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EURASIP Journal on Advances in Signal Processing 2012, **2012**:221 doi:10.1186/1687-6180-2012-221

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ISSN	1687-6180
Article type	Research
Submission date	8 March 2012
Acceptance date	2 September 2012
Publication date	12 October 2012
Article URL	http://asp.eurasipjournals.com/content/2012/1/221

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An imaging algorithm based on keystone transform for one-stationary bistatic SAR of spotlight mode

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Abstract

This article proposes an imaging algorithm based on Keystone Transform for bistatic SAR with a stationary receiver. It can efficiently be applied to high-resolution spotlight mode, and can directly be process the bistatic SAR data which have been ranged compressed by the synchronization reference pulses. Both simulation and experimental results validate the good performance of this algorithm.

Keywords

bistatic SAR, imaging algorithm, keystone transform.

Introduction

Bistatic SAR is more flexible in data acquisition geometry compared with traditional monostatic SAR. However, this flexibility is gained at the cost of increasing system complexity, which not only refers to increasing hardware system complexity due to synchronization needs of transmitter and receiver, but also refers to increasing processing complexity. As for the synchronization, the easy to realize and commonly used strategy is using an additional antenna to receive the direct pulses from transmitter, and then using these directly received pulses as a reference for range compression. As for bistatic SAR imaging, a number of studies have been done and several kinds of imaging algorithms have been proposed for different configurations [1-9]. Furthermore, a number of bistatic SAR experiments with different configurations [10-15] have successfully been carried out till now.

Among the various configurations of bistatic SAR, the so-called one-stationary configuration, which is usually formed by an existing moving transmitter (i.e., spaceborne SAR, airborne SAR, or even navigation satellite [16]) and a stationary passive receiver, is, in the authors' opinion, one of the most practical configurations. On the one hand, it is inexpensive to build, and on the other hand, it can easily be extended to multi-receiver stations and then obtain multi-baseline interferometric SAR images to rebuild accurate DEM of regions of interest.

The main difficulty of imaging processing for the one-stationary bistatic configuration has been pointed out and solved to some extent in the authors' previous publication [17,18]. However, the former algorithm mainly aims at the stripmap mode and may not be suitable for the high-resolution spotlight mode. In spotlight mode, the pulse repetition frequency (PRF) is usually smaller than the Doppler bandwidth of a single target. So, the dechirp method is commonly used for efficient processing. Meanwhile, if range compression is done by the directly received pulses from the synchronization channel, the dechirp in azimuth has already been done within this range compressing step. After this dechirp step, the residual range and phase histories are still range-azimuth variant, while the linear term is predominant. In the high-resolution case, the range histories are bending more severely as the range bins are smaller. Hence, the differential range histories for those targets with the same bistatic range will exceed one range gate; therefore, the precondition of the NLCS algorithm based on azimuth perturbation in [18] is no longer valid. Till now, almost all the published images of the one-stationary bistatic SAR experiments have been focused by the universal backprojection (BP) algorithm [10,16]. Although good quality images can be obtained using this algorithm, the main shortcoming is its computational inefficiency. The computation load of BP algorithm for producing an image, whose size is M * M and the synthetic aperture length is K, is on the order of M^*M^*K (i.e., $O(M^*M^*K)$). This can be very large for a big size highresolution image.

In this article, an efficient imaging algorithm based on the Keystone Transform for onestationary bistatic SAR, whose computation load is on the order of $M^2 \log_2 M$, is proposed. The Keystone Transform is usually used in ISAR processing. The idea of using this transform to correct the azimuth variant range cell migration (RCM) in medium-earth–orbit SAR imaging has been proposed in the authors' another article (H Lijia, Q Xiaolan, H Donghui, D Chibiao, A novel algorithm based on keystone transform and azimuth perturbation for medium-earth-orbit SAR, submitted). In this study, we propose to use the Keystone Transform for bistatic SAR imaging. The approach can directly be performed on bistatic SAR data which has been range compressed by the synchronization reference pulses, which makes it convenient to use. The experimental data of the HITCHHIKER system at University of Siegen/ZESS is used to test this algorithm, and good bistatic SAR images are obtained by this algorithm.

This article is organized as follows: "Geometry and signal model" section describes the onestationary bistatic SAR geometry, and builds the signal model; "Imaging algorithm based on Keystone Transform" section introduces the proposed imaging algorithm step-by-step and shows the block diagram of the algorithm; "Simulation and experimental results" section validates the imaging algorithm through simulations and experimental results, and "Conclusion" section concludes the article.

