

Bi- and Multistatic SAR: Potentials and Challenges

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Abstract

Bi- and multistatic synthetic aperture radar (SAR) operates with distinct transmit and receive antennas which are mounted on separate platforms. Such a spatial separation has several operational advantages which will increase the capability, reliability and flexibility of future SAR missions. We will introduce various spaceborne bi- and multistatic SAR configurations and compare their potentials for different applications like frequent monitoring, wide swath imaging, scene classification, single-pass cross-track interferometry or resolution enhancement.

1 Introduction

Bistatic radar is defined as a radar where the transmitter and receiver are spatially separated. In some definitions, it is also assumed that this spatial separation has to be a ‘considerable distance’ which is ‘comparable’ [1] or ‘a significant fraction’ [2] of either the target–receiver or the target–transmitter distance, but we will not limit our discussion to such systems with large baselines. The only assumption is that the transmit and receive antennas are on different platforms. Bistatic radar is not a new concept and its fundamental principles have been known and demonstrated many years before the development of an operational monostatic radar [3]. However, the interest in bistatic radar dropped quickly after the invention and demonstration of the monostatic radar principle in the late 1930’s. The major reason for this decline was the desire of many users to have a radar operated from a single site. Since then bistatic radars have been ‘re-discovered’ several times, mainly for military applications like precise target location or receiver camouflage. Only recently, bistatic radar received also increasing interest with respect to Synthetic Aperture Radar (SAR) and a number of bi- and multistatic radar systems are now under development or in planning [4]-[10]. The suggested systems may be divided into fully and semi-active configurations. In a fully active configuration, each radar has both transmit and

receive capabilities as illustrated in Fig. 1 on the left. Examples for fully active systems are the multistatic TechSAT 21 constellation [7] and the bistatic Radarsat 2/3 tandem [8]. Semi-active systems combine an active illuminator with one or more passive receivers as shown in Figure 1 on the right. Examples are the Interferometric Cartwheel [6] and BISSAT [9]. In principle, it is also possible to use the scattered signal from communication or navigation satellites in combination with long coherent integration times for specific applications like differential interferometry [11]. The distributed functionality in bi- and multistatic SAR allows for a natural separation of the radar payloads and will therefore strongly support the use of small, low-cost satellites in the future. For example, deployable antennas and reduced power demands of passive receivers enable an accommodation of the radar payload on micro-satellites. Satellite constellations will allow for a modular design where the re-use of major building blocks shortens development time, increases flexibility, and reduces costs. The ultimate goal is a highly reconfigurable and scalable satellite constellation for a broad spectrum of remote sensing applications. Such a multi-purpose system offers a flexible imaging geometry which may be dynamically adapted to different operational tasks. The following sections will give some examples of the potentials and challenges associated with bi- and multistatic SAR systems.

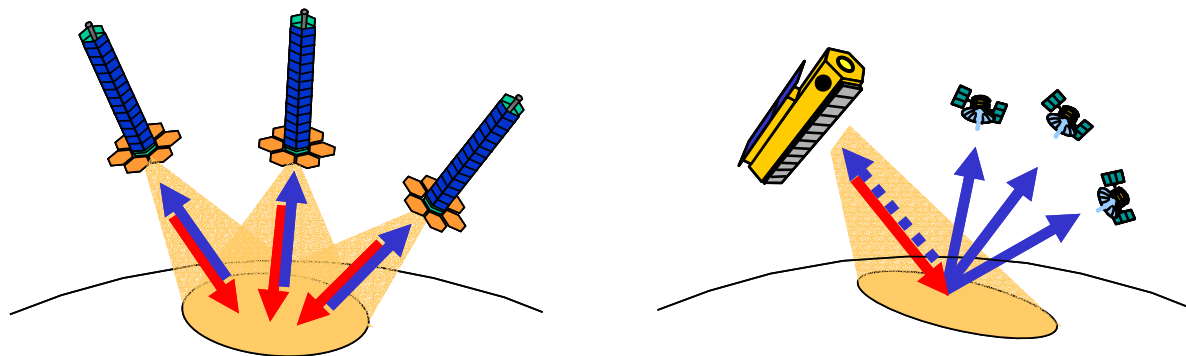


Fig. 1: Fully active (left) and semi-active (right) multistatic radar systems.

