1

Bistatic Synthetic Aperture Radar (BSAR) Survey

In this chapter, an overview of recent results on the scope of the bistatic synthetic aperture radar (BSAR) technology is presented. Emphasis is put on different BSAR geometries, methods, models and algorithms for signal processing and image extraction.

1.1. Introduction and main definitions

Synthetic aperture radar (SAR) is a coherent imaging technique capable of generating high-resolution images of stationary and moving targets on the ground, and it is an important tool in military intelligence, surveillance and reconnaissance [GRI 03, STO 09, CHA 08, NIE 08, WU 09, LIM 08]. With the advancement of sophisticated SAR signal processing and imaging methods, more specialized radar configurations and problems are being studied within the framework of SAR systems [LAZ 12c, LAZ 12e].

Bistatic synthetic aperture radars are a subclass of SAR systems. Based on the specific advantages of BSAR configurations in comparison with monostatic systems, such as the increased information content of BSAR data with regard to feature extraction and classification, it has been intensively researched over the last 20 years. This research could be worthwhile, e.g. for topographic features, surface deposits and drainage, to show the relationships that occur between forest, vegetation and soils. It provides important information for land classification and land-use management.

Agriculture monitoring, soils mapping and archaeological investigations could also benefit from BSAR imaging.

In addition, it has an impact on the progress in SAR and inverse synthetic aperture radar (ISAR) technologies and meets strong requirements for the further enhancement of microwave remote sensing systems. It is expected that the implementation of the BSAR concept in ISAR will enlarge the area of application and substantially improve the functionality of imaging radars.

The review of basic concepts, definitions and explanation of the mathematical development of relationships, such as geometry, Ovals of Cassini, dynamic range, isorange and isodoppler contours, target Doppler, and clutter Doppler spread, is performed in [WIL 05].

A historical overview and detailed descriptions of bistatic/multistatic radar technique for military, scientific and commercial application are suggested in [WIL 07, GRI 09, LAZ 12a]. The experience of leading scientists in bistatic clutter and signal processing, including autofocus and image formation methods to improve bistatic moving target identification performance, is thoroughly considered.

An analysis of a wide spectrum of bistatic radar applications is presented in [CHE 08]. It includes space exploration, defense, transport, aerospace and meteorology and is dedicated to more advanced studies in bistatic radars which are the subject of intensive research activity and development. With contributions from the leading experts in the field of bistatic radar research, the book collates the latest developments in the field focusing particularly on BSAR and passive bistatic radar systems (PBRS). Within these two areas, the author addresses the main BSAR topologies: spaceborne BSAR, airborne BSAR and space-surface BSAR, and analyzes the resurgent BSAR technology.

From the geometric point of view, BSAR is a SAR system whose transmitter and receiver are placed on separate platforms; one of them is stationary or both of them move on particular trajectories [SUN 09, WU 11, LOF 04]. BSAR uses a separated transmitter and receiver flying on different platforms to achieve benefits such as the exploitation of additional information contained in the bistatic reflectivity of targets, reduced vulnerability for military applications, forward-looking SAR imaging or increased radar cross section.

Even for objects that show a low radar cross section (RCS) in monostatic SAR images, we can find distinct bistatic angles to increase their RCS to make these objects visible in the final SAR image. On the other hand, urban areas are particularly affected by strong reflections due to the dihedral and polyhedral effects, which can be reduced by using different positions for the transmitter and receiver, which means a BSAR constellation. Bistatic interferometer SAR experiments with the tandem-X constellation are considered in [ROD 12]. The result is a more homogeneous SAR image in contrast to the monostatic case. Remote sensing with BSAR systems can be realized with different platform pairs. For example, future BSAR applications could use small “receive-only” SAR systems mounted on airplanes, unmanned aerial vehicles (UAVs) [MER 08], or mountains in conjunction with a satellite as transmitter or both the transmitter and receiver could be mounted on airplanes. In any case, the space–time synchronization of the antenna footprints is a big problem [WAL 06]. The key element to achieve an overlap of the footprints is the electronically steerable phased array antennas. The advantage of these antennas is the possibility of tracking the antenna beam very quickly.

