The Tangential Velocity MTI Algorithms in Space-borne Systems for Remote Sensing of the Earth

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Abstract. In this paper, the problem of moving target indication (MTI) using synthetic aperture radar (SAR) is considered. The focus of the article is the tangential component of velocity. Two tangential velocity MTI algorithms are considered. The first algorithm uses two apertures with various synthetic time of the radar image (AVST algorithm), and the second uses two apertures displaced along trajectory (ADAT algorithm). The structure of the MTI system based on the analysis of phase and amplitude radar images is considered. For S band and X band SAR, the phase change in the trajectory signal of a moving target, the effects of shift and bifurcation of target responses on the radar image are analyzed in detail. It was found that the AVST algorithm has a small working range of unambiguous velocity estimate (up to ±10 m/s). It is shown that the ADAT algorithm has a higher quality of work in a wide velocity range and can effectively suppress the signals of stationary objects by 20…30 dB. The obtained characteristics allow us to make demands on the parameters of space-borne systems for remote sensing of the Earth and processing systems.

1. Introduction

Modern Earth remote sensing systems have great potential in the fields of mapping and selection of moving targets with their subsequent processing [1–9]. In this case, the main tasks of such processing are detection the presence of moving targets and measuring their coordinates and motion parameters [4–13]. The methods and algorithms for target indication based on the Doppler frequency shift of the echo signal caused by the radial movement of the target are well understood [2–12]. At the same time, taking into account the radial component of the velocity allows the selection of only 2/3 of moving ground objects [1, 2]. The remaining moving targets are either skipped or identified as motionless. Therefore, at present, a number of authors pay close attention to algorithms for target indication by tangential velocity [14, 15]. This task becomes especially important when using the side view mode of the Earth’s surface.

An important point in the operation of any MTI algorithms in SAR is a detailed understanding of the trajectory signal transformations at all stages of its processing. First of all, we are talking about the amplitude and phase characteristics of the signals at the output of the MTI system. Such characteristics are the key to a deep understanding of the processes that occur during signal processing, and also provide the basis for designing the operating modes of the MTI system and the SAR survey modes as a whole. Unfortunately, these issues are poorly represented in basic scientific papers [2, 14, 15, etc.]. This circumstance determines the purpose of this article is the detailed study of the characteristics and features of the MTI system for tangential velocity in space-borne SAR.

This article presents the results in the following three areas.
1) Comparative analysis of two algorithms of moving targets indication by tangential velocity. One of the algorithms is based on the use of two apertures with various synthetic times and the other is based on the use of two apertures displaced along the trajectory of the SAR platform. For research, the method of mathematical modeling of SAR which implements these algorithms was used.

2) The study of changes in the phase and amplitude of signals in the process of indicating moving targets. To study the changes in phase and amplitude, a trajectory signal in the form of a radio hologram was simulated. Next, the results of the passage of the radio hologram in various sections of the signal processing unit and the MTI system were investigated.

3) Indication of moving targets and stationary objects on a radar image. For this purpose, a radar image was synthesized for different processing algorithms with a spatial SAR resolution of about 2.6 m. The results reveal the positive properties of the second algorithm: good suppression of stationary objects and reliable selection of moving targets that have double responses on the radar image.

The rest of this article is structured as follows. Section 2 gives the basic principles of MTI on tangential velocity and a description of two algorithms that are to be studied. The results of modeling the processing of the trajectory signal are shown in Section 3. Section 4 discusses the results obtained and the synthesized radar images. Finally, a brief conclusion is made in Section 5.

2. Method and algorithms of MTI on the tangential velocity

2.1. Principles of MTI on the tangential velocity

Consider the principle of moving targets indication on the tangential velocity for side-looking mode when the viewing angle $\theta_v = 90^\circ$ respect to the SAR platform velocity vector. Let a point target move with a constant tangential velocity $V_t$ (figure 1). The angular position of the target relative to the traverse position is set equal to $\theta_{MT} = 0^\circ$. Then the trajectory signal $s(t)$ reflected from the target in one element of range resolution is determined by the expression

$$s(t) = A_{MT}G(\theta)\exp\left(i \cdot \frac{4 \pi}{\lambda} r(t) + i \cdot \phi_0 \right),$$

where $A_{MT}$ and $\phi_0$ are amplitude and random phase shift of the echo signal, $r(t)$ is the function of changing the distance between the SAR platform and the object of observation.

