Direct Signal's Impact on BISAR Signal Formation and Image Reconstruction

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***Abstract**: In this work the evaluation of the direct signal impact on the process of signal formation and image reconstruction, and on the quality of the reconstructed image in Bistatic Inverse Synthetic Aperture Radar (BISAR) is discussed. Geometric description of BISAR topology with space-based transmitter and receiver, and moving target is given. Kinematic vector equations are derived. The composition of the BISAR pulse signal with linear frequency modulation (LFM) reflected from the object and direct signal from the transmitter is analytically described. Image reconstruction algorithm is suggested. Numerical experiments to verify the composed signal model and imaging algorithm are carried out.*

1. Introduction

In recent years BISAR principle enjoys considerable attention [1-3]. There exist several applications of BISAR systems with transmitter of opportunity. One of the most prospective BISAR applications is in early warning and prevention of air, land and maritime border intrusion. The concept of a forward scattering micro-sensors radar network for situational awareness and netted forward scattering micro radars for ground targets detection and identification by quasi-optimal signal processing is considered in [4]. Forward scattering radar power budget analysis Radar Cross Section (RCS) estimation for ground targets are presented in [5]. The solution of problems of forward scattering radars for vehicles classification and automatic ground target classification using principle component analysis and neural network is suggested in [6-7].

The problems posed in this work are as follows: analytically description of the BISAR discrete geometry and based on it derivation of a mathematical model of LFM BFISAR reflected signal composed of signal reflected from the target and direct signal from the transmitter of opportunity, definition of the image reconstruction algorithm with adaptive filtering of measured clutter direct signal from the transmitter.

2. BISAR Geometry

BISAR scenario consists of space-based transmitter, receiver located on the land surface and moving target, all are depicted in Cartesian coordinate system *Oxyz* (Fig. 1), where $\mathbf{R}^s(p)$ is the current position vector of the GPS transmitter in discrete time instant p, $\mathbf{R}_{00'}(p)$ is the current position vector of the mass center of the target, $\mathbf{R}^r$ is the stationary position vector of the receiver. The target presented as an assembly of point scatterers is described in Cartesian coordinate system $O'XYZ$, where $\mathbf{R}_{ijk}$ is the position vector of the ijkth point scatterer.

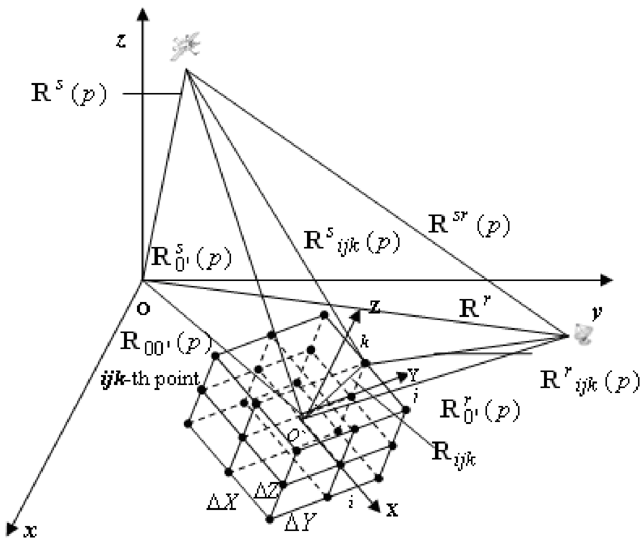


Figure 1. BISAR topology

Kinematic Equations

The position vector of the target's mass center with respect to the transmitter, $\mathbf{R}^s_{0'}(p)$ is defined by

$$\mathbf{R}^s_{0'}(p) = \mathbf{R}^s(p) - \mathbf{R}_{00'}(p), \tag{1}$$

where $\mathbf{R}^s(p) = \mathbf{R}^s(0) - \mathbf{V}_s\left(\frac{N}{2} - p\right)T_p$ is the current position vector of the transmitter, $\mathbf{R}_{00'}(0) = \mathbf{R}_{00'}(0) - \mathbf{V}\left(\frac{N}{2} - p\right)T_p$ is the current position vector of the target mass centre; $\mathbf{V}_s$ is the transmitter velocity vector, $\mathbf{V}$ is the target velocity vector, $p = \overline{0, N-1}$ is the current number of the emitted pulse, N is the full number of emitted pulses used for purposes of the aperture synthesis, T_p is the time acquisition interval (pulse repetition interval), $\left(\frac{N}{2} - p\right)T_p$ is the discrete slow time measured on azimuth (cross-range) direction.

