Moving Target Signals in High Resolution Wide Swath SAR

Martina Gabele, Gerhard Krieger
German Aerospace Center (DLR), Oberpfaffenhofen, Germany

Abstract

In this paper the impact of two high resolution wide swath synthetic aperture radar imaging techniques, extraction of signals from azimuth subsampled spectra and subpulse azimuth beamsteering on transmit, on ground moving target signals is analyzed. A modelling of the interfering signals in range-Doppler domain is introduced, that is suitable for studying the performance of low PRF sampled GMTI and subpulse beamsteering in azimuth and elevation on transmit and receive for HRWS-SAR imaging and GMTI. The combination of the two techniques yields an operation mode for high resolution wide swath synthetic aperture radar imaging and long observation time wide swath ground moving target indication. The mode is analyzed in terms of signal to interference plus noise ratio and coverage for ground moving target indication.

1 Introduction

Classical synthetic aperture radar (SAR) imaging modes like Stripmap-SAR, Scan-SAR, and Spotlight-SAR require a trade-off between unambiguous swath width and azimuth resolution: Scan-SAR is dedicated to the imaging of wide swaths, however, at an impaired azimuth resolution. Spotlight-SAR can be used to improve the azimuth resolution at the cost of a lower coverage. Stripmap-SAR has a performance in between Scan-SAR and Spotlight-SAR with respect to coverage and azimuth resolution. The reason for these constraints is that for space-based SAR systems an increase of the swath width requires a reduction of the pulse repetition frequency (PRF). But a reduction of the PRF raises azimuth ambiguities.

The limitations of classical SAR systems can be overcome with SAR systems consisting of an antenna aperture divided into multiple subapertures with full receiver chains in azimuth and elevation [1] $-$ [3]. By use of horizontal degrees of freedom azimuth ambiguities caused by low PRF Doppler spectrum sampling can be suppressed, while vertical degrees of freedom can be used to suppress range ambiguities [4]. Processing methods and system concepts for high resolution wide swath (HRWS) SAR imaging were suggested in [5],[6]. A post-Doppler space time adaptive processing (STAP) approach was suggested in [7]. This approach is outlined here, because it allows to uniformly study the performance of HRWS-SAR imaging and ground moving target indication (GMTI):

Step 1**:** Temporal processing: An azimuth FFT is used to divide the echoes received by each spatial channel into many spectrum components which are separated in the spatial domain.

Step 2**:** Spatial processing: Use of array processing techniques in order to extract the spatially separated spectrum components. The interference plus noise covariance matrix is

$$R(f) = \sigma_n^2 I + \sum_k \sigma_k^2 \overrightarrow{C}_k(f) \overrightarrow{C}_k^\dagger(f), \qquad (1)$$

where σ_n^2 is the noise power, $\overrightarrow{C}(f) = [C_1(f), C_2(f), ..., C_N(f)]$ is a vector containing the Doppler frequency spectrum of the received signals of all N receiver subapertures, and † denotes conjugate complex transposed. The sum is performed over all interference signals k with σ_k^2 the power of the interference sources. For GMTI the received signal $\overrightarrow{Z}(f)$ is a superposition of the moving target signal $\overrightarrow{S}(f, v_y)$, the interference signals $\overrightarrow{C}_k(f, v_y)$ and noise $\overrightarrow{N}$:

$$\overrightarrow{Z}(f, v_y) = a\overrightarrow{S}(f, v_y) + \sum_k \sigma_k \overrightarrow{C}_k(f) + \overrightarrow{N}, \qquad (2)$$

where a denotes the moving target signal amplitude. The signal to interference plus noise ratio (SINR) of the optimum processor for GMTI is

$$SINR(f, v_y) = |a|^2 \overrightarrow{S}^\dagger(f, v_y) R^{-1}(f) \overrightarrow{S}(f, v_y), \qquad (3)$$

Step 3**:** Rearranging spectrum components: After all the spectrum components are extracted they are rearranged to achieve the unambiguous full spectrum.

Step 4**:** Conventional SAR processing: The full-spectrum signal can finally be processed by conventional SAR imaging operations.