The design and construction of a BSAR receiver suitable for airborne applications, using orbital SAR systems (ENVISAT, ERS-2, RADARSAT, TerraSAR-X among others) as opportunity transmitters is described in [MER 08]. The challenge of this design is to reduce the required data throughput of the recorded data. This is achieved by storing data only in the time intervals when scattered signals from the target area appear. The task of detecting these time intervals is performed in real time using a matched filter of the signal received directly from the SAR transmitter.

A vector model of BSAR processing is applied in [LOF 03]. Transmitter and receiver trajectories are considered in the case of arbitrary transmitter and receiver motion with no identical velocity vectors in a BSAR constellation. The point target response is defined in the space-time domain and transformed to the frequency domain by the method of stationary phase giving the point target reference spectrum.

New aspects of BSAR processing and experiments using separated transmitter and receiver flying on different platforms are discussed in

[END 04]. Two SAR systems are mounted on two different airplanes: the AER-II system has been used as a transmitter and the PAMIR system as a receiver. Different spatially invariant flight geometries have been tested. High-resolution BSAR images were successfully generated.

1.2. Passive space-surface bistatic and multistatic SAR

Passive space-surface bistatic SAR (SS-BSAR) is a particular class of BSAR system [CHE 08]. It comprises a spaceborne transmitter and a receiver which is located on or near the Earth's surface. Even though it represents a subclass of BSARs, it encompasses a wide variety of system topologies. Any satellite can be used as a transmitter, dedicated or non-cooperative. On the other end, the receiver could be airborne, onboard a ground moving vehicle or stationary on the ground. Throughout the years, this class of BSAR system has attracted the interest of many SAR research groups, each one considering a unique configuration, bistatic radar using a spaceborne illuminator [WHI 07], a sub-aperture range-Doppler processor for bistatic fixed-receiver SAR [SAN 06], a ground-based parasitic SAR experiment [CAZ 00], bistatic exploration using spaceborne and airborne SAR sensors [END 06] and a hybrid SAR processing method for data collected using a stationary bistatic receiver [SIK 08]. The main focus has been the investigation of passive SS-BSAR, with global navigation satellite systems (GNSS) as transmitters of opportunity (such as GPS, GLONASS and the newly launched Galileo) and an airborne receiver that includes an SS-BSAR image formation algorithm [ANT 07], signal detectability in SS-BSAR with a GNSS non-cooperative transmitter [HE 05], interference level evaluation in SS-BSAR with GNSS non-cooperative transmitter [CHE 04], SS-BSAR with GNSS transmitter of opportunity – experimental results [CHE 07], motion compensation algorithm for passive SS-BSAR [ANT 09] and non-cooperative transmitter selections for SS-BSAR [ZUO 07]. A new topology of SS-BSAR, a subclass of BSAR is presented in [CHE 09]. The topology for local area monitoring comprises GNSS as transmitters of opportunity and a stationary receiver on the ground.

A three-dimensional (3D) multistatic SAR imaging system, which utilizes reflected GPS signals from objects on the Earth's surface, is described in [LI 02]. The principle of bistatic radar is used to detect the movement of, or changes to, the imaged object. The indirect GPS signals are processed by a match filter with the aim of improving the spatial resolution of detection. Bistatic geometry and new SAR acquisition techniques based on opportunity sources are presented in [DAR 04]. Within the first order Born approximation, seismic bistatic acquisitions are transformed into monostatic ones using a simple operator named Dip Move Out. In essence, the elliptical locus of the reflectors corresponding to a spike in the bistatic survey is forward modeled as if observed in a monostatic one. The outcome of the model, the so-called *smile*, is a short operator, slowly time varying but space stationary. To transform a bistatic survey into a monostatic one, it is enough to convolve the initial data set with this *smile*. Based on the well-known similarity between seismic and SAR surveys, Dip Move Out is first described in its simple geometric understanding and is then used in the SAR case.