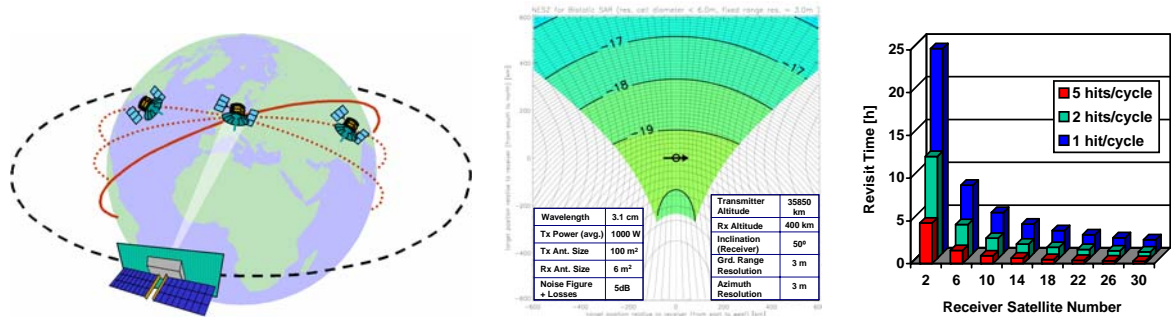


Fig. 2: Frequent monitoring with a bistatic SAR satellite constellation. Left: Geostationary illuminator with LEO receivers. Middle: Results from sensitivity analysis (NESZ). Right: Revisit times for local acquisition scenario.

2 Frequent Monitoring

Most users require instant access to up-to-date SAR data. The revisit times of current spaceborne SAR sensors – ranging from several days to several weeks – will not suffice for important applications like traffic monitoring, risk and disaster management, or security. Distributed satellite constellations have the potential to shorten the revisit times substantially. One promising approach uses multiple passive receiver satellites in conjunction with a geostationary illuminator (cf. Fig 2, see also [12]-[17]). This concept allows for a systematic reduction of the revisit times as well as an upgrade to other imaging modes like cross-track interferometry (cf. Sect. 4) or sparse aperture sensing (cf. Sect.5) by increasing only the number of low-cost, passive receivers. Multiple missions may also share a common illuminator, thereby reducing the costs of each individual mission significantly. The performance of such a multiple orbit system has been analyzed in detail in [14]. The middle plot of Fig. 2 shows an example of the results from the sensitivity analysis for an X-Band system with a ground resolution of 3 m (see also [17]). It becomes clear that the NESZ for the exemplary configuration defined by the inset will be in the order of -19dB for targets in the neighborhood of the receiver nadir. In this context, it is interesting to note that – in contrast to a monostatic SAR – a good ground resolution can also be achieved in the forward, downward and backward direction of the moving receiver. This property increases the access region and may also open new application areas like a data fusion with simultaneously acquired data from different sensors (optical, altimeter, etc.) on the same platform. The right diagram of Fig. 2 shows an example for the revisit times of a receiver constellation optimised to frequent monitoring of a selected ground area at 50° northern latitude. By choosing appropriate receiver orbits it is possible to cover the given area up to five times within the exemplary two day repeat cycle [14]. In this case, revisit times below one hour can be achieved with a moderate number of 10 receiver satellites. The coverage region of a geostationary illuminator will be restricted to approximately $\pm 55^\circ$ latitude due to the shallow incident angle with respect to the illuminator [14]. Such a restriction may be avoided by using satellites in geosynchronous, medium Earth, or Molniya orbits.