Geometry and signal model

One-stationary bistatic SAR geometry

The one-stationary bistatic SAR geometry is illustrated in Figure 1. In some Earth-fixed coordinates, the vector of stationary receiver location is $\mathbf{R}_{\mathbf{R}} = (X_R, Y_R, Z_R)^T$. The vector of the moving transmitter is $\mathbf{R}_{\mathbf{T}}(\eta) = [X_T(\eta), Y_T(\eta), Z_T(\eta)]^T$, when the azimuth time (slow time) is η . An arbitrary point scatter on the earth is denoted as $\mathbf{r} = (x, y, z)^T$.

Figure 1 Bistatic SAR geometry of one-stationary configuration

Signal model

If the time when the received echo reaches the maximum power is considered as $\eta = 0$, the range history of the direct pulses and that of the target **r** in spotlight mode can be, respectively, represented as follows.

$$R_D \eta = \mathbf{R}_{\mathbf{R}} - \mathbf{R}_{\mathbf{T}} \eta \tag{1}$$

$$R_{bi} \eta; \mathbf{r} = \mathbf{r} - \mathbf{R}_{\mathbf{T}} \eta + \mathbf{r} - \mathbf{R}_{\mathbf{R}}$$
(2)

If the nominal frequency of the transmitted signal is f_{0T} and the transmitted signal has a rectangular envelope with a time duration T and a wide bandwidth, the received signal in direct channel and echo channel before down conversion at time $\eta + \tau$ can be written as follows, respectively,

$$g_{D}(\eta,\tau) \approx w_{D}(\eta,\tau) \operatorname{rect}\left[\frac{\tau - R_{D}(\eta)/c}{T}\right] p \tau - R_{D}(\eta)/c$$

$$\cdot \exp\{j2\pi f_{0T}[\eta + \tau - R_{D}(\eta)/c] + j\phi_{T}[\eta + \tau - R_{D}(\eta)/c]\}$$

$$g(\eta,\tau) \approx \iint_{x,y} \begin{cases} w(\eta,\tau;\mathbf{r})\sigma(\mathbf{r}) \operatorname{rect}\left[\frac{\tau - R_{bi}(\eta;\mathbf{r})/c}{T}\right] \\ \cdot p \tau - R_{bi}(\eta;\mathbf{r})/c \\ \cdot \exp\{j2\pi f_{0T}[\eta + \tau - R_{bi}(\eta;\mathbf{r})/c]\} \\ \cdot \exp\{j2\pi f_{0T}[\eta + \tau - R_{bi}(\eta;\mathbf{r})/c]\} \end{cases} dxdy$$

$$(4)$$

where $p(\tau)$ represents the transmitted waveform; τ represents the fast time (range time), whose origin is when the pulse is transmitted; ϕ_T is the phase error of the transmitter oscillator; $\sigma(\mathbf{r})$ is the scattering coefficient of target \mathbf{r} ; $w_D(\eta, \tau)$ and $w(\eta, \tau; \mathbf{r})$ mean the weight due to the transmitter and receiver antenna pattern, propagation loss, etc. Without loss of generality, $w(\eta, \tau; \mathbf{r})$ and $w_D(\eta, \tau)$ are considered as constants here and are ignored in the following analysis.

The approximate equal marks in Equations (3) and (4) come from neglecting the variation of R_D and R_{bi} with τ , respectively.

If the nominal frequency of the receiver is f_{0R} , the down conversion signal at $\eta + \tau$ is then

$$g_R \eta + \tau = exp - j2\pi f_{0R} \eta + \tau - j\phi_R \eta + \tau$$
(5)

where ϕ_R is the phase error of the receiver oscillator.