In side-looking mode, the change in radar-target distance can be expressed [2]

$$r(t) = R_0 + \frac{(V_0 + V_t)^2 t^2}{2 R_0},$$

where $R_0$ is the range between a point on the ground and the radar position at $t = 0$.

The instantaneous phase of the echo signal can be expressed in terms of $r(t)$ by known relation

$$\phi(t) = 4 \pi r(t)/\lambda.$$ 

![Figure 1. The geometry of the survey to explain the principle of MTI.](image-url)
Put \( G(\theta) = 1 \), then the expression for the trajectory signal is written in the form

\[
s(t) = A_0 \exp \left[ i \frac{4\pi}{\lambda} \left( \frac{V_0^2 + 2V_0V + V^2}{2R_0} \right) t + i \cdot \varphi_0 \right].
\]

After compensating for the quadratic phase change caused by the platform motion by multiplying by the azimuth reference function, the complex signal \( \hat{\rho} \) at the output of the processing system, which is matched over the synthetic time interval \([-T_s/2; T_s/2]\) with the signal of a stationary object, taking into account the smallness of the term \( V_0^2 t^2/(2R_0) \), is written as

\[
\hat{\rho} = A_{MT} e^{i\varphi_0} \int_{-T_s/2}^{T_s/2} \exp \left[ i \frac{4\pi V_0 V}{\lambda R_0} t^2 \right] dt.
\]  

(1)

The complex amplitude \( \hat{\rho} \) can be represented in exponential form

\[
\hat{\rho} = |\hat{\rho}| e^{i\varphi},
\]

where \(|\hat{\rho}|\) is the amplitude of the radar image; \( \varphi \) is the phase of the signal.

As follows from expression (1), an unambiguous determination of the target tangential velocity from the phase characteristic of the output signal of the processing unit is impossible, since the phase \( \varphi \) of the signal depends not only on the motion parameters but also on the random phase \( \varphi_0 \) of the echo signal. Therefore, to solve the problem of determining the tangential target velocity, an additional synthesis channel is needed, which will eliminate the ambiguity that arises. The role of such a channel can be played by the second aperture, which: 1) can have a different duration or 2) can be displaced along the trajectory relative to the first [2]. We consider both cases.

2.2. AVST algorithm based on the use of synthetic apertures of various durations

Let the trajectory signals which are received by two apertures with various synthetic times \( T_{s1} \) and \( T_{s2} \) in figure 2 be fed to the inputs of two SAR processing units. By analogy with (1), at the outputs of processing units we obtain complex signals \( \hat{\rho}_1 \) and \( \hat{\rho}_2 \)

\[
\hat{\rho}_1 = A_{MT} e^{i\varphi_0} \int_{-T_{s1}/2}^{T_{s1}/2} e^{i2\pi \mu t} dt = A_{MT} e^{i\varphi_0} \int \left[ 0.5 \cdot T_{s1} (-i \cdot 2\pi \mu)^{1/2} \right] (-i \cdot 2\mu)^{-1/2},
\]

\[
\hat{\rho}_2 = A_{MT} e^{i\varphi_0} \int_{-T_{s2}/2}^{T_{s2}/2} e^{i2\pi \mu t} dt = A_{MT} e^{i\varphi_0} \int \left[ 0.5 \cdot T_{s2} (-i \cdot 2\pi \mu)^{1/2} \right] (-i \cdot 2\mu)^{-1/2},
\]

![Figure 2](image-url)

