Digital Beamforming and MIMO SAR: Review and New Concepts

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Abstract

Spaceborne Synthetic Aperture Radar (SAR) is a unique tool for large scale Earth observation, but the current generation of SAR sensors suffers from some fundamental limitations with regard to their imaging and mapping capabilities. To overcome these limitations, several new instrument architectures and SAR imaging modes have been suggested that employ digital beamforming (DBF), multiple aperture data recording and MIMO SAR techniques. This paper provides a critical review of these techniques and makes some suggestions for further improvements. Special attention is given to advanced DBF and MIMO SAR concepts for ultra-wide swath imaging.

1 Introduction

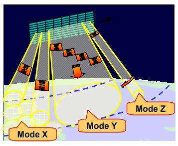
Synthetic Aperture Radar (SAR) is a powerful remote sensing technique that can provide high resolution images of the Earth surface independent of weather and sunlight illumination. Further unique opportunities emerge from the coherent combination of multiple SAR images. Thanks to these capabilities more and more applications ask for uninterrupted time series of radar images acquired in short intervals. However, all current high-resolution SAR systems are rather limited with respect to their acquisition capabilities. An example is TerraSAR-X which provides different trade-offs between resolution and coverage (see Fig. 1). In stripmap mode, which offers a spatial resolution of 3 m, only 2% of the Earth's landmass can be mapped during its 11 days repeat cycle. This limitation posed also a challenge in the design of the TanDEM-X mission and actually constrains the accuracy and resolution of the digital elevation model [1].

The lower part of Fig. 1 shows that future SAR missions may ask for a mapping capability that is one or even two orders of magnitude better than that of TerraSAR-X. A prominent example is Tandem-L, which has the goal to investigate dynamic processes on the Earth surface [2]. For this, an extremely powerful SAR instrument is required that has the capability to continuously map a 350 km wide swath in full polarisation and with a geometric resolution well below 10 m. Other missions may ask for a higher resolution but do not need a weekly coverage of the Earth.

The key technologies to boost the performance of future SAR systems are digital beamforming (DBF) and multiple aperture signal recording. Several suggestions have been made to exploit either one or both of these techniques to improve the imaging capabilities of SAR instruments. A prominent example is the high-resolution wide-swath (HRWS) SAR [5] which is currently under development at EADS Astrium with support from DLR. This system shall map a 70 km wide swath with a resolution of 1 m, thereby ex-

State of the Art (TerraSAR-X)	Imaging Mode (single pol)		
	ScanSAR	Stripmap	Spotlight
Resolution	16 m	3 m	1 m
Swath Width	100 km	30 km	10 km
Orbit Duty Cycle	3 minutes per orbit		

Resolution ⟷ Swath Width ⟷ Repeat Cycle



Future Requirements	Imaging Mode (quad pol)		
	Mode X	Mode Y	Mode Z
Resolution	5 m	1 m	<< 1 m
Swath Width	400 km	100 km	30 km
Orbit Duty Cycle	30 minutes per orbit		

Figure 1: Spaceborne SAR imaging: State-of-the-art and future requirements.

ceeding the number of acquired ground resolution cells if compared to the TerraSAR-X stripmap mode by a factor of 21. The HRWS system uses digital beamforming on receive to steer in real-time a narrow beam towards the direction from which the radar echo from the ground is expected to arrive. By this, the one-to-one relationship between the radar pulse travel time and its angle of arrival is exploited. A large receiving antenna can hence be used to improve the sensitivity without narrowing the swath width.

The unambiguous swath width of the HRWS system is, as in a conventional stripmap SAR, limited by the antenna length. Hence, a long antenna is required to map a wide swath. To improve the azimuth resolution, the receiving antenna is divided into multiple subapertures that are mutually displaced in the along-track direction and connected to individual receiver channels [3]. By this, multiple azimuth samples can be acquired for each transmitted pulse, while every subaperture sees a wider Doppler spectrum. The coherent combination of all sub-aperture signals in a dedicated multichannel SAR processor enables then the unambiguous generation of a high-resolution wide-swath SAR image beyond the classical limits [8]. This technique has been successfully demonstrated in airborne campaigns [18] and recently also in a spaceborne experiment using the dual receive antenna mode of TerraSAR-X [21].