Passive Radar is an advanced remote sensing technology used for detecting and tracking airborne targets. Passive radar concept has two types of implementations: passive emitter tracking (PET) and passive coherent location (PCL). PCL is a bistatic or multistatic radar application that uses transmitters-illuminators of opportunity, for example, analog TV, analog LF radio, digital video broadcasting terrestrial (DVB-T), digital audio broadcasting (DAB), GSM, WiFi and GPS transmitters. All of these illuminators transmit continuous wave (CW) signals using different analog or digital modulation. The concept of the joint action of PCL and electronic support measurements (ESM) Tracker Systems that leads to higher positioning accuracy is considered in [PLS 13]. Analysis and estimation of the influence of position heights of components of BSAR scenario on location accuracy of PCL systems is discussed in [SUT 13]. The other class of passive radars uses non-cooperative pulse transmitters as illuminators, consisting of existing pulse radar networks as Air Traffic Control or Early Warning radars. In such a case, the main parameters of the signal (e.g. carrier frequency, pulse length, pulse repetition frequency, pulse bandwidth, chirp signal parameters, etc.) coming from the transmitter of opportunity need to be estimated. An extended generalized chirp transform-based recursive algorithm for signal parameter estimation in bistatic passive pulse radar is considered in [SAM 13]. Transmitter identification as well as single frequency network and FM signal characterization and DAB features for network analysis for a Cassidian passive radar sensor using FM, DAB and DVB-T broadcast signals is addressed in [WIN 13]. The capability of a DVB-T based passive bistatic radar system to detect both low flying aircrafts and ground moving targets has been proved by experimental results in [LAN 13].

EADS Cassidian develops an improved multiband passive radar demonstrator for 24/7 operation and sensor cluster measurements, processing FM, DAB and DVB-T waveforms in real time. The stationary passive radar system is realized as a nearly one-to-one copy of the FM part of the mobile van. Passive radar 3D localization is based on the intersection of multiple ellipsoids. System architecture, ASTERIX protocol and fusion into external networks are presented in [SCH 13].

1.3. Forward scattering radars

Recently, the advantages of forward scattering radar (FSR) has generated continuous interest in this system in universities, institutes and industries. This stimulates research activities focused on FSR bistatic RCS and target detection [BLA 99], shadow inverse synthetic aperture radar [CHA 00], FSR detection [GOU 02], FSR moving object coordinate measurement [BLA 00], FSR for vehicles classification [ABD 03] and ISAR data processing results from forward scatter radar measurements of ships [OVE 06]. The fundamentals of FSR can be found in the works of Willis [WIL 05] and Chernyak [CHE 98]. FSR exhibits some unique advantages, such as: robustness to stealth targets, enhanced target cross-sections, long coherent interval of the receiving signal, absence of signal fluctuations and reasonably simple hardware. It also has a number of drawbacks, such as the absence of range resolution and narrow operational area. Most studies of FSR have been carried out in a small number of scenarios. Publications are basically dedicated to FSR studies on airborne targets. BSAR study on ground FSR application has been performed. It included FSR vehicle classification [ABD 04], FSR analysis for ground target detection [CHE 05], FSR automatic ground target classification [CHE 06] and did not assume different levels of noise masking the received signal in which it makes the detection and classification process more difficult.

Surveillance, monitoring and protecting sea borders, coastlines and offshore territories is one of the challenges for homeland security, defense and for the safeguard of the national economy. A chain of buoys, located on the sea surface and equipped with FSR transceivers has been proposed in [DAN 08]. Objects crossing the baselines connecting adjacent transceiver buoys are detected through extraction and analysis of their Doppler signature. It is proposed that this system could detect even relatively small targets with low radar reflectivity such as jet-skis, inflatable boats and possibly swimmers. There are severe constraints in application of the FSR system for the detection of small marine targets. FSR has no range resolution in the main zone of ambiguity, and so, sea clutter will dominate over the signal level occupying the same Doppler band. A radar system for use in the marine environment, Ultra Wideband (UWB) FSR with estimation of signal-to-clutter ratio, is suggested [CHE 07, LIA 07]. The accent is made on the system's performance; UWB FS cross section of expected targets, UWB signal propagation above the sea surface at very small grazing angles (~0°), clutter levels and spectrum for varying sea conditions. It is proven that the level of clutter is lower and its spectrum much narrower than the narrowband FSR counterpart. As a consequence, the system performance increases and it becomes possible to detect small targets against the sea clutter. An analysis of FSR cross sections for typical small marine targets at various frequencies and spectrum bandwidths is performed. The simplified model is proposed in which the complex targets are replaced by equivalent target rectangular apertures for which an analytical solution for the FS RCS is known.

