cdot e^{j\phi_e(t_s)} \; ; \; |t_s - T_m| < \frac{T_L}{2} \right), \tag{1.2}$$

where R_{T_0} is the distance between antenna and reflector, τ_p the pulse duration, λ the carrier wavelength, $A(t_s)$ the antenna pattern function and σ_m the backscattering coefficient of the point target m. The distance between two neighbouring point targets is given by the pulse repetition frequency f_p. It s assumed that the M point targets are simultaneously illuminated by the antenna, their azimuth signals have the same phase−error $\phi_e(t_s)$but different amplitude,

i.e. $$A(t_s - T_{m1}) = A(t_s - T_{m2}) \quad ; \quad \forall \; m1, m2 \in \{1, .., M\} \tag{1.3}$$

An analysis of the statistics of reflectors shows that the reflectivity function $\sigma(t_s)$ of a reflector is approximately symmetric and its power−density spectrum consists mainly of real and positive frequency components. Hence an estimate of the reflectivity function can be obtained by evaluating the power−density spectrum $S_{\sigma\sigma}(\omega)$ of the azimuth signal $r(t_s)$

$$\hat{\sigma}(t_s) \approx FT^{-1}\left\{\sqrt{S_{\sigma\sigma}(\omega)}\right\} \tag{1.4}$$

An estimate of the reflectivity function $\sigma(t_s)$ based on these assumption produces an estimation error according to an SNR of 15 dB.

From the reflectivity function $\sigma(t_s)$, the backscattering coefficients σ_m of the point targets $m;\; m = 1, .., M$ of the reflector can be determined

$$\sigma_m = \hat{\sigma}(T_m) \tag{1.5}$$

By deramping the signal $r(t_s)$ we obtain

$$d(t_s) = r(t_s) \cdot e^{-j\pi f_R t_s^2} \tag{1.6}$$

and with Eq.1.2

$$d(t_s) = \sum_{m=1}^{M} \left(A(t_s - T_m) \cdot \sigma_m \cdot \tau_p \cdot e^{j\frac{4\pi}{\lambda} R_{T_0}} \cdot e^{j\omega_m\, t_s} \cdot e^{j\pi f_R T_m^2} \cdot e^{j\phi_e(t_s)} \; für \; |t_s - T_m| < \frac{T_L}{2}, \right. \tag{1.7}$$

where $\omega_m = -2\pi f_R T_m$.

In order to determine the deramped azimuth signal of a single point target Eq. 1.7 is redrafted. As result the deramped signal $d(t_s)$ can be described as

$$d(t_s) = d_{m_p}(t_s) \cdot \left[1 + \sum_{m \neq m_p} \left[\frac{\hat{\sigma}(T_m)}{\hat{\sigma}(T_{m_p})} \cdot e^{j\pi f_R (T_m{}^2 - T_{m_p}{}^2)} \cdot e^{j(\omega_m - \omega_{m_p}) \cdot t_s} \right] \right], \tag{1.8}$$

where

$$d_{m_p}(t_s) = A(t_s - T_{m_p}) \cdot \sigma_{m_p} \cdot \tau_p \cdot e^{j\frac{4\pi}{\lambda} R_{T_0}} \cdot e^{j\omega_{m_p}\, t_s} \cdot e^{j\pi f_R T_{mp}^2} \cdot e^{j\phi_e(t_s)} \; für \; |t_s - T_m| < \frac{T_L}{2}, \tag{1.9}$$

is the requested deramped azimuth signal of the point target m_p with the backscattering coefficient $\sigma_{0,m_p} = \hat{\sigma}(T_{m_p})$. Eq. 1.8 is used only to determine the phase $\phi_{m_p}(t_s)$ of the signal $d_{m_p}(t_s)$:

$$\phi_{m_p}(t_s) = \phi(t_s) - \phi_q(t_s), \tag{1.10}$$

where $\phi(t_s)$ is the phase signal of the observed signal $d(t_s)$ and $\phi_q(t_s)$ the phase signal of the term $\left[1 + \sum_{m \neq m_k} \left[\frac{\hat{\sigma}_k(T_m)}{\hat{\sigma}_k(T_{m,k})} \cdot e^{j\pi f_R(T_m{}^2 - T_{m_k}{}^2)} \cdot e^{j(\omega_m - \omega_{m_k}) \cdot t_s}\right]\right]$.

The Amplitude of $d_{m_p}(t_s)$ is calculated by using the known antenna pattern function as

$$A_{m_p} = A(t_s - T_{m_p}) \cdot \tau_p \cdot \hat{\sigma}(T_{m_p}) \quad ; \quad |t_s - T_{m_p}| < \frac{T_L}{2}. \tag{1.11}$$

Finally the azimuth signal $\hat{r}_{m_p}(t_s)$ of the point target is obtained by carrying out the inverse Deramping operation