Hence, after down conversion, the direct channel signal is

$$s_{D}(\eta,\tau) = \operatorname{rect}\left[\frac{\tau - R_{D}(\eta)/c}{T}\right] p \tau - R_{D}(\eta)/c$$

$$\cdot \exp\{-j2\pi f_{0T}R_{D}(\eta)/c\}$$

$$\cdot \exp\{j2\pi (f_{0T} - f_{0R})(\eta + \tau)\}$$

$$\cdot \exp\{j\phi_{T}[\eta + \tau - R_{D}(\eta)/c] - j\phi_{R}(\eta + \tau)\}$$
(6)

and the echo channel signal is

$$s(\eta,\tau) = \iint_{x,y} \begin{cases} \sigma(\mathbf{r}) \operatorname{rect} \left[\frac{\tau - R_{bi}(\eta;\mathbf{r})/c}{T} \right] p \left[\tau - \frac{R_{bi}(\eta;\mathbf{r})}{c} \right] \\ \cdot \exp\{-j2\pi f_{0T} R_{bi}(\eta;\mathbf{r})/c\} \\ \cdot \exp\{j2\pi (f_{0T} - f_{0R})(\eta + \tau)\} \\ \cdot \exp\{j\phi_{T}[\eta + \tau - R_{bi}(\eta)/c] - j\phi_{R}(\eta + \tau)\} \end{cases} dxdy$$

$$(7)$$

Compress $s(\eta, \tau)$ in range direction using $s_D(\eta, \tau)$, which is

$$s_1 \eta, \tau = \text{IFFT}^{\tau} \text{ shift FFT}^{\tau} s \eta, \tau \cdot \text{conj FFT}^{\tau} s_D \eta, \tau$$
 (8)

Here, *shift* means to shift the spectrum which is centered at $f_{0T} - f_{0R}$ to be centered at zero in the range frequency domain and *conj* means conjugation. Then we have

$$s_{1}(\eta,\tau) \approx \iint_{x,y} \begin{cases} \sigma(\mathbf{r}) \operatorname{sinc} \left[\tau - \frac{R_{bi}(\eta;\mathbf{r}) - R_{D}(\eta)}{c} \right] \\ \cdot \exp\{-j2\pi f_{0T} [R_{bi}(\eta;\mathbf{r}) - R_{D}(\eta)]/c \} \end{cases} dxdy$$
(9)

The approximation in the above equation comes from omitting of the phase difference between rect $\frac{\tau - R_D \eta / c}{T} exp - j\phi_R \eta + \tau$ and ect $\frac{\tau - R_{bi} \eta \cdot r / c}{T} exp - j\phi_R \eta + \tau$, which can usually be ignored.

It can be seen from Equation (9) that, after range compression using the reference signal from the direct channel, the time synchronization problem is solved because all the received echo

pulses are aligned to the known $R_D(\eta)$. The frequency synchronization problem is solved because the direct and the echo pulses are generated by the same transmitter. The phase synchronization is also solved as long as no additional phase difference is introduced by the two receive channels. This is because the phase errors caused by the transmitter are the same in direct and echo pulses and hence can be counteracted; besides, as the direct and the echo pulses are received with small time difference, the phase errors caused by the receiver in direct and in echo pulses are nearly the same and also can be counteracted. So, as has been said in the introduction, this is the easiest and commonly used synchronization method. Therefore, it is reasonable to start bistatic SAR focusing from $s_1(\eta, \tau)$.

The residual range history after range compression is

$$R_{bic} \eta; \mathbf{r} = R_{bi} \eta; \mathbf{r} - R_D \eta \tag{10}$$

It can be seen that, if the receiver is near the scenario, the higher order terms in $R_{bic}(\eta; \mathbf{r})$ will be much smaller than those in the original range history $R_{bi}(\eta; \mathbf{r})$, so the Doppler bandwidth of the targets after range compression by the reference pulses is much smaller than the original Doppler bandwidth. For example, in the spaceborne-ground bistatic SAR configuration, such as in TerraSAR-X/HITCHHIKER experiment, the original Doppler bandwidth is about 5192 Hz, but after the range compression using the direct pulses, the residual Doppler bandwidth shrinks to be about 62 Hz. Therefore, if traditional imaging algorithms, which correct RCM in the azimuth frequency domain, are applied, a Doppler wideband signal rebuilding step should be adopted, which makes them not very convenient to use. In the next section, an algorithm based on the Keystone Transform which does not need Doppler signal rebuilding will be introduced.