Aspects of FSR ground target detection are described in [MOH 08]. The accent is made on the procedure of extracting signal scattered from the ground target crossing the FSR baseline. The target signal is embedded and hidden inside the high clutter and noise interference. The problem of extracting the Doppler signature in different interference environments is addressed. Hilbert transform and Wavelet techniques have been used to predict the existence of a target. It is shown that using these techniques effectively target crossing the FSR baseline can be predicted. The capability of FSR to detect low-signal targets and low S/N (signal-to-noise) ratio signals, as well as its low cost, are reasons for the various applications of FSR in civil, defense, maritime, medical and security systems.

The design and construction of a BSAR receiver suitable for UAV and continuously synchronized with the pulse repetition frequency of the SAR transmitted signal is discussed in [MER 08]. Synchronism is recovered by matched-filtering of the acquired signal, which is performed efficiently in the frequency domain using the fast Fourier transform (FFT) algorithm. The concept of a microsensor FSR wireless network has recently been presented for situational awareness in ground operations [ANT 08, CHE 06]. Its primary objectives are the detection, parameter estimation (such as speed) and automatic target classification (ATC) of various ground targets (personnel and vehicles) entering or crossing its coverage area. Obviously, the radar carrier frequency cannot be too low (implying a long wavelength).

This is because the target RCS decreases significantly. In [CHE 06, SIZ 07, SIZ 07], it was shown that a human target (as the smallest of ground targets of interest for situational awareness) has a resonance scattering in the FSR configuration for waves with vertical polarization and carrier frequencies in the very high frequency (VHF) band (70–120 MHz). An investigation on the nature of foliage clutter [SIZ 08] shows the significant dependence of the received clutter power on the operational frequency. ATC requires the radar wavelength to decrease. First, experiments on car recognition were done on carrier frequencies around 870 MHz [ABD 03, RAS 08]. It was shown that FSR can be effectively used for ATC and the targets can be recognized and classified accurately.

An evaluation of a low-frequency FSR network for the classification of ground targets and ATC experiments for different operational frequencies are presented and discussed in [RAS 08]. The possibility of target recognition is shown for system-operating frequencies in the VHF band.

Full-polarized 3D geometry theory of diffraction (GTD)-based model of BSAR imaging system, which takes into account the motion of each element of the system (receiver, transmitter and target) and image reconstruction processing based on extended range Doppler algorithm (RDA) method, is considered in [COM 06].

Experimental results from the study of possibility for radar target detection in FSR using L1-based non-cooperative GPS transmitter and simple algorithms for target detection in FSR using local statistics are presented in [KAB 13] and [VER 13], respectively.

1.4. A moving target problem as an inversion problem in multistatic SAR

Based on compressed sensing theory, moving targets can be effectively imaged with transmitters and receivers randomly dispersed in a multistatic geometry within a narrow forward cone around the scene of interest. Existing approaches for dealing with moving targets in SAR solve a coupled nonlinear problem of target scattering and motion estimation, typically through matched filtering. In contrast, by using an overcomplete dictionary approach, the forward model is effectively lineated to solve the moving target problem as a larger, unified regularized inversion problem subject to sparsity constraints. Imaging of moving targets with multistatic SAR system, using an overcomplete dictionary of target velocities and compressed sensing theory, and a method for imaging of moving targets using multistatic SAR by treating the problem as one of spatial reflectivity signal inversion over an overcomplete dictionary of target velocities, is presented in [STO 09].

1.5. BSAR models, imaging, methods and algorithms

Focused monostatic and bistatic range Doppler imaging of rotating targets with coherent pulse radar are discussed in [KLE 93]. Several bistatic models, imaging methods and algorithms [LOF 04] and approximate bistatic point target spectrums [NEO 07, LI 08, WON 09] have been suggested. BSAR obtains more flexible imaging geometry configuration than the conventional SAR because of the spatial separation of transmitter and receiver. Bistatic geometry contributes to various SAR functions such as passive imaging and reconnaissance, forward-looking imaging, interferometric imaging and moving target indication. [KAS 06a, KAS 06b, KRI 06]. The BSAR imaging algorithm is different from the algorithms for SAR due to the separation of transmitter and receiver. A time-domain back-projection algorithm is popular in current applications [WAL 06] despite its inefficiency in computation.