2 Theoretical Considerations

Assuming a single transmit antenna and multiple receive antennas, according to [8] the moving target SAR raw data signal in Doppler frequency domain of an antenna subaperture at azimuth position x_d relative to the array origin is:

$$S(f, x_d) = A\,(f - \Delta f) \cdot S_{SA}(f) \cdot S_{RA}(f, x_d), \qquad (4)$$

$$S_{SA}(f) = \exp\left\{ -j2\beta y_0 \sqrt{1 - \left(\frac{\lambda}{2v_{rel}}\,(f - \Delta f) \right)^2 } \right\}, \qquad (5)$$

$$S_{RA}(f, x_d) = \exp\left\{ j\beta x_d \left(\frac{\lambda}{2v_e} f + \frac{v_y}{v_e} \right) \right\}, \qquad (6)$$

where $A(f)$ is the two-way amplitude weighting versus Doppler frequency f, $\Delta f = -2v_y/\lambda$ is the Doppler frequency shift due to the target across-track velocity v_y, λ is the carrier wavelength, $t_0 = x_d/(2v_e)$ is the time displacement relative to the array origin, $v_e = (v_p - v_x) + v_y^2/(v_p - v_x)$ is the effective platform velocity, v_p is the true platform velcity and v_x the target along-track velocity, $\beta = 2\pi/\lambda$ is the wavenumber, y_0 is the slant range to the target, and $v_{rel} = \sqrt{(v_p - v_x)^2 + v_y^2}$ is the relative platform velocity. The signal consists of two parts, where $S_{SA}(f)$ contains the phase terms due to the synthetic aperture geometry, and $S_{RA}(f)$ contains the phase information of the subapertures due to their angles of arrival.

2.1 Subsampling Azimuth Spectrum

Increase of swath width and high azimuth resolution for space-based SAR systems is possible via reduction of the PRF. However, a reduction of the PRF below the -3dB Doppler bandwidth of the antenna beam causes Doppler backfolding of the SAR signals. This introduces an additional linear frequency modulation term $G(f) = exp\{j2\pi t_0 f\}, t_0 = k\lambda y_0 PRF/(2v_p^2)$, where k is the index of the PRF band in the SAR signal, and an offset in angle of arrival $\Delta\phi = k\lambda PRF/(2v_p)$ in the real aperture signal. Moving target signals are additionally shifted in angle of arrival by $\Delta\phi_{v_y} = -v_y/v_e$. The linear frequency modulation term causes the fact, that in the Doppler subsampled case azimuth ambiguous signal parts from scatterers separated in azimuth by t_0 interfere. Since the scatterers stem from different azimuth positions they have different angles of arrival. Hence, the backfolding of the useful signals into the Nyquist Doppler spectrum can be removed in the processing by use of horizontal degrees of freedom. The Doppler frequency histories versus angle of arrival for the resulting useful SAR raw data signals, i.e. stationary targets in case of HRWS-SAR, moving targets in case of GMTI-SAR, as well as the required filtering for extracting the Nyquist sampled part from the useful signal are sketched in Figure 1.

For reconstructing the full SAR response within one azimuth beam sufficient horizontal degrees of freedom have to be provided. In general, if the antenna main beam width contains K azimuth ambiguities, K horizontal degrees of freedom are required for stationary target signal extraction [5], while for moving target signal extraction at least one more degree of freedom is required (although the quality of signal reconstruction depends also on factors like beam shape and processed bandwidth). Since for stationary target signals the angle-Doppler relationship of the signals in all PRF bands is known, unambiguous rearranging of the extracted spectrum components is possible, and long synthetic aperture signals with high azimuth resolution can be generated. The angle-Doppler relationship of moving target signals depends on the target velocity. Hence, unambiguous rearranging of the extracted spectrum components is not possible, and techniques such as staggered pulse repetition interval (PRI) [4], multiple carrier frequencies [4], or use of range cell migration information [9] have to be applied.