Determination of the phase−error function

In the second step the phase−error function $\phi_e(t_s)$ is determined using the estimated azimuth point target signals $\hat{r}_{k,m_p}(t_s)$ $k = 1,..,K$. Therefore, first a local phase−error function $\phi_{k,e}(t_s)$ is calculated

$$\phi_{k,e}(t_s) = \phi_{\hat{r}_{k,mp}}(t_s) - \phi_{k,nom}(t_s), \tag{1.12}$$

where $\phi_{k,nom}(t_s)$ is the phase signal of a nominal azimuth chirp situated at the position $T_{m,p}$. The local phase−error functions $\phi_{k,e}(t_s)$ $k = 1,..,K$ are only valid for the section of the associated reflector. The entire phase−error function $\phi_e(t_s)$ is then constructed from the local phase−error functions using a weighted superposition technique. Due to different coordinate−errors of the selected reflectors the gradients of the local phase−error functions feature an amplitude−offset. In order to avoid an impact by coordinate−errors not the error gradients are superpositioned but their derivatives $q_k(t_s)$ $k = 1,..,K$ weighted by the quality criterion $G_k(t_s)$

$$q(t_s) = \frac{\sum_{k=1}^{K} G_k(t_s) \cdot q_k(t_s)}{\sum_{k=1}^{K} G_k(t_s)}, \tag{1.13}$$

with
$$G_k(t_s) = G_{u,k} \cdot A(t_s - T_k) \quad ; \quad k = 1,..,K \tag{1.14}$$

The Gradient $Q(t_s)$ of the phase−error function is then determined as

$$Q(t_s) = \int_0^{T_S} q(t_s)\ dt_s + Q_0. \tag{1.15}$$

The initial value Q_0 in Eq. 1.15 may be taken from the precedent strip. Finally the phase−error function $\phi_e(t_s)$ is obtained from $Q(t_s)$ by means of integration.

Experimental results

The developed algorithm has been applied to simulated synthetic and to real raw data. Synthetic data is obtained by means of simulating a fly using real motion parameters and reflectors with different reflectivity functions. The algorithm is evaluated subjectively by comparing the achieved image quality with the results of the Phase−Gradient Algorithm. For the objective evaluation two quality criteria are used. The first criterion evaluates the sharpness of the SAR image. Therefore several image sections are evaluated. The quality criterion for each section is given by the maximum value within the normalized section (energy−content = 1).

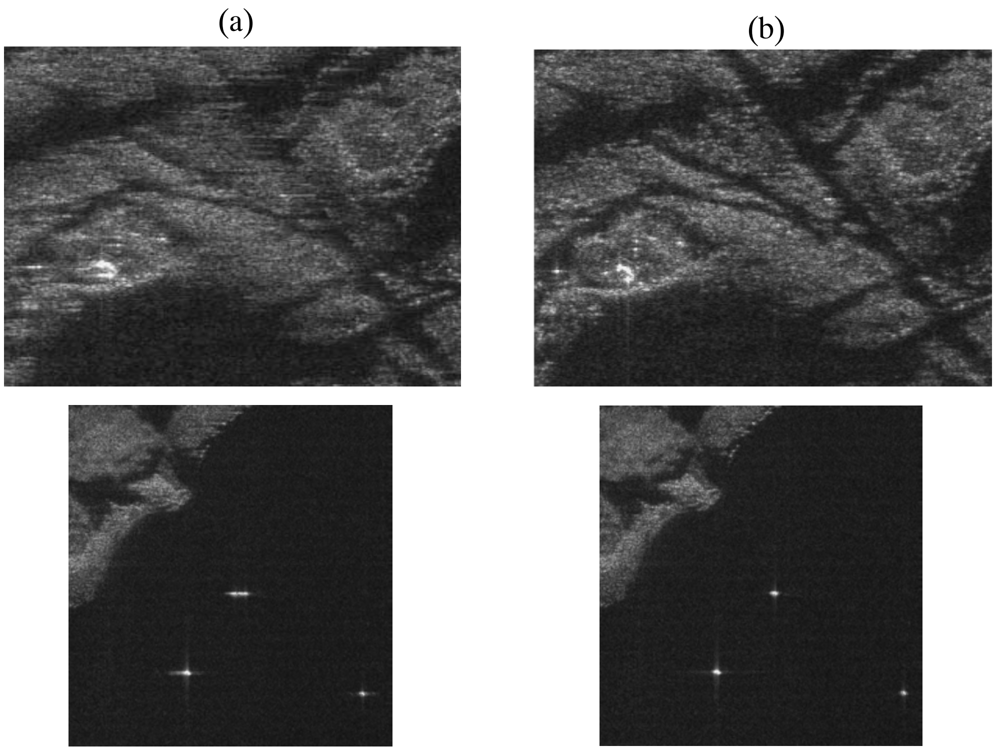

Figure 1. Image sections of a focussed SAR image using the
(a) Phase−Gradient Algorithm
(b) developed Algorithm

The second criterion is defined by the standard deviation of coordinate−errors of objects in the SAR−image and can be applied only on simulated data, since the requested real positions of the examined objects are unknown in case of real data. Fig. 1 shows two different sections of images that have been focussed using the PGA and the developed algorithm. Beside the improvement of target representation, the background appears finer when using the developed focussing algorithm. The image quality especially in case of high−frequency motion errors of the SAR antenna is improved significantly. Compared to the phase−gradient algorithm the quality criterion for evaluating the sharpness of SAR images is improved by 15%. The standard deviation of coordinate−errors of objects in the SAR−image is reduced from 94 to 3.8 pel.

Conclusion

Compared to the Phase−Gradient−Algorithm the developed estimator for the phase−error function provides a more accurate estimate by interpreting a reflector as a sequence of several neighbouring point targets instead of one single target. Consequently the backscattering coefficients of the neighbouring point targets have to be determined by an additional estimator. Furthermore a more accurate weighted super position technique, which avoid the impact by coordinate−errors of the selected reflectors, is used for the construction of the entire phase−error function from several functions.

By selecting reflectors with symmetrical arranged point targets the estimator error can be reduced and a more accurate phase−error−function may be achieved in a future development.

Literature

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