Figure 2. The geometry of the survey when using two apertures with various synthetic times \( T_{s1} \) and \( T_{s2} \).
where \( \mu = 2V_t V_r (\lambda R_0)^{-1} \), \( J(x) = \int_0^x e^{-t^2} dt \) is integral proportional to the error function \( \text{erf}(x) \):
\[
\text{erf}(x) = 2J(x)/\sqrt{\pi} .
\]

The expressions obtained above can also be represented as
\[
\hat{\rho}_1 = A_M T e^{i \varphi_0} \left[ \int_{-T_1/2}^{T_1/2} \cos \left( \frac{\pi t^2}{2} \right) dt + i \cdot \int_{-T_1/2}^{T_1/2} \sin \left( \frac{\pi t^2}{2} \right) dt \right] = A_M T e^{i \varphi_0} \left[ \int_{-T_1/2}^{T_1/2} \cos \left( \frac{\pi t^2}{2} \right) dt + i \cdot \int_{-T_1/2}^{T_1/2} \sin \left( \frac{\pi t^2}{2} \right) dt \right] ;
\]
\[
\hat{\rho}_2 = A_M T e^{i \varphi_0} \left[ \int_{-T_2/2}^{T_2/2} \cos \left( \frac{\pi t^2}{2} \right) dt + i \cdot \int_{-T_2/2}^{T_2/2} \sin \left( \frac{\pi t^2}{2} \right) dt \right] = A_M T e^{i \varphi_0} \left[ \int_{-T_2/2}^{T_2/2} \cos \left( \frac{\pi t^2}{2} \right) dt + i \cdot \int_{-T_2/2}^{T_2/2} \sin \left( \frac{\pi t^2}{2} \right) dt \right].
\]

The phases of the signals at the phase shift value \( \varphi_0 = 0 \) are equal
\[
\varphi_1 = \arctan \left[ \int_0^{T_1/2} \sin \left( \frac{\pi t^2}{2} \right) dt \right] = \arctan \left[ \frac{F_s(T_1 \sqrt{\mu})}{F_s(T_1 \sqrt{\mu})} \right],
\]
\[
\varphi_2 = \arctan \left[ \sin \left( \frac{\pi t^2}{2} \right) \right] = \arctan \left[ \frac{F_s(T_2 \sqrt{\mu})}{F_s(T_2 \sqrt{\mu})} \right],
\]

where \( F_s(x) = \int_0^x \sin \left( \frac{\pi t^2}{2} \right) dt \) and \( F_s(x) = \int_0^x \cos \left( \frac{\pi t^2}{2} \right) dt \) are Fresnel integrals.

For small values of the argument \( x \) when \( \arctan(x) \approx x \) the phase difference \( \Delta \varphi = \varphi_1 - \varphi_2 \) can be approximated by the linear expression
\[
\Delta \varphi = 0.5 \mu (T_1^2 - T_2^2).
\]

It follows that the estimate of the target tangential velocity \( V_t \) is proportional to the phase difference of the output signals generated by two processing channels:
\[
\hat{V}_t = \frac{\lambda R_0}{V_0 (T_1^2 - T_2^2)} \Delta \varphi.
\]

Thus, the operation of the described MTI algorithm consists in comparing the phase difference of the signals reflected from the target. Moreover, to increase the accuracy of estimating the tangential velocity of the target, it is necessary to increase the differences in the synthetic times.

2.3. ADAT algorithm based on the use of two synthetic apertures displaced along trajectory

When implementing this algorithm, two synthetic apertures are used displaced by a distance \( d \) along trajectory of the SAR platform (figure 3). The amount of displacement \( d \) determines the characteristics and capabilities of the MTI system.

The MTI algorithm on the tangential velocity when using two apertures displaced along the trajectory, consists of the following steps [2]:

1. synthesis of two frames of complex radar images \( \hat{\rho}_1 \) и \( \hat{\rho}_2 \) of the same area;
2. estimating the tangential velocity of the target, it is necessary to increase the differences in the synthetic times.
Figure 3. The geometry of the survey when using two synthetic apertures displaced along trajectory by a distance $d$. $MT$ is moving target.