Imaging algorithm based on Keystone Transform

Keystone Transform for linear RCM correction

In one-stationary spotlight bistatic SAR cases, such as spaceborne-ground cases and straight path airborne-ground cases, the residual range history can be approximated as follows:

$$R_{\text{bic}} \eta; \mathbf{r} \approx R_{\text{bic}} 0; \mathbf{r} + A\eta + B\eta^2 + C\eta^3 + D\eta^4$$
(11)

where A, B, C, D are functions of the target position **r**. In case of simple trajectories such as uniform linear motion, the formula of these parameters A, B, C, D can be obtained as derivatives of $R_{bic}(\eta ; \mathbf{r})$. For example, if the transmitter flies along y-axis with a constant velocity V_T , then the parameters A and B are as follows

$$A \mathbf{r} = V_T \frac{Y_T \ 0 \ -y}{\mathbf{r} - \mathbf{R}_T \ 0} - \frac{Y_T \ 0 \ -Y_R}{\mathbf{R}_R - \mathbf{R}_T \ 0}$$
(12)

$$B \mathbf{r} = V_T^2 \frac{\cos^2 \theta_T \mathbf{r}}{\mathbf{r} - \mathbf{R}_T \mathbf{0}} - \frac{\cos^2 \theta_T \mathbf{R}_R}{\mathbf{R}_R - \mathbf{R}_T \mathbf{0}}$$
(13)

where

$$\theta_T \mathbf{r} = \cos^{-1} \frac{\overline{X_T \ 0 - x^{\ 2} + Z_T \ 0 - z^{\ 2}}}{\mathbf{r} - \mathbf{R}_T \ 0}$$
(14)

$$\theta_T \mathbf{R}_{\mathbf{R}} = \cos^{-1} \frac{\overline{X_T \ 0 - X_R \ ^2 + Z_T \ 0 - Z_R \ ^2}}{\mathbf{R}_{\mathbf{R}} - \mathbf{R}_{\mathbf{T}} \ 0}$$
(15)

It can be seen that $A(\mathbf{r})$ nearly linearly depends on y, which means it is strongly azimuth variant, while $B(\mathbf{r})$ depends on $|\mathbf{r} - \mathbf{R}_{\mathbf{T}}(0)|$ and $\theta_T(\mathbf{r})$, which is more slightly azimuth variant than $A(\mathbf{r})$. The higher-order terms are much smaller than the first two-order terms, so here we pay more attention to $A(\mathbf{r})$ and $B(\mathbf{r})$.

In case of a complex trajectory, these parameters can numerically be obtained by polynomial fit to the residual range history.

After performing a range Fourier transform on $s_1(\eta, \tau)$, we have

$$S_{1}(\eta, f) = \iint_{x, y} \sigma(\mathbf{r}) \exp\left\{-j2\pi \frac{f_{0T} + f}{c} R_{bic}(\eta; \mathbf{r})\right\} dxdy$$

$$\approx \iint_{x, y} \left\{ \sigma(\mathbf{r}) \exp\left\{-j2\pi \frac{f_{0T} + f}{c} R_{bic}(0; \mathbf{r})\right\} \\ \cdot \exp\left\{-j2\pi \frac{f_{0T} + f}{c} A\eta + B\eta^{2} + C\eta^{3} + D\eta^{4}\right\} \right\} dxdy$$
(16)

The Keystone Transform for linear decoupling is as follows. Let

$$\xi = \frac{f_{0T} + f}{f_{0T}} \eta \tag{17}$$

then

$$S_{1}(\xi,f) \approx \iint_{x,y} \begin{cases} \sigma(\mathbf{r}) \cdot \exp\left\{-j2\pi \frac{f_{0T}+f}{c} R_{bic}(0;\mathbf{r})\right\} \\ \cdot \exp\left\{-j\frac{2\pi}{\lambda} A\xi\right\} \exp\left\{-j\frac{2\pi}{\lambda} \left(\frac{f_{0T}}{f_{0T}+f}\right)^{2} B\xi^{2}\right\} \\ \cdot \exp\left\{-j\frac{2\pi}{\lambda} \left(\frac{f_{0T}}{f_{0T}+f}\right)^{2} C\xi^{3}\right\} \\ \cdot \exp\left\{-j\frac{2\pi}{\lambda} \left(\frac{f_{0T}}{f_{0T}+f}\right)^{3} D\xi^{4}\right\} \end{cases}$$
(18)

where $\lambda = c / f_{0T}$.