The position vector of the target mass center with respect to the receiver, $\mathbf{R}^r_{0'}(p)$ is defined by

$$\mathbf{R}^r_{0'}(p) = \mathbf{R}^r - \mathbf{R}_{00'}(p) = \mathbf{R}^r - R_{00'} - \mathbf{V}\left(\frac{N}{2} - p\right)T_p. \tag{2}$$

The position vector of the ijkth point scatterer with respect to the transmitter, $\mathbf{R}^s{}_{ijk}(p)$ is defined by

$$\mathbf{R}^s{}_{ijk}(p) = \mathbf{R}^s_{0'}(p) + \mathbf{A}\mathbf{R}_{ijk} = \mathbf{R}^s_{0'}(p) - \mathbf{R}_{00'}(0) - \mathbf{V}\left(\frac{N}{2} - p\right)T_p + \mathbf{A}\mathbf{R}_{ijk}, \tag{3}$$

where $\mathbf{A}$ is the coordinate transition matrix.

The position vector of the ijkth point scatterer with respect to the receiver, $\mathbf{R}^s{}_{ijk}(p)$ is defined by

$$\mathbf{R}^r{}_{ijk}(p) = \mathbf{R}^r_{0'}(p) - \mathbf{AR}_{ijk} = \mathbf{R}^r - \mathbf{R}_{00'}(0) - \left(\frac{N}{2} - p\right)T_p - \mathbf{AR}_{ijk}. \quad (4)$$

The round trip distance measured between spacebased transmitter, ijkth point scatterer of the target, and receiver is calculated by

$$R_{ijk}(p) = \left|\mathbf{R}^s{}_{ijk}(p)\right| + \left|\mathbf{R}^r{}_{ijk}(p)\right|. \quad (5)$$

Equation (5) is used to calculate the round trip time delay of the signal reflected by a particular point scatterer from the target area while signal modeling.

3. Model of LFM BISAR signal reflected from the target

The deterministic component of the BISAR signal, reflected by ijkth point scatterer of the target for each pth emitted pulse has the form

$$\dot{S}_{ijk}(p,k) = a_{ijk}\,\mathbf{rect}\frac{t - t_{ijk}(p)}{T}\,\mathbf{exp}\left\{-j\left[\omega\left(t - t_{ijk}(p)\right) + b\left(t - t_{ijk}(p)\right)^2\right]\right\}, \quad (6)$$

where $\mathbf{rect}\dfrac{t - t_{ijk}(p)}{T} = \begin{cases} 1, 0 \le \dfrac{t - t_{ijk}(p)}{T} < 1, \\ 0, \text{otherwise.} \end{cases}$

a_{ijk} is the reflection coefficient of the ijkth point scatterer, a three-dimensional (3-D) image function; $t_{ijk}(p) = \dfrac{R_{ijk}(p)}{c}$ is the round trip time delay of ijkth point scatterer signal; $t = t_{ijk\,\min}(p) + (k-1).\Delta T$ is the current time, where $k = \overline{1, [k_{ijk\,\max}(p) - k_{ijk\,\min}(p)] + K}$ is the sample number of a LFM pulse; $K = T/\Delta T$ is the full number of samples of the LFM pulse, ΔT is the time duration of a LFM sample, $k_{ijk\,\min}(p) = \left\lceil \dfrac{t_{ijk\,\min}(p)}{\Delta T} \right\rceil$ is the number of the radar range bin where the signal, reflected by the nearest point scatterer of the target is detected, $t_{ijk\,\min}(p) = \dfrac{R_{ijk\,\min}(p)}{c}$ is the minimal time delay of the BISAR signal reflected from the nearest point scatterer of the target, $K(p) = k_{ijk\,\max}(p) - k_{ijk\,\min}(p)$ is the relative time dimension of the target; $k_{ijk\,\max}(p) = \left\lceil \dfrac{t_{ijk\,\max}(p)}{\Delta T} \right\rceil$ is the number of the radar range bin where the signal, reflected by the farthest point scatterer of the target is detected; $t_{ijk\,\max}(p) = \dfrac{R_{ijk\,\max}(p)}{c}$ is the maximum time delay of the BISAR signal reflected from the farthest point scatterer of the target.