2 Advanced DBF Concepts

The HRWS system requires a very long antenna to map an ultra-wide swath with high azimuth resolution. As a rule of thumb, a length of 10 m is required for every 100 km swath extension. To avoid an undue increase of the antenna length, several new instrument architectures and modes have been suggested in [12]. One example is the combination of the displaced phase center technique of the previous section with a ScanSAR or TOPS mode (cf. Fig. 2, top left). As in classical ScanSAR, azimuth bursts are used to map several swaths. The associated resolution loss from sharing the synthetic aperture among different swaths is compensated by illuminating a wider Doppler spectrum and collecting the radar echoes with multiple displaced azimuth apertures. Such a system is currently considered by ESA as a possible successor to Sentinel-1 [13]. The goal is to map a 400 km wide swath with 5 m resolution. The peculiarities of the multichannel ScanSAR processing and their impact on system performance have been analyzed in [17]. A possible drawback of this multichannel ScanSAR approach is the rather high Doppler centroid with which some targets will be mapped if a high resolution is desired. The situation becomes even worse in a multichannel TOPS mode. High squint angles may moreover challenge co-registration in interferometry.

Besides multichannel ScanSAR, several alternative concepts have been suggested in [12]. A common feature of these alternatives is that they record not only one but several radar echoes arriving simultaneously from different directions. For this, multiple narrow elevation beams are formed where each beam follows the echo of a different pulse transmitted by a wide beam illuminator. This enables an increase of the coverage area without the necessity to either lengthen the antenna or to employ burst modes. The top right of Fig. 2 provides an illustration, where three narrow Rx beams follow the echoes from three simultaneously mapped image swaths that are illuminated by a broad Tx beam. A sufficiently high antenna is needed to separate the echoes from the different swaths by digital beamforming on receive. An alternative is range variant null steering as already suggested for the quad-element array SAR in [4]. Since the azimuth resolution is, as in a classical stripmap SAR, given by half of the antenna length, this will typically lead to a shorter but higher SAR antenna. Such a more compact shape may have constructive advantages, avoiding e.g. a complicated folding for the satellite launch. Note that this mode makes also effective use of the hardware already available for digital beamforming in elevation and avoids its duplication to implement multiple azimuth channels.

The required ultra-wide swath illumination can either be accomplished by a separate small Tx antenna, or by using a combined Tx/Rx antenna together with (a) phase tapering, (b) spectral Tx diversity or (c) an illumination with a sequence of sub-pulses [11].

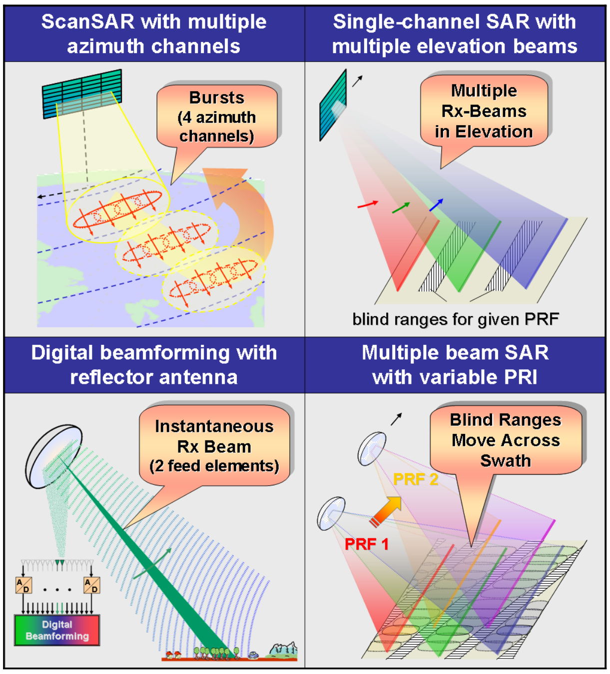


Figure 2: Advanced concepts for ultra-wide swath imaging with high resolution.

An interesting alternative to a planar antenna is a reflector that is fed by a multichannel array as illustrated on the lower left of Fig. 2. A parabolic reflector focuses an arriving plane wave on one or a small subset of feed elements. As the swath echoes arrive as plane waves from increasing look angles, one needs only read out one feed element after the other to steer a high gain beam in concert with the arriving echoes. This technique was originally suggested in a patent [6] and then reinvented independently by DLR and NASA/JPL during a joint Tandem-L/DESDynI study [2]. JPL suggested an analogue switching between the feed elements [16], while DLR argued in favour of connecting each feed element with its own A/D converter [12]. The former may allow a cheaper implementation, while the latter enables a performance improvement by combining multiple feed signals in a digital signal processor [15], [20]. The solution with the digital feed is also in favour of more advanced modes like the multiple beam technique introduced above. Compared to a direct radiating array, the computational requirements for real-time beamsteering are significantly reduced since only few feed signals have to be combined at each instant of time.