2.2 Subpulse Beamsteering

As pointed out e.g. in [10] after Fourier transformation the clutter interference including range and azimuth ambiguities concentrates to some distinct directions in a Range-Doppler cell, where the interfering scatterers for sidelooking radar are placed on a regular grid in range and azimuth, and the Doppler frequency of range ambiguities is the same as their range unambiguous counterpart. If the pulses are split into subpulses, each subpulse adds a grid of interfering scatterers. The range shift ΔY between the grids of the subpulses depends on the transmission time spacing ΔT between the subpulses and transforms to an incidence angle spacing $\Delta\theta$ between subpulses $\Delta\theta = Acos\,(H/(Y - \Delta Y)) - Acos\,(H/Y)$, where H is the platform altitude and Y the slant range to the target. The antenna pattern weighting of the scatterers on a grid belonging to one subpulse depends on the transmit and receive antenna pointing direction during that subpulse.

Transmit beamsteering in azimuth : Increase of coherent integration time is possible by splitting up the transmit pulses into multiple subpulses and subsequently steering the transmit antenna beam into different azimuth directions in fast-time [6]. Adopting the above described model, this means that multiple azimuth ambiguities separated in range are generated. The range and azimuth ambiguities generated by subpulse beamsteering in azimuth are sketched in Figure 2 for an example radar system. In the extreme case of transmitting K subpulses simultaneously, their range ambiguities coincide and the effective antenna pattern has a wide azimuth beam. In the extreme case of transmitting K subpulses such that the transmission procedure is equal to a constant PRF K times as high as the original PRF the range ambiguities have maximum range spacing and the operation mode corresponds to slow-time transmit beam switching with $K \cdot PRF$.

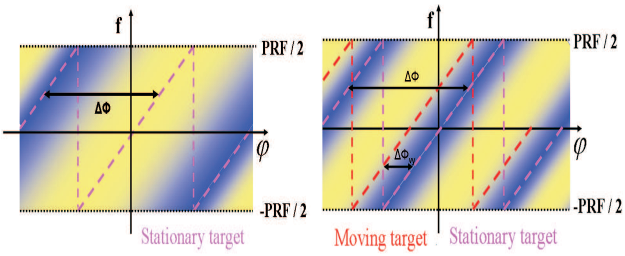

Figure 1: Filtering required for extracting the Nyquist sampled signal part (yellow: beam maximum, blue: beam minimum). Left: HRWS-SAR. Right: GMTI.

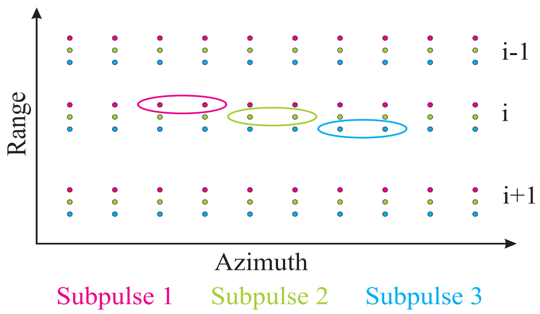

Figure 2: Clutter and its range/azimuth ambiguities for azimuth beamsteering on transmit with three subpulses and two azimuth ambiguities per subpulse due to azimuth subsampling. $i-1$ denotes the ambiguities caused by the preceding, $i+1$ the ambiguities by the subsequent pulse.

3 Simulation Results

The combination of the two techniques for achieving long integration time, wide swath illumination of a scene was suggested in [6]. In the following we look at an example HRWS-SAR system with system parameters as listed in Table 1. Due to the restrictions of the timing diagram concerning the fact that a radar system that uses the same antenna aperture for transmission and reception cannot transmit and receive at the same time, low PRF is more beneficial for observation of large incidence angle intervals in case of space-based radar systems. The low PRF requires an antenna aperture with multiple horizontal degrees of freedom for signal extraction. Increase of observation time is achieved by subpulse azimuth beamsteering on transmit, where the azimuth pointing directions differ by the $-6dB$ mainbeam width of a full transmit antenna - one subaperture receive antenna pair. This condition provides the opportunity to arrange the data of the subpulses such that a long coherent integration time SAR signal can be constructed and multiple moving target observations can be combined. For reasons of clarity, in the simulations SNR is assumed independent of the number of subpulses, PRF and antenna dimensions.

