MIMO SAR Techniques and Trades
(Focused Session on Future Radar)

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Abstract—A Synthetic Aperture Radar (SAR) system utilizing multiple-receive and multiple-transmit channels (Multiple-Input Multiple-Output: MIMO) is commonly referred to as MIMO SAR. The trade-space for such a system includes the instrument and antenna parameters taking into consideration the digital beamforming techniques described through the operation modes of the radar. The purpose of exploring this trade-space is to improve and optimize the performance of the system, described through the performance parameters. In this paper we first introduce digital beamforming operation modes for SAR exploiting multiple channels. Then we explain the multi-dimensional trade-space in terms of a set of parameters. Based on an example MIMO SAR system we show that there are new and unexpected ways of trading the system and performance parameters versus each other.

I. INTRODUCTION

A view at the evolution of spaceborne Synthetic Aperture Radar (SAR) sensors reveals several development stages. The first sensors were on/off sensors with a single fixed mode of operation (fixed beam, incidence angle, bandwidth, etc.). Obviously, the performance of these first sensors in terms of e.g. resolution or swath width was also fixed. Later, sensors were developed which could be operated in multiple modes, such as StripMap, ScanSAR or Spotlight; however the macro-based commanding was basically restricted to selecting a specific mode without the flexibility to alter/access individual instrument settings. Operating the instruments in different modes allowed improving specific performance parameters, however, at the expense of impairing others. A good example is the use of ScanSAR to increase the swath width which worsens the azimuth resolution.

Current SAR sensors—third generation—offer a greater flexibility in commanding nearly each individual parameter of the instrument (see TerraSAR-X [1] for example). This can be understood as providing the basic building blocks to construct any operation utilizing different instrument settings. This allows fine tuning the performance parameters (e.g. changing the azimuth resolution in Spotlight mode) or even operating in new modes not considered in the instrument design phase, the TOPS operation mode being a good example [2]. However, even current sensors still operate within the same trade-space subject to the same “fundamental limitation” as the first SAR sensors. An exception can be seen for some sensors, which already offer two channel capabilities, partly as a by-product of the redundancy concept such as for TerraSAR-X or as a design to offer along-track capabilities as is the case for RADARSAT-2. This step towards multi-channel SAR marks a cumbersome paradigm change following what has persistently been published.

Intensive research is on-going for a new generation of multi-receive-channel SAR published for example in [3]–[6]. Further, such systems are already considered for future missions such as Sentinel-1 successor or Tandem-L [7]. The main innovative characteristic of forthcoming generations of SAR systems is the use of multiple elevation and/or azimuth receiver channels combined with digital beamforming (DBF) capability [4], [8]. This allows for the synthesis of multiple or dynamic digital receiver beams.

Further, multiple transmit channels are being suggested as an extension to DBF systems. On a first view, this trend does not seem to make sense. Indeed a prerequisite of synthetic aperture radar is a moving platform, which suggests that the spatial position of an additional transmitter will also be reached by a single moving transmitter after a short time delay. Nevertheless, a more detailed view reveals that adding transmitters can be beneficial as it can be used—among others—to add interferometric capabilities or for sub-pulse techniques [3], [9]. With this, we have arrived at what is commonly referred to as MIMO SAR (Multiple-Input Multiple-Output SAR), a term originating from communication.

The virtue of MIMO SAR is that it extends the dimension of the trade-space. This allows the conception of systems which overcome or bypass the limitation of conventional SAR. A good example is the High-azimuth-Resolution and Wide-Swath SAR also known as HRWS [10]. By dividing the receive antenna into multiple sub-apertures and recording the data from each of them the effective sampling rate is increased. This improves the azimuth resolution without sacrificing swath width [8], [11]. Obviously multi-channel SAR offer the engineers a wide variety of options for constructing new operation techniques (modes) and combining them in multiple ways. The question is whether these techniques are useful in the sense of improving the performance? Indeed there are several published MIMO operation techniques which turn out to increase the complexity while in the end not improving the performance.

It is the aim of this paper to present techniques (i.e. operation modes) utilized by MIMO SAR systems exploring digital beamforming. Further the trade-space of MIMO SAR is introduced in terms of a set of parameters describing the system and the performance. Interesting and unexpected compromises will be shown for an exemplary SAR mission.
II. MIMO SAR OPERATION MODES

In the following the basic multi-channel operation modes divided into elevation and azimuth are introduced.

A. Digital Beamforming in Elevation

In 1981 Blyth [12] suggested a basic approach for analog beam-steering such that the receive beam moves over the swath in accordance with the position of the echo. About twenty years later, his idea finds a more detailed description and justification in the independent and almost contemporary works by Kare [13], and Suess & Wiesbeck [14], [15]. The later for the first time presents digital beamforming techniques in conjunction with a time varying receive beam-steering in elevation.

The SCan-On-Receive (SCORE) mode of operation is primarily based on generating a wide transmit beam that illuminates the complete swath and a narrow, high gain beam on receive that follows the pulse echo on the ground. The high gain SCORE beam results in an increased signal-to-noise ratio compensating the low gain (wide beam) transmit antenna loss. Specifically at the swath edges (half-power beamwidth angles) the typical two-way loss is reduced. Further, the narrow receive beam has the advantage of attenuating the range ambiguities. DBF is used to combine the signals received by the sub-apertures, in order to obtain at each instant a sharp and high gain pattern, steered towards the expected direction of arrival of the echo. Also DBF in principle allows forming more than one receive beam as shown in Fig. 1. Multi-SCORE basically means that the same Rx data are combined in multiple different ways, where each combination yields a different beam.