3 Bistatic Observation

Bistatic SAR imaging provides additional observables for the extraction of scene and target parameters (cf. Fig. 3). Bistatic data may also be combined with monostatic data for multi-angle observations. A system dedicated to the simultaneous acquisition of mono- and bistatic SAR data has been suggested in [5][9] together with a wealth of scientific applications. For example, a quantitative evaluation of the bistatic radar cross section (RCS) facilitates the detection and recognition of targets based on their characteristic bistatic radar signatures [18][19]. The segmentation and classification in radar images is expected to be improved by comparing the spatial statistics of mono- and bistatic scattering coefficients [20]. Multi-angle observations in a polarimetric configuration will allow for the quantitative estimation of important bio- and geophysical parameters of the Earth surface and its vegetation cover [21][22]. The increased bistatic scattering coefficient in a forward scattering geometry may also enhance the radiometric sensitivity of a bistatic radar. For example, an increase of the bistatic in-plane scattering coefficient ($\phi=0^\circ$) from -23dB to +6dB has been reported in [23] for rural land in X-Band (see also [3]). Furthermore, reduced retro-reflector effects have been observed in [24] for urban areas at large bistatic angles, thereby improving the detectability of scattered signals with low intensity. Further potentials arise from a combined mono- and bistatic range and Doppler evaluation for target localisation and velocity estimation, measurements of ocean wave spectra, analyses of bistatic scattering from rough water surfaces, atmospheric measurements, stereogrammetric applications, etc. [5][9].

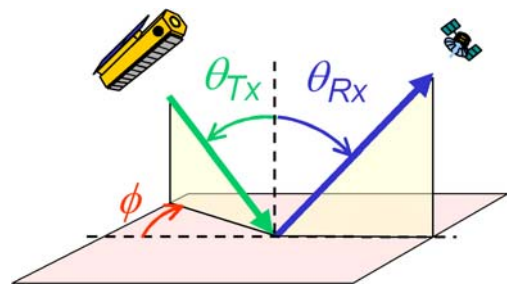


Fig. 3: Extended observation space in bistatic radar.

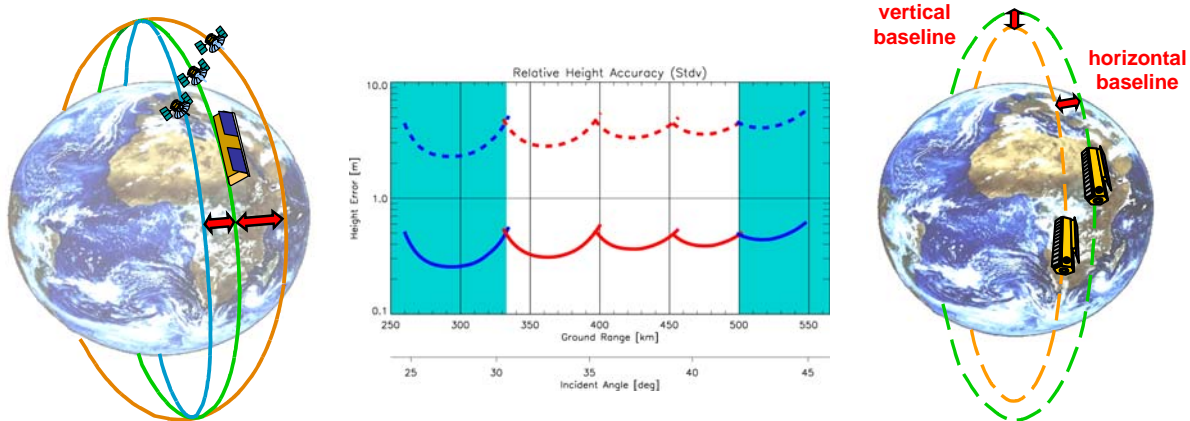


Fig. 4: Left: Multi-baseline cross-track interferometry with Trinodal Pendulum. Middle: DEM performance for Trinodal Pendulum in combination with TerraSAR-L. The estimated height accuracy is shown for two baselines with a height of ambiguity of 100 m (dashed) and 10 m (solid). Right: HELIX constellation for TanDEM-X.