The deterministic complex component of the BISAR signal is presented as a superposition of signals reflected by all point scatterers placed on the target, i.e.

$$\dot{S}(p,k) = \sum_{ijk} a_{ijk}\,\mathbf{rect}\frac{t - t_{ijk}(p)}{T}\,\mathbf{exp}\left\{-j\left[\omega\left(t - t_{ijk}(p)\right) + b\left(t - t_{ijk}(p)\right)^2\right]\right\}. \quad (7)$$

4. Model of the Direct LFM signal from the transmitter

$$\dot{S}_s(p,k) = a_s \mathbf{rect}\frac{t - t_s(p)}{T}\mathbf{exp}\left\{-j\left[\omega\left(t - t_s(p)\right) + b\left(t - t_s(p)\right)^2\right]\right\}, \qquad (8)$$

where $\mathbf{rect}\frac{t - t_s(p)}{T} = \begin{cases} 1, 0 \le \frac{t - t_s(p)}{T} < 1, \\ 0, \text{otherwise.} \end{cases}$

where a_s denotes the amplitude of the signal from the transmitter; $t_s(p) = \frac{R_s(p)}{c}$ is the time delay of the wave front of the transmitted signal, $t = t_s(p) + (k-1)\Delta T$ is the current time measured on the range direction.

The general signal is an algebraic sum of the target signal (7) and direct transmitter signal (8), i.e.

$$\hat{S}(p,k) = S(p.k) + S_s(p,k)\,. \qquad (9)$$

In case $t_s(p) < t_{ijk\,\min}(p)$ the current time parameter t in (7) and (8) has to be written as $t = t_s(p) + (k-1)\Delta T$. In case $t_{ijk\,\min}(p) < t_s(p)$ the current time parameter t in (7) and (8) has to be written as $t = t_{ijk\,\min}(p) + (k-1)\Delta T$.

5. Image Reconstruction Algorithm and Direct Signal Removing

The main steps of the image reconstruction algorithm are as follows:

Phase correction: $\tilde{S}(p,k) = \hat{S}(p,k).\exp[j\Phi(p,k)]$, where $\Phi(p,k) = a_2(pT_p)^2 + b_2(\Delta T)^2$, a_2 and b_2 are the coefficients defined iteratively by image enhancement cost function.

Range compression by IDFT: $\tilde{S}(p,\hat{k}) = \frac{1}{K}\sum_{k=1}^{K}\tilde{S}(p,k).\exp\left(j2\pi\frac{k\hat{k}}{K}\right)$.

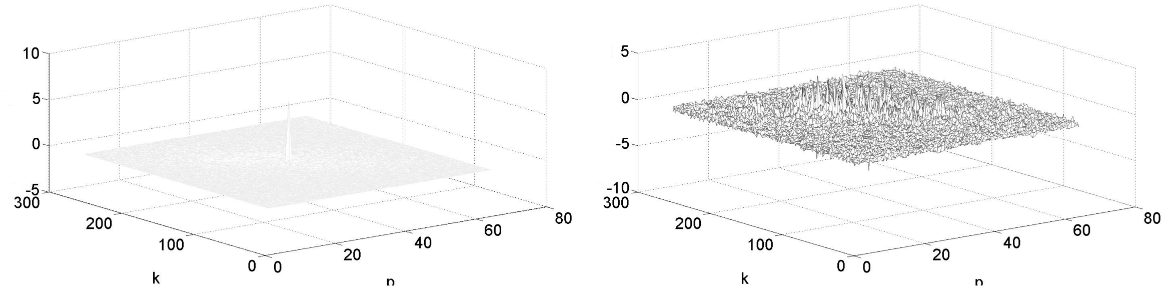
Azimuth compression IDFT: $a_{ijk}(\hat{p},\hat{k}) = \frac{1}{N}\sum_{p=0}^{N-1}\tilde{S}(p,\hat{k}).\exp\left(j2\pi\frac{p\hat{p}}{N}\right)$.

The direct signal from the transmitter can be removed by applying statndart procedure of Recursive Least-Squares (RLS) Finite Impulse Response Filter (FIR) adaptive filter.