System parameter	Value
Orbit height	$576\ km$
Platform velocity	$7560\ m/s$
Incidence angle range	$27° - 37°$
Pulse repetition frequency	$1.22\ kHz$
Transmit antenna dimension (az., el.)	$14.4\ m$, $0.18\ m$
Receive antenna dimension (az., el.)	$14.4\ m$, $1\ m$
Azimuth subapertures	6
Subpulses	3
Subpulse time spacing	$55\ \mu s$

Table 1: System parameters of example radar system

3.1 Reconstruction of Azimuth Subsampled Spectrum

In Figure 3 the SINR after extraction and rearranging of the moving target signal components in five PRF bands is shown. The abscissa shows the target radial velocities, the ordinate the Doppler frequency spectra of the PRF bands. In the simulations it is assumed that the moving target signal parts can unambiguously be assigned to the PRF bands. For the small transmit antenna case the $-6\ dB$ signal Doppler bandwidth of one transmit-receive antenna pair is $B = 3\ kHz$. Hence, for $PRF = 1\ kHz$ there are six interfering clutter patches in the mainbeam and six antennas are not sufficient for reconstructing the signal of interest. As can be seen in Figure 3 on the left, already for $PRF = 1.22\ kHz$ signal reconstruction is possible at the cost of about $5\ dB$ loss in SINR compared to $SNR = 10\ dB$ for target velocities $v_y = (2k+1)PRF\lambda/4$, $k = 0, \pm 1, \pm 2, ...$ The full signal bandwidth can be reconstructed without SINR loss for these target velocities at $PRF = 3\ kHz$. For the large transmit antenna case (Figure 3 on the right) the $-6\ dB$ signal Doppler bandwidth of one transmit-receive antenna pair is $B = 1.7\ kHz$. For $PRF = 1.22\ kHz$ signal reconstruction is possible at a $1\ dB$ improvement in SINR (same SNR assumed) compared to the short transmit antenna case due to the narrow transmit antenna beam tapering.

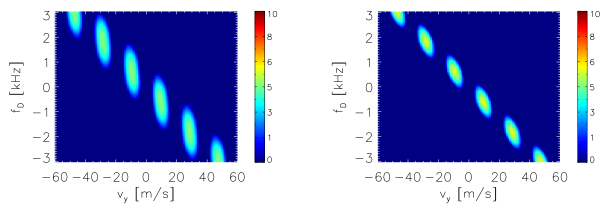

Figure 3: SINR after reconstruction and rearranging, but before SAR compression of moving target signals in five PRF bands ($SNR = 10\ dB$). Left: Transmit antenna length: $7.2\ m$. Right: Transmit antenna length: $14.4\ m$.

3.2 Extraction of Subpulses from Azimuth Beamsteering

If the observation time respectively the signal Doppler bandwidth is increased by use of fast-time azimuth beamsteering on transmit on a subpulse basis the signal of interest additionally competes with the range displaced azimuth ambiguities caused by the other subpulses. In Figure 4 SINR versus target radial velocity after interference suppression and SAR compression is shown. For the left diagram $PRF = 1.22kHz$ was chosen. Since in this special case the interferometric phase ramps of the additional range displaced azimuth ambiguities coincide with the single pulse ambiguities, the SINR loss for transmit beamsteering in azimuth with three subpulses is about $1\ dB$

compared to the single subpulse case. For the right diagram $PRF = 1.35kHz$ was chosen such that the interferometric phase offsets of the additional ambiguities do not coincide with the ones of the single pulse operation mode and an increased loss in SINR of about 2 dB compared to the single subpulse operation mode can be observed. The loss in SINR caused by the transmit beamsteering in azimuth can be reduced by providing additional horizontal degrees of freedom, a larger elevation antenna diagram or vertical degrees of freedom.
After extraction of all three subpulses and reconstruction of the Doppler subsampled signals a total signal Doppler bandwidth of about $5kHz$ and an SINR of up to 13 dB per subpulse dependent on the target radial velocity can be reconstructed. However, the low PRF causes multiple ambiguous clutter notches in the target velocity interval of interest. The elimination of the blind velocity intervals requires techniques like staggered pulse repetition interval or frequency diversity [4]. On the other hand, the low PRF allows to observe the whole incidence angle interval $27° - 37°$: The small transmit antenna simultaneously illuminates the whole swath while scan on receive, i.e. real-time beamscanning on receive for following the travelling of a pulse on ground [6], can be used for observation of the whole swath.