In the general SAR case, $|f| \ll f_{0T}$, so the following approximation can be applied.

$$\frac{f_{0T}}{f_{0T}+f} \approx 1 - \frac{f}{f_{0T}} + \frac{f}{f_{0T}}^2 - \frac{f}{f_{0T}}^3$$
(19)

$$\frac{f_{0T}}{f_{0T}+f}^{2} \approx 1 - 2\frac{f}{f_{0T}} + 3 \frac{f}{f_{0T}}^{2} - 4 \frac{f}{f_{0T}}^{3}$$
(20)

$$\frac{f_{0T}}{f_{0T}+f}^{3} \approx 1 - 3\frac{f}{f_{0T}} + 6 \frac{f}{f_{0T}}^{2} - 10 \frac{f}{f_{0T}}^{3}$$
(21)

Substituting Equations (19)-(21) into Equation (18) and reorganizing yields

$$S_{1}(\xi, f) \approx \iint_{x, y} \begin{cases} \sigma(\mathbf{r}) \exp\left\{-j\frac{2\pi}{\lambda} \frac{f_{0T} + f}{f_{0T}} R_{bic}(0; \mathbf{r})\right\} \\ \exp -j\psi_{A}(\xi; \mathbf{r}) \\ \exp -j\psi_{coup}(\xi, f; \mathbf{r}) \end{cases} dxdy$$

$$(22)$$

where

$$\psi_A \xi; \mathbf{r} = \frac{2\pi}{\lambda} A\xi + B\xi^2 + C\xi^3 + D\xi^4$$
(23)

is the azimuth phase which only depends on ξ . And

$$\psi_{\text{coup}}(\xi, f; \mathbf{r}) = \frac{2\pi}{\lambda} \frac{f}{f_{0T}} - B\xi^2 - 2C\xi^3 - 3D\xi^4 + \frac{2\pi}{\lambda} \left(\frac{f}{f_{0T}}\right)^2 B\xi^2 + 3C\xi^3 + 6D\xi^4 + \frac{2\pi}{\lambda} \left(\frac{f}{f_{0T}}\right)^3 - B\xi^2 - 4C\xi^3 - 10D\xi^4$$
(24)

is the phase containing the azimuth-range coupling. It can be seen from this phase that no linear coupling between f and ξ exists, which means that the linear RCMs for all targets have been corrected by the Keystone Transform. Then, a bulk phase compensation according to the reference target can be done by the following function

$$H_{\text{comp}}(\xi, f) = \exp\left\{-j\frac{2\pi}{\lambda}\left(\frac{f}{f_{0T}}\right) B_{\text{ref}}\xi^{2} + 2C_{ref}\xi^{3} + 3D_{\text{ref}}\xi^{4}\right\}$$

$$\cdot \exp\left\{j\frac{2\pi}{\lambda}\left(\frac{f}{f_{0T}}\right)^{2} B_{\text{ref}}\xi^{2} + 3C_{ref}\xi^{3} + 6D_{\text{ref}}\xi^{4}\right\}$$

$$\cdot \exp\left\{-j\frac{2\pi}{\lambda}\left(\frac{f}{f_{0T}}\right)^{3} B_{\text{ref}}\xi^{2} + 4C_{ref}\xi^{3} + 10D_{\text{ref}}\xi^{4}\right\}$$
(25)

where subscript *ref* means the value calculated at the reference position (usually to be the scene center). Here, we denote $S_2(\xi, f) = S_1(\xi, f)H_{\text{comp}}(\xi, f)$.

Because B, C, D are all changing with **r**, there is a coupled phase remaining in $S_2(\xi, f)$. The second- and higher-order terms of f / f_{0T} in the remaining coupled phase will decrease the

range focusing quality. Usually, if the quadratic phase error is smaller than $\pi/4$, the imaging quality is acceptable. So, the following condition is used to restrict the processing area.

$$\max\left\{\frac{2\pi}{\lambda}\left(\frac{f_B}{2f_{0T}}\right)^2 \mid B(\mathbf{r}) - B_{\text{ref}} \xi^2 + 3 C(\mathbf{r}) - C_{\text{ref}} \xi^2 + 6 D(\mathbf{r}) - D_{\text{ref}} \xi^2\right\} \le \frac{\pi}{4}$$
(26)

This ensures that in each processing area, all targets **r** at each ξ have quadratic phase error that smaller than $\pi/4$, so the imaging quality is guaranteed.