An extended exact transfer function algorithm for BSAR imaging of a translational invariant case is presented in [SUN 09]. This algorithm directly adopts the two dimensional (2D) transfer function of conventional SAR, instead of deriving a new one, by converting the BSAR into an equivalent SAR. A new azimuth phase compensation function is constructed by exploiting this equivalency. Correction of geometry distortion in a BSAR image is considered in the proposed algorithm. One desirable property of the proposed algorithm is that the computing flow and efficiency are the same as the exact transfer function algorithm for SAR. The effectiveness is validated by point target simulations with tandem and forward-looking configuration.

1.5.1. *Range migration algorithm for invariant and variant flying geometry*

The first approach to a bistatic range migration algorithm for the special case of equal velocity vectors of transmitter and receiver was introduced in [SOU 91] for a 2D geometry. In [END 04], another bistatic range migration algorithm for a 3D geometry was proposed, where the SAR image is directly reconstructed in the ground plane. The processor is not optimum in the sense of the monostatic range migration processor, but the degradation is negligible for wide ranges of geometrical parameters. The advantage of such a Fourier-based processor is its numerical efficiency.

A further approach of a range migration processor [GIR 05] is very similar to [END 04] and [WAL 05], but it uses a physical reference and approximates the linear phase term by a Taylor series. Another type of a BSAR processor is presented in [DAR 04] and [LOF 04]. In both approaches, the bistatic processing will be done by quasi-monostatic processing after initially convolving the raw data with a bistatic deformation term.

Besides technical problems such as synchronization of the oscillators, involved adjustment of transmit pulse versus receive gate timing, antenna pointing, flight coordination and motion compensation, the development of a bistatic focusing algorithm is still in progress and not sufficiently solved. As a step to a numerically efficient processor, [WAL 05] presents a bistatic range migration algorithm for the translational invariant case, where transmitter and receiver have equal velocity vectors.

1.5.2. *Bistatic point target reference spectrum based on Loffeld's bistatic formula*

A bistatic point target reference spectrum based on Loffeld's bistatic formula (LBF) is analyzed in [WAN 09]. For LBF, the same contributions of the transmitter and receiver to the total azimuth modulation are assumed. This assumption results in the failure of LBF in the extreme configuration (i.e. spaceborne/airborne configuration). Simulations show that the proposed bistatic point target reference spectrum can work well for spaceborne/airborne configurations.

Focusing BSAR data in the frequency domain requires 2D point target reference spectrum. LBF and the method of series reversion have been applied to compute the point target reference spectrum of BSAR. In [WU 11], an original LBF is generalized by introducing the Doppler contribution functions of transmitter and receiver. An original LBF and its derivatives (e.g. extended LBF) are considered as special forms of the generalized LBF with constant Doppler contributions. Based on this, an ideal LBF with no computing error, except the error resulting from the principle of stationary phase is derived. Precise analytical point target reference spectrum for general BSAR is derived from an approximated ideal LBF. It expresses the Doppler contributions of the transmitter and receiver as a power series and approaches the ideal LBF. The error limit for the validity of bistatic point target reference spectrum is also considered. The results can be used to develop imaging algorithms for extreme bistatic (e.g. spaceborne/airborne) and high squint (e.g. bistatic forward-looking) cases.

The problem of wide bandwidth management in ultra-high resolution SAR systems can be solved by adopting stepped chirps and applying a synthetic bandwidth approach. However, high-resolution SAR image formation is a non-separable 2D impulse compression processing; so, the synthetic bandwidth procedure should be modified in correspondence with the image formation algorithm adopted. The application of a synthetic bandwidth approach in a SAR polar format algorithm (PFA) is demonstrated in [NIE 08]. The problem of motion compensation between the sub-pulses within a burst is discussed, and the signal processing flows are investigated in detail. The presented approach is validated by point target simulation.