4 Single-Pass Interferometry

SAR interferometry is a powerful technique to extract important bio- and geophysical parameters about the Earth's surface. However, conventional repeat-pass interferometry suffers from temporal decorrelation and atmospheric distortions. Such limitations may be avoided by a transition to bi- and multistatic satellite systems which offer a natural way to implement single-pass interferometry in space. Satellite formations enable a flexible imaging geometry with large baselines, thereby increasing significantly the interferometric performance for applications like DEM generation in comparison to a single platform system like SRTM. Single pass interferometry may be implemented either by a semi-active (Fig. 4, left, see also [6][25][26]) or by a fully active (Fig. 4 right, see also [7][8][10]) satellite constellation. Fully active systems have in general a higher sensitivity and flexibility, are less prone to ambiguities, and enable easier phase synchronization like in a ping-pong mode with alternating transmitters or by a direct exchange of radar pulses. Furthermore, they provide also a pursuit monostatic mode as a natural fallback solution in case of problems with orbit control or instrument synchronization. On the other hand, semi-active radar constellations have a significant cost-advantage and will therefore provide more interferometric baselines per money. An interferometric data acquisition with multiple baselines is well suited to resolve phase ambiguities in the interferogram and the middle plot of Fig. 4 shows that an excellent performance may be achieved by combining a small with a large baseline. Multiple baseline interferometry has furthermore the potential to solve problems arising from volume decorrelation in vegetated areas. The transition to a fully polarimetric constellation will enable a quantitative estimation of important biophysical parameters like vegetation height and density [27][28]. Another opportunity is along-track interferometry, e.g. for the measurement of ice drift and ocean currents [29][30].

5 Sparse Aperture Sensing

A constellation of multiple radar satellites recording the signals from a common illuminated footprint can also be regarded as a large aperture system with sparsely distributed sub-aperture elements. The linear combination of multiple receiver signals can hence be treated in the framework of array processing. The opportunity to form very narrow antenna beams will, e.g., allow for a space variant suppression of range and azimuth ambiguities. This will in turn lead to a reduction of the required antenna size for each receiver, thereby enabling cost-effective and powerful SAR missions with broad coverage and high resolution. Examples for such wide swath systems have been suggested in [14][31][32][33]. Note, that any cross-track separation of the receivers will introduce topography-dependent phase differences between the received signals, which have to be compensated, e.g. via the simultaneous acquisition of a digital elevation model in case of multiple satellites. This will lead to a combination of cross-track interferometry with linear beamforming in a generalized nonlinear spatiotemporal SAR processing [14][33]. Sparse aperture systems enable highly accurate velocity measurements of moving objects on the ground and may also overcome the problem of blindness against certain directions of target motion [34][35]. Another opportunity is precise target localization [36][7]. A coherent combination of multiple SAR images acquired from slightly different view angles can also improve the geometric resolution. This super-resolution technique may again be regarded as a formation of narrow beams which is complementary to the ambiguity suppression mentioned above. Super-resolution in range has the potential to overcome the bandwidth limitations for spaceborne SAR sensors posed by international frequency regulations. A further promising application is SAR tomography [37] which enables e.g. a real 3-D imaging of the vegetation structure for biomass estimation on a global scale.

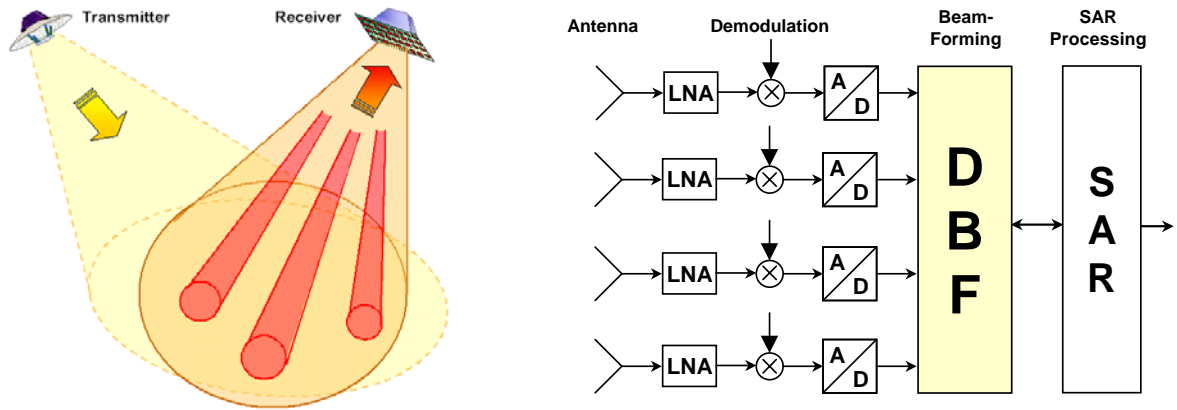


Fig. 5: Bistatic SAR with digital beamforming on receive. Left: Illumination of a large footprint and reception of the scattered signals with multiple beams. Right: Block diagram of digital beamforming on receive (see text).