Residual RCM correction

If the higher-order term phases of $S_2(\xi, f)$ are restricted and their effects can be neglected. Then, applying an inverse Fourier transform to $S_2(\xi, f)$, the signal in the time domain is

$$s_{2}(\xi,\tau) \approx \iint_{x,y} \begin{cases} \sigma(\mathbf{r}) \exp\left\{-j\frac{2\pi}{\lambda}R_{bic}(0;\mathbf{r})\right\} \\ \cdot \operatorname{sinc}\left(\tau - \frac{R_{bic}(0;\mathbf{r}) - R_{RCM}^{r}(\xi;\mathbf{r})}{c}\right) \\ \cdot \exp\left[-j\psi_{A}(\xi;\mathbf{r})\right] \end{cases} dxdy$$

$$(27)$$

where

$$R_{\rm RCM}^r \xi; \mathbf{r} = B - B_{\rm ref} \xi^2 + 2 \ C - C_{\rm ref} \xi^3 + 3 \ D - D_{\rm ref} \xi^4$$
(28)

It can be seen that the position of a target in the image plane along the fast time axis is determined by $R_{bic}(0; \mathbf{r})$, and the residual RCM is a function of the target location, which is range–azimuth variant. Usually, the RCM, which is within half a slant range resolution cell ρ_r , can be neglected in SAR imaging field. So, if the following restriction

$$max \ R_{\rm RCM}^r \ \xi; \mathbf{r} \ < \frac{\rho_r}{2}$$
(29)

is satisfied for any **r**, then residual RCM correction step can be omitted. If this cannot be satisfied for the whole scene, then the sub-swath strategy can be used to deal with the azimuth variance and interpolation in two-dimensional time domain can correct the range variance of $R_{\text{RCM}}^{r}(\zeta; \mathbf{r}_i)$.

The sub-swath dealing with the azimuth variance is as follows. First, a reference position \mathbf{r}_i is chosen for each range gate *i* (usually choose to be in the middle of azimuth swath). Then, the azimuth processing sub-swath is restricted according to the following condition

$$max \ R_{\rm RCM}^r \ \xi; \mathbf{r} \ -R_{\rm RCM}^r \ \xi; \mathbf{r}_i \ <\rho_r/2 \tag{30}$$

Consider the main component (i.e., the second-order term) in $|R_{\text{RCM}}^r(\xi; \mathbf{r}) - R_{\text{RCM}}^r(\xi; \mathbf{r}_i)|$ and calculate the above restriction, we have

$$\max \left| R_{\text{RCM}}^{r}(\xi; \mathbf{r}) - R_{\text{RCM}}^{r}(\xi; \mathbf{r}) - R_{\text{RCM}}^{r}(\xi; \mathbf{r}) \right|$$

$$\approx \max \left\{ V_{T}^{2} \xi^{2} \left| \frac{\cos^{2} \theta_{T}(\mathbf{r})}{|\mathbf{r} - \mathbf{R}_{T}(0)|} - \frac{\cos^{2} \theta_{T}(\mathbf{r}_{i})}{|\mathbf{r}_{i} - \mathbf{R}_{T}(0)|} \right| \right\}$$

$$\approx \max \left\{ \frac{V_{T}^{2} \xi^{2}}{|\mathbf{r}_{i} - \mathbf{R}_{T}(0)|} \left| \cos^{2} \theta_{T}(\mathbf{r}) - \cos^{2} \theta_{T}(\mathbf{r}_{i}) \right| \right\} < \frac{\rho_{r}}{2}$$

$$(31)$$

It can be seen that the azimuth sub-swath can be restricted through θ_T (**r**), and the limitation of θ_T (**r**) is variant with range.

Azimuth compression

After the above steps, the final azimuth compression step can be done. The higher-order term of $\psi_A(\xi; \mathbf{r})$, which is

$$\psi_A^h \xi; r = \frac{2\pi}{\lambda} B\xi^2 + C\xi^3 + D\xi^4$$
(32)

is desired to be removed for fine focusing. If the azimuth variation of $\psi_A^{\ h}(\xi; \mathbf{r})$ is smaller than $\pi/4$, then for each range gate, the following phase compensation filter is applied

$$H_{\rm Ac} \xi; \mathbf{r}_{\mathbf{i}} = exp \ j\frac{2\pi}{\lambda} B \mathbf{r}_{\mathbf{i}} \xi^2 + C \mathbf{r}_{\mathbf{i}} \xi^3 + D \mathbf{r}_{\mathbf{i}} \xi^4$$
(33)

Then the final focused image can be obtained through azimuth Fourier transform. The final image can be written as

$$s_{3}(f_{\xi},\tau) = \iint_{x,y} \left\{ \sigma(\mathbf{r}) \exp\left\{-j\frac{2\pi}{\lambda}R_{bic}(0;\mathbf{r})\right\} \\ \cdot \operatorname{sinc}\left(\tau - \frac{R_{bic}(0;\mathbf{r})}{c}\right) \cdot \operatorname{sinc}\left(f_{\xi} + \frac{A(\mathbf{r})}{\lambda}\right) \right\} dxdy$$
(34)