- detection the target responses on radar images against the background of the underlying surface;
- calculation of the phase difference $\Delta \varphi$ of the signals of the detected targets;
- estimation of the tangential velocity of the detected targets by the measured phase difference $\Delta \varphi$.

The described algorithm can be represented as a block diagram of the MTI system (figure 4). In this figure, Arg is the phase calculation block; Abs is the block of the calculation of the module.

3. Modeling of the trajectory signal processing algorithms

To study the behavior of the amplitude and phase characteristics of signals and radar images, we perform the modeling of the abovementioned algorithms of the MTI system. When modeling, the following conditions and characteristics of SAR were used: normal side-looking mode ($\theta_e = 90^\circ$); orbital velocity of the spacecraft (SAR platform) $V_0 = 7610$ m/s; wavelength of radiated signal in S band $\lambda = 0.094$ m and in X band $\lambda = 0.03$ m; SAR spatial resolution $\delta_x = 2.7$ m and $\delta_y = 2.6$ m; slant range $R_0 = 753$ km; grazing angle $\gamma = 40.2^\circ$. It is assumed that a moving target has only the tangential velocity $V_t$ with a maximum value of up to 120 km/h (33 m/s).

Figure 4. Block diagram of the MTI system on the tangential velocity.
3.1. AVST algorithm

First we consider the characteristics of the MTI of an aircraft X band SAR. Figure 5 shows the phase $\Delta \phi$ and amplitude $|\hat{\rho}|$ characteristics of a radar image depending on the tangential velocity $V_t$ of a moving target with parameters typical of an aircraft SAR for $T_{s1} = 1$ s and $T_{s2} = 0.5$ s. It can be seen from the graphs that an unambiguous estimate of the tangential velocity is possible within $\pm 12$ m/s.

Similar dependences for space-borne SARs of the S and X bands are presented in figures 6, 7 and figures 8, 9, respectively.

**Figure 5.** Phase $\Delta \phi$ (1) and amplitude $|\hat{\rho}|$ (2) characteristics depending on $V_t$ for aircraft SAR with parameters $R_0=35$ km, $V_0=200$ m/s, $\lambda=0.03$ m, $T_{s1}=1$ s, $T_{s2}=0.5$ s

**Figure 6.** Phase characteristics of the MTI system of space-borne SAR at $\lambda=0.094$ m: $\phi_1$ (1), $\phi_2$ (2), $\Delta \phi$ (3), $\Delta \phi'$ (4).

**Figure 7.** Amplitude characteristics of the MTI system of space-borne SAR at $\lambda=0.094$ m: $|\hat{\rho}_1|$ (1), $|\hat{\rho}_2|$ (2), $|\hat{\rho}_1 - \hat{\rho}_2|$ (3).
Figure 8. Phase characteristics of the MTI system of space-borne SAR at $\lambda=0.03$ m: $\varphi_1$ (1), $\varphi_2$ (2), $\Delta\varphi$ (3), $\Delta\varphi'$ (4).

Figure 9. Amplitude characteristics of the MTI system of space-borne SAR at $\lambda=0.03$ m: $|\hat{\rho}_1|$ (1), $|\hat{\rho}_2|$ (2), $|\hat{\rho}_1 - \hat{\rho}_2|$ (3).

From the characteristics shown in figures 6–9, it follows that the MTI AVST algorithm has unambiguous limits for estimating the target tangential velocity. In this case, an increase in the azimuthal resolution $\delta_\varphi$ of the SAR by reducing the wavelength $\lambda$ of radiated signal leads to narrowing of the range of uniquely selectable tangential velocities. So, for $\delta_\varphi < 1$ m and achievable SAR parameters, the range $\Delta\hat{V}_t$ of an unambiguous estimate of the tangential velocities of ground moving targets does not exceed $\pm(5\ldots7)$ m/s or $\pm(18\ldots25)$ km/h. In addition, with the same values of $\lambda$, aircraft SARs will have a wider range of $\Delta\hat{V}_t$ than space-borne ones. It should also be noted that the linear approximation of the phase difference $\Delta\varphi$ gives satisfactory results within the range of unambiguous estimate of the tangential velocity. If you go beyond this range, the error in the measurement of speed begins to increase rapidly. These features limit the use of the algorithm for the ground moving targets indication on the tangential velocity using space-borne SAR.