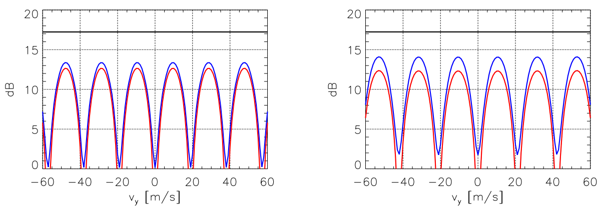

Figure 4: SINR after SAR compression for the medium out of three subpulses. Left: $PRF = 1.22\ kHz$. Right: $PRF = 1.35\ kHz$. (black: SNR in case of no interference, blue: SINR without azimuth beamsteering on transmit, red: with azimuth beamsteering on transmit.)

4 Summary

An operation mode for wide swath long integration time SAR/GMTI for space-based systems based on low PRF sampling and transmit beamsteering in azimuth on transmit was analyzed. The large swath observation which is made possible by the low PRF sampling is traded against an endo-clutter situation for the whole target velocity interval of interest and multiple blind velocity intervals. The increased observation time provided by the transmit beamsteering in azimuth on a subpulse basis causes severe range ambiguities. Eliminating their impact requires either a large antenna height or vertical degrees of freedom. The analysis considered achievable signal to interference and noise ratio. Another important performance parameter for space-based SAR/GMTI systems is azimuth angle estimation accuracy.

References

[1] Currie, A., Brown, M.A., *Wide-swath SAR*, IEE Proceedings F - Radar and Signal Processing, vol. 139, pp. 122-135, 1992.

[2] Callaghan, G.D., Longstaff, I.D., *Wide-swath spaceborne SAR using a quad-element array*, Radar, Sonar and Navigation, IEE Proceedings, vol. 146, pp. 159-165, 1999.

[3] Suess, M., Grafmueller, B., Zahn, R., *A novel high resolution wide swath SAR system*, Proc. IEEE Geoscience and Remote Sensing Symposium, Sydney, Australia, pp. 1013-1015, 2001.

[4] Klemm, R., *Principles of space-time adaptive processing*, IEE Radar, Sonar, Navigation and Avionics Series 12, The Institution of Electrical Engineers, London, United Kingdom, 2002.

[5] Gebert, N., Krieger, G., Moreira, A., *Digital Beamforming on Receive: Techniques and Optimization Strategies for High Performance SAR Imaging*, to appear in IEEE Transactions on Aerospace and Electronics, 2008.

[6] Krieger, G., Gebert, N., Moreira, A., *Multidimensional Waveform Encoding: A New Digital Beamforming Technique for Synthetic Aperture Radar Remote Sensing*, to appear in Proc. IEEE Transactions on Geoscience and Remote Sensing, Jan. 2008.

[7] Li, Z., Wang, H., Su, T., Bao, Z., *Generation of Wide-Swath and High-Resolution SAR Images From Multichannel Small Spaceborne SAR Systems*, Proc. IEEE Geoscience and Remote Sensing Letters, vol. 2, no., 1, January 2005.

[8] Gabele, M., Sikaneta, I., *A New Method to Create a Virtual Third Antenna from a Two-Channel SAR-GMTI System*, Waveform Diversity and Design Conference, Pisa (Italy), June 2007.

[9] Gabele, M., Sikaneta, I., *Motion Parameter Estimation of Doppler-Ambiguous Moving Targets in SAR-GMTI*, International Radar Symposium, Cologne (Germany), September 2007.

[10] Ender, J., Cerutti-Maori, D., W. Bürger, *Radar antenna architectures and sampling strategies for space-based moving target recognition*, IGARSS, Seoul (South Korea), July 2005.