If the azimuth variation of $\psi_A{}^h(\xi; \mathbf{r})$ is larger than $\pi/4$, an additional step of sub-segment azimuth processing is needed. This means to cut the above image into several small segments along azimuth direction (according to the azimuth variation of $\psi_A{}^h(\xi; \mathbf{r})$), and then to perform an inverse Fourier transform to get the azimuth time domain signal for each segment. The differential phase between $\psi_A{}^h(\xi; \mathbf{r})$ of this segment and the phase of $H_{Ac}(\xi; \mathbf{r})$ for each range gate can be calculated through range history, and be compensated for this segment. Finally, all the segments are transformed to the frequency domain and combined together to get the final fine focused image.

Geocoding

As can be seen from Equation (34), the axes of the focused image are τ and f_{ξ} , whose limitations are $[\tau_1 : 1 / f_s : \tau_1 + (N_r - 1) / f_s]$ and $[-f_{PRF} / 2 : f_{PRF} / N_a : f_{PRF} / 2]$, respectively. Here, N_r is the image size in range direction and N_a is the size in azimuth direction. f_s is the sample rate and f_{PRF} is the PRF. τ_1 corresponds to the sample delay of the first range gate after

range compression. When trigger time of the echo channel is the same as that of the direct pulse channel, then $\tau_1 = R_D(0) / c$.

The position of target \mathbf{r} in the image plane is as follows

$$\begin{cases} \tau_{\mathbf{r}} = \frac{R_{\rm bic}(0;\mathbf{r})}{c} \\ f_{\xi \mathbf{r}} = -\frac{A(\mathbf{r})}{\lambda} \end{cases}$$
(35)

where

$$A(\mathbf{r}) = \frac{dR_{\text{bic}}(\eta; \mathbf{r})}{dt}\Big|_{\eta=0}$$

$$= \frac{-\mathbf{V}_{\mathbf{T}}(0) \bullet \mathbf{r} - \mathbf{R}_{\mathbf{T}}(0)}{|\mathbf{r} - \mathbf{R}_{\mathbf{T}}(0)|} - \frac{-\mathbf{V}_{\mathbf{T}}(0) \bullet \mathbf{R}_{\mathbf{R}} - \mathbf{R}_{\mathbf{T}}(0)}{|\mathbf{R}_{\mathbf{R}} - \mathbf{R}_{\mathbf{T}}(0)|}$$
(36)

Here, V_T is the transmitter velocity vector in the Earth-fixed coordinates. If a DEM of the scenario is provided, then geocoding can be done according to Equations (1), (2), (10), (35), and (36).

Block diagram of the algorithm

The block diagram of the proposed algorithm for one-stationary bistatic SAR of spotlightmode is shown in Figure 2. It can be seen that the algorithm is quite efficient as only a pair of range Fourier transforms and a single azimuth Fourier transform are needed for the nonsevere azimuth variant case.

Figure 2 Block diagram of the proposed algorithm for one-stationary bistatic SAR of spotlight mode

Simulation and experimental results

To testify this algorithm, both simulated bistatic SAR data and the real experimental data of HITCHHIKER are processed using this algorithm, and results are analyzed and compared in this section.

Point target simulation

The parameters of point target simulation are according to the TerraSAR-X/HITCHHIKER bistatic experiment in Siegen, Germany. The locations of the stationary receiver and the scene center described by [latitude, longitude, height] are [50.910787 deg, 8.027111 deg, 434.91 m] and [50.913650 deg, 8.059843 deg, 292 m], respectively. The transmitter and receiver parameters are shown in Table 1 and the locations of simulated targets in East-North-Height coordinates with the receiver as the origin are shown in Figure 3. These targets represent the main scenario area of the real experiment. In order to observe the azimuth variation of the range history, each column of targets has the same bistatic range, so each column of targets are on an ellipse arc.