A drawback of the multi-beam mode are the blind ranges that are due to the fact that the radar cannot transmit and receive at the same time. This can be overcome in a bistatic SAR where the transmitter is sufficiently separated from the receiver. To avoid a separate transmit satellite, one can employ a variation of the PRF which shifts the blind ranges across the swath (Fig. 2, lower right). The PRF variation could either be implemented in discrete steps leading to a multiple beam ScanSAR mode or a pulse-to-pulse variation of the PRI. The latter provides better performance but requires a dedicated SAR processing which is currently under development.

3 MIMO SAR

A receiver with n subapertures allows a simultaneous sampling of the arriving wavefronts with n phase centers. The effective number of phase centers can be increased by using additional transmitters. Such an extension was already suggested for resolution improvement in the context of a forward looking imaging radar experiment on a helicopter [7] and later elaborated in more detail for a 3-D radar system on a UAV [10]. In a SAR, the possible benefits of using multiple transmitters range from an increase of the coverage area to the suppression of range and azimuth ambiguities to the provision of additional baselines for interferometric and tomographic applications [9], [10], [11], [14], [19].

To separate the radar echoes from the different transmitters, several authors suggested to simultaneously transmit mutually orthogonal waveforms. Notable confusion arose, however, what exactly is meant by "orthogonal". Some authors just require

$$\int s_i^*(t)\cdot s_j(t)\cdot dt = 0 \quad \text{if} \quad i \neq j \tag{1}$$

where $s_i(t)$ and $s_j(t)$ are the transmitted signals from any two different apertures. While this condition allows perfect separation of the scattered waveforms from a single point target, it is not sufficient to separate the signals in case of an extended scattering scenario [11]. The reason is that the orthogonality is not ensured for arbitrary shifts between the transmit signals. As a result, the energy from spatially separated scatterers illuminated by the other waveform(s) will not vanish after range focusing but appear either smeared or at different positions [11]. This reasoning is also evident by considering range focusing as an all-pass filter in the frequency domain. Depending on the number of transmitters, the smeared energy from the orthogonally illuminated scatterer ensemble may even exceed the focused target impulse response.

To avoid this problem, some other authors require

$$\int s_i^*(t)\cdot s_j(t+\tau)\cdot dt = 0 \;\; \forall\; \tau \in \mathbb{R}, i \neq j \tag{2}$$

This enables a perfect signal separation also in case of a distributed scatterer scenario (all effects from wavenumber and Doppler shift are neglected here for the ease of discussion). However, an immediate consequence of this requirement is that $s_i(t)$ and $s_j(t)$ must have nonoverlapping spectral support. This is immediately evident from the cross-correlation theorem

$$s_i(t)\otimes s_j(t) = \mathcal{F}^{-1}\left[S_i^*(f)\cdot S_j(f)\right] \tag{3}$$

where $\otimes$ is a short hand for the cross-correlation integral of Eq. (2), $\mathcal{F}^{-1}$ denotes the inverse Fourier transform and $S_i(f)$ and $S_j(f)$, are the Fourier transforms of $s_i(t)$ and $s_j(t)$, respectively. This theorem is similar to the well-known convolution theorem and states that the cross-correlation of two functions can be expressed in the frequency domain via the product of their individual Fourier transforms.

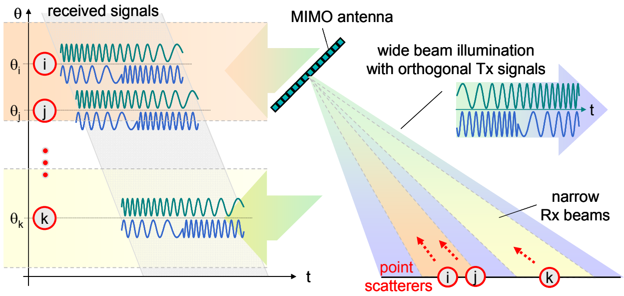


Figure 4: MIMO SAR based on two orthogonal transmit signals. The Tx-waveforms are designed such that their cross-correlation vanishes for small time offsets (cf. signal returns i and j). For larger time offsets, the otherwise correlated signals are separated via narrow Rx beams (cf. signals i and k). This trick of exploiting the spacetime imaging geometry enables the simultaneous use of multiple Tx signals and the unambiguous separation of their radar echoes also in case of distributed scatterer scenarios. Note that both waveforms have the same spectral support.

It is evident from Eq. (3) that Eq. (2) can only be fulfilled if the product between $S_i(f)$ and $S_j(f)$ vanishes for all f. This implies that $S_i(f)$ and $S_j(f)$ have no common spectral support, making them of limited use if coherent image combinations are desired.