3.2. ADAT algorithm
Let us carry out the simulation of the MTI system shown in figure 4 for the side-looking mode. Let a moving point target have only the tangential component $\hat{V}_t$ of velocity. Let us set the displacement of the apertures equal to $d = 450$ m.

Consider the case of a stationary target when $\hat{V}_t = 0$ (figures 10–11). The magnitude response of stationary point target at the output of the radar signal processing units has the form shown in figure 10 (responses 1). The azimuthal position of the target is indicated by a square marker. At the
output of the MTI system, the magnitude response of the stationary target is suppressed (figure 10, response 2). The phase difference $\Delta \varphi$ in the target azimuthal sample is close to zero (figure 11).

As further modeling of the MTI algorithm showed, with the tangential movement of a point target, its magnitude response in the radar image is blurred (expanded) in azimuth and shifted by $\Delta x$ in the direction of the target’s movement. These effects are more intense with increasing $V_t$ and the resolution of the SAR.

Figures 12–13 show the results of a similar simulation for the point target with tangential velocity $V_t = 10$ m/s and moving in the same direction as the SAR platform. Figure 12 shows that the magnitude responses on the radar image of the MTI system have become wider, while the center of the response does not coincide with the true azimuthal position of the target (shown by the marker). The amplitude of the response of the MTI system (difference signal) has increased significantly, and the response has a deep falling in the center, indicating the coincidence (in phase) of the complex signals $\hat{\rho}_1$ and $\hat{\rho}_2$ in this sample.

The phase difference in this range channel is linear (figure 13). In this case, the phase of the azimuthal coordinate corresponding to the target position lags behind the center of the response by $\Delta \varphi' \approx 30^\circ$.

With an increase in the tangential velocity of the target to a value of $V_t = 20$ m/s, the described effects appear proportionally (figures 14–15): the response amplitude in the radar image decreased, the response amplitude of the MTI system almost doubled, the azimuthal shift of the response is $\Delta x \approx 13$ samples, the phase difference increased to a value $\Delta \varphi' \approx 60^\circ$, the linear region of the phase response $\Delta \varphi$ has become wider.
Figure 12. Magnitude responses of the simulated point target with $V_t = 10$ m/s at the output of the processing units (1) and at the output of the MTI system (2) at $d = 450$ m.

Figure 13. Phase difference $\Delta \phi$ in the range channel with the detected point target with $V_t = 10$ m/s at $d = 450$ m.

Figure 14. Magnitude responses of the simulated point target with $V_t = 20$ m/s at the output of the processing units (1) and at the output of the MTI system (2) at $d = 450$ m.

Figure 15. Phase difference $\Delta \phi$ in the range channel with the detected point target with $V_t = 20$ m/s at $d = 450$ m.
When modeling the tangential motion of a point target in the direction opposite to the motion of the SAR platform (negative values of $V_t$), the response on the radar image is shifted in the direction of the target movement, the amplitude of the difference signal is equal to the value obtained at $+V_t$, the phase characteristics change sign to the opposite.

Similar characteristics were also obtained for other displacement values: $d = 180$ m, $d = 450$ m and $d = 900$ m. Summarized results are presented in figures 16–18.

From the analysis of figure 16 it follows that with an increase in $V_t$, the amplitude of the response of the MTI system increases. Moreover, with increasing displacement $d$, the response amplitude increases with greater steepness, however, the range of an unambiguous estimate of the target tangential velocity decreases. At the same time, it can be noted that the signals of stationary targets and background are suppressed, and the value of the suppression coefficient depends on the distance $d$ and amounts to 20–30 dB in the considered example.