Symbol	Meaning	Quantity
for	Transmitter frequency	9.65 GHz
f_B	Signal bandwidth	300 MHz
f_s	Sample rate	330 MHz
PRF	PRF	3224.35 Hz
for	Receiver frequency	9.70 GHz
T_a	Data acquisition time	2.48 s
N_a	Azimuth pulse number	8000
N _r	Range sample number	30000

Table 1 Transmitter and receiver parameters for simulation

Figure 3 Locations of the targets and the receiver

After the range compressing using reference pulses, the residual range histories (without the constant term) of the simulated targets are shown in Figure 4. It can be seen that the RCMs are different for different targets. From Figure 4a, we can see that, for each column of targets, the liner components of their RCMs are changing with their azimuth location. This is consistent with Equation (12). The residual RCMs after the linear terms have been removed by the Keystone Transform are shown in Figure 4b. It can be seen that the residual RCMs are mainly range variant. The targets within the same column (which have the same bistatic range when $\eta = 0$ have almost the same residual RCMs. After the bulk residual RCM correction by H_{comp} , the residual RCMs for the simulated targets are all smaller than 0.35 m (see Figure 4c). This is smaller than half a range resolution cell (a range resolution cell is about 0.886 m here), so the range variant residual RCM correction can be omitted in this case. The residual azimuth phases after azimuth phase compensation for each range gate using H_{Ac} are shown in Figure 5. It can be seen that the azimuth phase errors for all the targets in the scene are smaller than 25°, so the sub-segment processing step is not needed in this simulation. The imaging results are shown in Figure 6. It can be seen that targets at different locations are all well focused.

Figure 4 Range history after each processing step

Figure 5 Residual azimuth phase errors

Figure 6 Imaging result of the simulated targets

To testify the phase preserving ability of this algorithm, and to answer the question: whether the image processed by this algorithm is able to do the further interferometry processing, another set of raw data is simulated. All the parameters are the same with the first raw data, except that the receiver's location described by [latitude, longitude, height] is [50.910787 deg, 8.027111 deg, 435.91 m]. The differential phases of target N, M, F are shown in Table 2, from which we can see that the differential phases are very close to the ideal differential phases calculated by $-\frac{2\pi}{\lambda} R_{\rm bic} 0$; $\mathbf{r} - R_{\rm bic}^{\rm new} 0$; \mathbf{r} , where $R_{\rm bic}^{\rm new}$ means the range corresponding to the second receiver. The variance of the differential phase errors of all the simulated targets is 0.0919°. This means that the algorithm provided here is well phase preserving and can support the interferometry processing.

Target	Differential phase (degree)	Phase error (degree)	
	Measured from images	Ideal value	
Ν	156.9894	157.1157	-0.1263
М	-55.1917	-55.0924	-0.0993
F	76.2087	76.1398	0.0689

Table 2 Interferometry phases of the simulated targets

Experimental data processing and results

The experimental data of the TerraSAR-X/HITCHHIKER bistatic SAR experiment is processed by the proposed algorithm. The focused image before geocoding of the scenario is shown in Figure 7b, and zoomed patches of the image are shown in Figure 7a, from which we can see that the image is well focused.

Figure 7 Imaging result of the experimental data processed by the proposed algorithm without geocoding

The image is then geocoded based on the DEM data of the scenario. Overlay the image on to Google earth, all the buildings and roads match very well with the orthophoto, which validates the correctness of the geocoding method in "Geocoding" section. The geocoded image by proposed algorithm is compared with the imaging result of BP algorithm in Figure 8. It can be seen that the imaging result of the algorithm provided here can compare beauty with the result of BP algorithm. In the imaging results, the buildings are well focused, while the trees are a little blur because the weather is windy while data acquisition. The same size (4096*6000) image processed by the algorithm here using Matlab on a single PC takes about 5 min, while processed by BP algorithm.

Figure 8 Comparison of the geocoded image results processed by the proposed algorithm and by BP algorithm

Conclusion

This article proposed an imaging algorithm for the one-stationary bistatic SAR in spotlight mode. The main property of the algorithm is using the Keystone Transform to correct the linear part of the two-dimensional variant RCM. The algorithm can directly be applied to the bistatic SAR data which has been range compressed by the reference pulses; therefore, it is efficient and convenient to use. Both simulation and experimental data processing results validate the algorithm.

Competing interests

The authors declare that they have no competing interests.

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Acknowledgments

This study was supported in partly by the Special Foundation of President of the Chinese Academy of Sciences, the National Science Foundation of China (No. 61101200), and the authors are gratefully acknowledging the support of K.C. Wong Education Foundation Hong Kong.

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residual azimuth phase error





Figure 6

range

(a)



(b)





(b)



(c)