To overcome this fundamental challenge, it was suggested in [9], [11] to employ especially designed waveforms together with digital beamforming on receive. The basic idea can be expressed by a kind of restricted orthogonality condition

$$\int h(\tau)\cdot s_i^*(t)\cdot s_j(t+\tau)\cdot dt = 0 \tag{4}$$

where in comparison to Eq. (2) an additional weighting function $h(\tau)$ has been included which depends on the relative time shift τ (there may also be an implicit dependency of $h(\tau)$ on t but this is neglected in the following for ease of understanding). The function $h(\tau)$ is a direct consequence from the side looking geometry of our ground imaging radar. To understand this, note that there exists a close correspondence between the angle of arrival and the radar signal delay. This means that signals from targets at different ranges arrive also from different look angles. As a result, the echoes from targets with sufficient mutual range delay τ can be separated by an appropriate beamforming in the receiver (cf. Fig. 4). For this, the antenna height should exceed the value given in Eq. (14) of [11]. For small antenna heights an accurate null steering may be required.

As an example, consider the function $h(\tau)$ = rect(τ/T), which is one within the interval [$-T/2, T/2$] and zero elsewhere. We hence must only ensure that the left hand side of Eq. (2) vanishes for shifts τ that are smaller than $T/2$. This offers a new degree of freedom to re-introduce spectral overlap between $S_i(f)$ and $S_j(f)$. One possibility would be to use mutually shifted chirp pulses [11]. A similar approach is illustrated in Fig. 4 which employs a signal with linear frequency modulation for $s_i(t)$ and a second signal $s_j(t)$ with a sufficient offset in its instantaneous frequency. This offset can e.g. be obtained by a cyclic shift of $s_i(t)$.

Recently, it was suggested to employ orthogonal frequency division multiplexing (OFDM) techniques to obtain a pair of transmit signals that satisfy Eq. (2). For this, the bandwidth was divided among two waveforms by assigning subsequent frequencies to either one or the other waveform. This results in a comb-like spectrum for each signal and no spectral overlap between the two waveforms. It has further been argued that there exists a strong correlation between adjacent range frequency components in SAR images. This is then exploited to obtain coherence between the scattered signals in spite of using two waveforms with non-overlapping spectral support for scene illumination. Such a correlation between frequency components is, however, incompatible with the assumption that the scene can be modelled by a stationary stochastic process. This is immediately evident from the Fourier shift theorem. Only if the total scene extension is shorter than the transmitted pulse length, such a correlation may occur. While this could apply to some airborne or ground-based scenarios, it is typically not justified in a spaceborne SAR. To overcome this fundamental problem, one may again exploit the spacetime relationship discussed in the previous paragraph. By using multiple narrow elevation beams one may divide a large scene into narrow sub-scenes. For long transmit pulses and a sufficiently large antenna, this may introduce the desired correlation among the frequency components [11]. Further analyses have to show the advantages or disadvantages if compared to the approaches suggested above.

4 Outlook and Conclusions

This paper discussed advanced digital beamforming techniques that will significantly improve the performance of future SAR missions. The imaging capabilities can be further improved by MIMO SAR techniques if (1) appropriately designed “short-term orthogonal” waveforms are transmitted and (2) the spacetime relationship of a side-looking radar is exploited by forming narrow Rx beams that suppress the non-orthogonal cross-terms arising from larger shifts between the transmitted waveforms. By this, one may for example double the swath width in the HRWS system if not one but two transmit antennas are used at the beginning and end of the elongated Rx antenna. Interferometric, tomographic and GMTI systems may also benefit from such a MIMO SAR architecture which provides additional baselines.

The imaging of a wide swath with high resolution requires typically a large receiver array to compensate the low effective radiated power associated with a wide beam illuminator. An interesting alternative to an extended planar array may be a large unfoldable reflector that is illuminated by a digital feed array. This architecture is not only suitable for a high performance SAR in a conventional orbit, but it opens also the door for a radar in a medium Earth orbit with very short revisit times (MEOSAR, cf. Fig. 5).

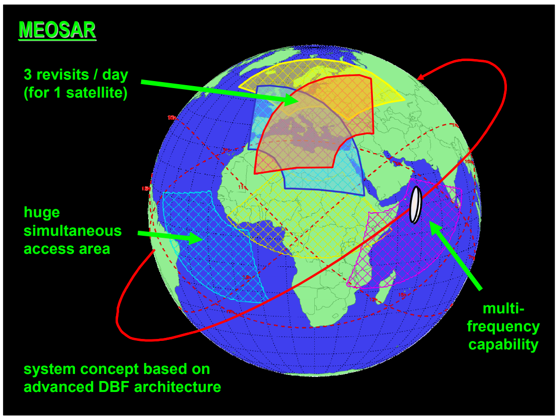


Figure 5: A MEOSAR can provide multiple revisits per day with a single satellite. This offers unique opportunities to monitor dynamic processes on the Earth surface.

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