6. Numerical experiment

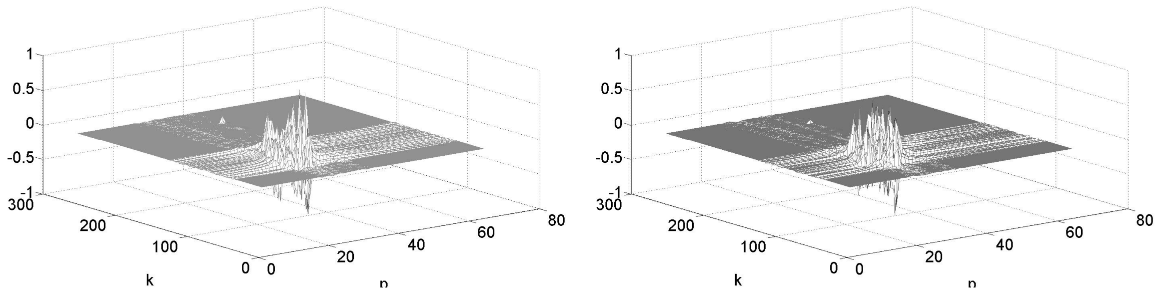
Assume the target is moving rectilinearly in a 3-D Cartesian coordinate system of observation $Oxyz$. Initial coordinates of the space-based transmitter: $x^s = 250$ m; $y^s = 100$ m; $z^s = 2.10^5$ m. Coordinates of the receiver: $x^r = -250$ m; $y^r = 100$ m; $z^r = 80$ m. Target parameters: velocity $V = 18$ m/s, mass-centre coordinates: $x_{00}(0) = 25$ m; $y_{00}(0) = 10$ m; $z_{00}(0) = 2$ m at the moment of imaging. LFM signal parameters: wavelength $\lambda = 3.10^{-2}$ m, pulse repetition period $T_p = 2.10^{-3}$ s, pulsewidth $T = 0.9.10^{-6}$ s, number of LFM samples $K = 256$, LFM sample timewidth $\Delta T = 3{,}5.10^{-8}$ s, LFM signal bandwidth $\Delta F = 1{,}5.10^{8}$ Hz, number of emitted pulses $N = 64$.

General complex BISAR signal composed of the target signal and direct signal after range and azimuth compression is depicted in Fig. 2, *a* and *b*, where Fig. 2, *a* represents a real part and Fig. 2, *b* represents an imaginary *(b*) part of a complex image in isometric projection.



(*a*) (*b*)

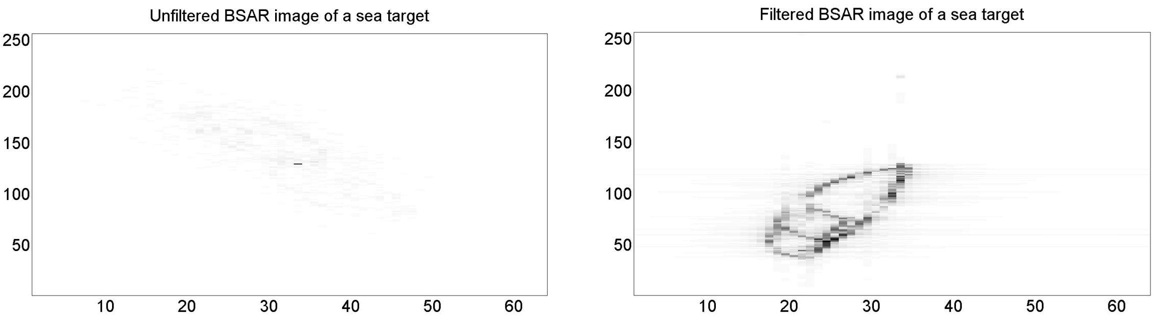
Figure 2. General BISARrange and azimuth compressed signal: real (a) and (b) imaginary part of a complex image in isometric projection.



(*a*) (*b*)

Figure 3. BISAR range and azimuth compressed and filtered signal: real (a) and (b) imaginary part of a complex image in isometric projection.

Complex BISAR range and azimuth compressed signal with filtered direct signal is depicted in Fig.3: a real (*a*) and (*b*) imaginary (*b*) part of a complex image in isometric projection.



(*a*) (*b*)

Figure 4. BISAR final image depressed by dominated direct signal (*a*), and BISAR final image with filtered dominated direct signal (*b*).

As can be seen in Fig. 4, *a*, the final BISAR image is depressed by the dominated direct signal. The final image presented in Fig.4, *b* is obtained by RLS FIR adaptive filter. The dominated direct signal from the transmitter to the receiver is substantially removed.

7. Conclusion

In this work BISAR geometry, models of the signal reflected from the object and direct signal from the transmitter as well as composed signal from the object and the transmitter have been discussed. BISAR topology with a transmitter mounted on a satellite and stationary receiver, and a moving target have been analytical descried. Kinematical vector equations and a mathematical model of BISAR signals from the object and the transmitter with linear frequency modulation have been derived. Numerical experiment using BISAR scenario, a sea target and LFM signal demonstrates correctness of BISAR geometry description, signal modeling and target image extraction.

Acknowledgment

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