An implementation of bistatic PFA using chirp scaling is discussed in [WAN 10]. The new algorithm applies chirp scaling in the range direction to realize the range resampling, which involves only complex multiplications and FFTs. The dechirped and the chirped signals are treated separately. The new approach obtains results comparable with the original algorithm, however, significantly improves the efficiency. Point target simulation validates the new algorithm.

A new way of looking at LBF is presented for tandem configuration in [CHE 12]. The factors that affect the precision of the spectrum are obtained through a comparison with another analytical one. It has been proved that the cosine of the half bistatic angle plays a more important role with respect to the other factor, which is whether the baseline-to-range ratio is equal to the tangent of the half bistatic angle or not. As long as the cosine of the half bistatic angle is very close to one, the LBF spectrum is of high quality, and it does not have a direct influence on the length of the baseline (baseline-to-range ratio) or the size of the squint angle. The factors that affect the precision of the spectrum are discussed in detail through simulated experiments.

1.5.3. *Target parameters extraction*

Bistatic ISAR can be implemented by two (or more) spatially separated radars and can observe moving targets in particular. A bistatic configuration can also be obtained by using one radar's antenna as a transmitter and the other radar's antenna as a receiver. Bistatic configurations for the estimation of 3D motion parameters and 3D interferometry ISAR image reconstruction have been proposed in [ZHA 04]. A generalized point spread function (PSF) for bistatic ISAR application is defined and classical motion compensation and RD image reconstruction techniques are discussed in [MAR 07].

The advantages of bi- and multistatic radar systems are based on the separation of their transmitter and receivers. The processing in bistatic radar must include the knowledge of geometry dependencies that exist in range, Doppler and S/N ratio. Extraction of target parameters, such as position, velocity and heading, could require the combination of data as a function of time and/or contribution from several systems. Bi- and multistatic radar requirements of synchronization in a separated transmitter–receiver system are discussed in [JOH 06]. Tracking in bi- and multistatic radars is also considered. Simulated input data are used to estimate parameters. Comparison of different methods for estimating measurement uncertainty is provided by using bistatic or multistatic radar input data.

A 2D point target spectrum for an arbitrary bistatic synthetic aperture radar configuration is derived from [NEO 07] based on series reversion, a method of stationary phase, and Fourier transform pairs. The accuracy of the spectrum is controlled by keeping enough terms in the two series expansions and is verified with a point target simulation.

A bistatic chirp scaling algorithm for processing the azimuth-invariant bistatic synthetic aperture radar data is described in [LI 08]. Two methods are used to derive the different parts of the range-Doppler expression of the point target. Compared with the method relying on the two-order expansion of the bistatic range model, the new algorithm provides a close-form azimuth modulation. The resolutions are enhanced through the introduction of the fractional Fourier transform into the range processing.

Based on an exact analytical bistatic point target spectrum, an efficient chirp-scaling algorithm is proposed in [CHE 13] to correct the range cell migration of different range gates to one of the reference ranges for tandem bistatic synthetic aperture radar data processing. FFTs and phase multiplications are used without any interpolation.

The existence of a double hyperbola in the bistatic range equation makes it difficult to find an exact analytical solution for the 2D point target spectrum. Several approximate solutions for the spectrum have been derived and used to focus bistatic synthetic aperture radar data. In [NEO 08], the relationship between three independently derived bistatic point target spectra is established by using LBF, Rocca's *smile* operator and method of series reversion. The accuracies of the point target spectra are demonstrated using simulations of X-band bistatic airborne radar with a fixed baseline.

A new RDA is presented in [WAN 11] for BSAR processing in a general configuration based on a bistatic point target reference spectrum: the improved extended Loffeld bistatic formula (ILBF). The ILBF spectrum is proved to be comparably accurate with the spectrum derived using the method of series reversion (MSR). Based on the expansion of the ILBF spectrum, a new bistatic RDA is developed to process the azimuth invariant and variant BSAR data. Compared with existing bistatic RDA, the new algorithm has a simpler formulation and is able to cope with moderate or high squint BSAR data.