The phase difference is proportional to both velocity $V_t$ and displacement $d$ (figure 17). The shift $\Delta x$ in the position of the response of the moving target relative to the true target position depends only on the tangential velocity $V_t$ and does not depend on $d$ (figure 18) and is determined by

$$\Delta x = V_t T_s / \delta_x .$$

![Figure 16](image16.png)

**Figure 16.** Amplitude of the responses on the radar image (dashed line) and the amplitude of the response of the MTI system (solid line) at $d = 180$ m (1), $d = 450$ m (2) and $d = 900$ m (3).

![Figure 17](image17.png)

**Figure 17.** Phase difference at $d = 180$ m (1), $d = 450$ m (2) and $d = 900$ m (3).
Figure 18. The shift of the response of a moving target relative to the true position of the target at \(d = 180\) m (1), \(d = 450\) m (2) and \(d = 900\) m (3).

Thus, the obtained expressions and characteristics make it possible to choose the most suitable parameters of the MTI system from the point of view of the requirements for it and its practical implementation.

4. Discussion of results and analysis of synthesized radar images

Let us simulate a scene containing two point targets – stationary object and moving target with tangential velocity \(V_t\) at \(d = 450\) m. Let the initial azimuthal position of these targets be the same, but the range position has a shift by \(\Delta r\) (figure 19).

The results of such modeling and synthesis of radar images are shown in figure 20. From this figure it follows that at the outputs of the processing units, a stationary and a moving target, which have the same scattering cross section, create responses of different intensities on the radar image. A stationary target has a point image, and the response of a target moving at a tangential velocity is blurred in azimuth in the direction of its movement and therefore has a lower intensity in the radar image (figure 20(a)). At the output of the MTI system, the response of a stationary target is suppressed (figure 20(b)), and the image intensity of a moving target remains, but it bifurcates, which corresponds to the amplitude characteristics obtained above.

Figure 19. Simulation scene in the presence of a stationary object \((O)\) and a moving target \((MT)\) with a tangential velocity \(V_t\).
Figure 20. Magnitude responses of stationary point object (1) and moving point target (2) with tangential velocity $V_t = 20$ m/s at the output of the processing unit (a) and at the output of the MTI system (b).

Thus, the feature of the MTI algorithm under consideration is that a target moving at a tangential velocity creates two responses at the output of the MTI system — “true” and “false”, which can be interpreted during subsequent processing as having two different targets in the frame.

The presence of double responses can also be used as an informative sign of a moving target, and the distance between them will help to evaluate the tangential velocity. Information that both responses relate to the same moving target can be extracted from an analysis of their phase characteristics (response phases are symmetric and anti-phase), or from a comparative analysis with radar images at the output of the processing unit, where there is one response.

As we see, the presented results cover a wider range of issues than are given in [14]. In the work [14], the main attention in the simulation was given to studying the influence of the Doppler frequency shift on the chirp signal compression procedure, which significantly narrows their scope. The numerical data obtained above in the study of two algorithms regarding the influence of the base between partial frames, the range of operating frequencies, and the region of ambiguous measurements of the tangential velocity can be the basis for designing the operating modes of the MTI system and choosing the optimal SAR parameters.

5. Conclusion
This article is the first to describe the phase structure of a signal in MTI systems on the tangential velocity. It is shown that of the two considered MTI algorithms, the algorithm with the use of two apertures displaced along the trajectory is most preferable. This algorithm has a wide range of unambiguous velocity measurements, effectively selects moving targets and suppresses responses from stationary targets and background by 20…30 dB. For initial detection and selection of moving targets, threshold processing may be used. At the same time, stationary objects and a background having a high reflectivity, due to incomplete suppression, retain a residual brightness level on the
differential radar image of the MTI system, reducing the image contrast and masking low-speed targets. The intensity of this level depends on the amplitude of the trajectory signal, the accuracy of combining complex images in the channels, and the aperture displacement $d$. The smaller the displacement $d$, the more effective the suppression of the response of a stationary object and the wider the range of uniquely selectable velocities $V_i$, but at the same time, the response amplitude of tangentially moving target decreases.

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