6 Digital Beamforming

A very promising technique for future bi- and multi-static SAR systems is digital beamforming on receive [38][39][40][33]. Consider as an example the geostationary illuminator concept of Section 2, where the antenna footprint of the transmitter will be more than 10 times larger than the receiver footprint. This will limit the simultaneous data collection area. Such a waste of signal energy and information may be avoided by splitting the receiver antenna into multiple sub-apertures. As shown in Fig. 5 on the right, each sub-aperture signal is separately amplified, down converted, and digitized. The digital signals are then combined in a dedicated processor to form multiple antenna beams with arbitrary shapes (Fig. 5, left).

Multiple independent beams in elevation allow for the simultaneous and unambiguous mapping of several distinct subswaths with full azimuth resolution and high antenna gain. Multiple subswaths can then be combined to form a wide image swath. Range ambiguities may further be suppressed by appropriate null-steering in elevation. Note that the spatial separation of the transmitter and receiver permits continuous recording, thereby avoiding possible gaps in the imaged swath (cf. [41]). The ability to suppress range ambiguities will enable very compact SAR sensors with reduced antenna length and increased antenna height. Multiple beams in azimuth will allow for the division of a broad Doppler spectrum into multiple sub-spectra with different Doppler centroids. The bandwidth in each subchannel corresponds to the total length of the receiver antenna, which determines the minimum PRF in case of a bistatic SAR (see also Sect. 5 in case of a multistatic SAR). A coherent combination of the sub-spectra will then yield a broad Doppler bandwidth for high azimuth resolution. This may also improve the signal-to-noise ratio or the radiometric resolution.

Further potentials of digital beamforming on receive are velocity estimation with multiple phase-centres (e.g. by STAP,[42]) and the directive suppression of interferences. All these modes may be implemented in a cost-efficient way by integrating receive-only modules with low power demands directly in the antenna.

7 Challenges

The focusing of bistatic SAR data will require robust and efficient processing algorithms. First steps in this direction have already been achieved (see e.g. [43][44][45]). Note that relative deviations of the satellite trajectories and/or velocities may cause different range-Doppler histories for each point on the ground, thereby leading to a non-stationary data acquisition. Coherent processing will also require a stable phase between the oscillators within the synthetic aperture time. First evaluations show that the phase noise of current oscillator technology will allow coherent integration times on the order of 10s for an ISLR of -20dB at X-Band [14]. High power amplifiers are a prerequisite for wide swath imaging with high geometric resolution. Sufficient signal energy for a large illuminated footprint may be provided by use of conventional reflector antenna technology, thereby avoiding expensive Tx-modules with lower efficiency. Interferometric and sparse aperture sensing will require close satellite formations. Hence, orbit selection and collision avoidance may become a major design driver, especially under contingency conditions. Many applications demand also precise relative position sensing, which may e.g. be achieved by a direct evaluation of the wave field from GPS signals. A special requirement for DEM generation is precise phase synchronisation over long time intervals to avoid an excess of ground control points. Possible solutions are a direct exchange of radar pulses or a ping-pong interferometric mode [8] in case of fully active systems and an appropriate phase synchronisation in case of semi-active constellations [46]. Small receiver antennas may cause increased ambiguity levels. The development of algorithms which combine second-order interferometry with linear ambiguity suppression in a generalised nonlinear SAR processing remains a challenge [47]. A further challenge arises from the huge amount of data collected by multiple independent apertures. This will require broadband data links and/or appropriate data reduction strategies, e.g. by on-board processing which exploits redundancies between the different channels.

8 References

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