An accurate bistatic point target reference spectrum based on a zero-order polynomial model is discussed in [WAN 10]. The spectrum contains only two hyperbolic square root terms that are very analogous in form to the analytical monostatic spectrum. The new formula can be considered as an improvement of the LBF and allows it to handle a wider range of bistatic configurations. The original LBF works well only in the case where the contributions of transmitter and receiver to the total Doppler modulation are approximately equal. The extended LBF (EBLF) defined in [WAN 09] uses a time bandwidth product to weight the azimuth phase modulation from each platform. However, this extension is valid only in the low squint bistatic geometry. Both LBF and ELBF are expanded up to the quadratic term to derive an approximate bistatic spectrum; however, they do not show a good focusing performance in the more complex bistatic geometry, for example, the high squint case. This is due to the inaccurate individual time-Doppler correspondences.

BSAR data are more challenging than the common monostatic data for processing because the flight geometry is more complicated and the data are usually non-stationary. Several frequency-domain monostatic algorithms have been modified to handle a limited number of bistatic cases, but a general algorithm, which can handle cases such as non-equal platform velocities, non-parallel flight tracks and high squints, is sought. A modified nonlinear chirp scaling (NLCS) algorithm to handle a general case of bistatic data is presented in [WON 08].

Traditional monostatic algorithms, such as the range Doppler and chirp scaling algorithms, do not work well in a bistatic environment. Based on the analysis of existing BSAR algorithms such as the wavenumber algorithm [SOU 91] and the back projection algorithm [DIN 02], it can be concluded that the NLCS algorithm [WON 01] could be a useful alternative. NLCS is an innovative way to focus on BSAR images. In [NEO 04], the existing NLCS algorithm is extended and improved to focus on a bistatic image where both platforms move in a parallel track with the same velocity.

A joint X-band BSAR experiment by ONERA/DLR [DUB 03] was carried out to explore the challenges associated with bistatic radar. It involves two separate monostatic SAR systems carried by E-SAR and RAMSES, imaging at broadside. Two separate configurations were used in experiments, both involving parallel flight paths and low squint angles. The algorithm developed can be used to focus on both cases.

Bistatic synthetic aperture radar processing (complex image formation) using the RDAs is discussed in [NEO 08]. The key step is to use an analytical form of the signal spectrum derived by the method of series reversion. The spectrum is used for secondary range compression (SRC), range cell migration correction and azimuth compression. The algorithm is able to focus the azimuth-invariant bistatic configuration where the transmitter and receiver platforms are moving in parallel tracks with identical velocities. Moreover, the algorithm is able to handle reasonably high squints and wide apertures because SRC can be performed in the 2D frequency domain.

Based on an exact analytical bistatic point target spectrum, an efficient chirp-scaling algorithm is proposed in [CHE 13] to correct the range cell migration of different range gates to one of the reference ranges for tandem BSAR data processing. The length of the baseline (baseline-to-range ratio) does not show any direct influence on the proposed algorithm, which can be applied to the processing of tandem bistatic data with a large baseline even when the baseline is equal to the range. No interpolation is needed during the entire processing; only FFTs and phase multiplications are needed, which result in efficiency. The validity of the proposed algorithm has been verified by simulated experiments.

Based on the BSAR survey, the main purposes of this work can be formulated, the solution of which will complement the impressive theoretical and practical achievements of authors whose publications are cited in this chapter:

1) analytical geometrical description of BSAR topologies and derivation of main kinematical equations of target, receiver and transmitter movements;

2) analytical description of waveforms and constructions of BSAR signals reflected from the objects of complicated shapes and the BSAR signal formation interpreted as a direct space transform;

3) derivation of image reconstruction procedures interpreted as direct space transforms for different BSAR signal constructions;

4) analytical geometrical determination of BSAR absolute and relative range resolutions;

5) numerical experiments to prove correctness and effectiveness of developed BSAR signal models and image reconstruction algorithms;

6) program implementation of waveforms and geometry and kinematics, signal modeling and image reconstruction procedures.

To achieve the aforementioned goals, approaches of the vector geometry and kinematics are applied to derive the main analytical, geometrical and kinematical equations for each BSAR scenario, and functional analysis to define BSAR signal models and image extraction algorithms are considered in this chapter.