The specific beamforming implementation depends on the system involved and can be implemented both for a planar or reflector antenna [16]. It can in general be described by a complex and time varying weighting of the subaperture signals followed by a summation. This effectively reduces the data rate by eliminating the redundancies, thus, in the ideal case the data reduction is lossless.

B. Digital Beamforming in Azimuth

Multiple phase centers in along-track (azimuth) enable an improved azimuth resolution, while requiring the data streams from each azimuth channel to be recorded separately for on-ground processing [6]. Here, in contrast to the elevation operation, the multiple channels cause a higher data volume resulting from the increased resolution. The principle behind multi-azimuth channel operation is different for the planar and reflector systems, which requires a separate treatment.

For the planar system, shown in Fig. 2(a), all sub-apertures cover the same angular segment, thus “seeing” identical Doppler spectra. Considering a single sub-aperture, the spatial separation between the samples, as determined by the pulse repetition frequency (PRF), is such that the Doppler spectrum is undersampled, i.e. aliased or ambiguous. It is only through the combination of the spatial samples of all sub-apertures, that the Doppler spectrum can be recovered unambiguously. Each sub-aperture can thus be considered as an additional spatial sample in the along-track direction carrying non-redundant information.

A reflector system of multiple azimuth phase channels will require multiple feeds displaced in along-track direction as shown in Fig. 2(b). In contrast to the planar case, here each azimuth element “looks” at a different angle and by this the angular segment (Doppler span) covered by each element does not overlap with those of the others. Here also, each channel carries non-redundant information but it samples a narrow Doppler spectrum corresponding to the half-power-beamwidth of the corresponding pattern. The PRF must be high enough such that the spatial sampling for each channel is adequate. The joint patterns yield the high azimuth resolution. Any overlap between the patterns (redundancies) can for example be used to suppress ambiguities [17].

III. SAR TRADE-SPACE PARAMETERS

The most relevant system and performance parameters are shown in Fig. 3. Here the system parameters basically describe the instrument both in terms of quantities fixed to the system design such as antenna dimensions, as well as operation parameters which can be set for a specific data take (e.g. PRF). The performance is usually derived from the mission requirement and described in terms of a set of values for the performance parameters [16].

To understand the trade-space parameters we consider the classical trade between swath and resolution. The process for
improving the azimuth resolution for a conventional single-channel SAR is shown in Fig. 4(a) where the interaction between system and performance parameters finally leads to a reduced swath width. Similarly, any attempt to increase the swath width leads to a worsening of the azimuth resolution. In both cases the reason can be traced back to Shannon's sampling theorem, which gives the minimum number of azimuth samples per time interval.

Fig. 3. The most relevant system and performance parameters for SAR. These parameters can be optimized using different techniques (modes).

Adding a second Tx antenna [19], [20] allows the system to be operated such that two pulses are transmitted within each Pulse Repetition Interval (PRI). This operation technique is known as the sub-pulse mode [9] where typically each sub-pulse is delayed by a small fraction of the PRI with respect to previous one as shown in Fig. 6. Doubling the number of Tx pulses within the same time interval consumes twice the power. But now the number of received samples per PRI is also doubled (i.e. the spatial sampling is doubled) which reflects the unambiguous Doppler bandwidth which can be processed and by this the azimuth resolution\(^3\) which becomes twice as good.

The echo signals of the two sub-pulses arrive at nearly the same time at the receiver. To separate the two echoes multi-SCORE is utilized here (see Fig. 1), where two receive beams are generated, each one maximized to the direction of arrival of one sub-pulse while suppressing the energy of the other [9].

Note that the SAR system described here is truly a MIMO SAR utilizing both multiple-transmit and multiple-receive channels.

Fig. 4. The interaction between the various trade-space parameters when improving the azimuth resolution. Here the parameter type is color coded, while up/down arrows indicate an increases/decreases of the value.

IV. EXAMPLE MIMO SYSTEM

The specific system configuration to demonstrate each trade tends to be different depending on the parameters involved. Here we present one generic system serving as a demonstration example. This system is shown in Fig. 5 and consists of two transmit reflector antennas with fixed beams and a single receive reflector with a digital multi-channel feed array. A detailed description of the system and its performance (although not necessary for the understand the subsequent sections) is given in [19], [20].

Fig. 5. Example MIMO SAR system showing the configuration consisting of two fixed beam Tx reflector antennas and a single Rx reflector utilizing a digital feed.

Of course this requires that the antenna lengths are adapted to match the increased Doppler bandwidth.

\(^2\)Higher (or better) resolution here implies a smaller value of the azimuth resolution performance parameter.

\(^3\)Of course this requires that the antenna lengths are adapted to match the increased Doppler bandwidth.
staggered PRF. It can be shown, that this technique increases the side-lobe level of the impulse response function (IRF) of the system, unless the average PRF is approximately doubled [21]. The system now operates in the somehow unusual mode, where a wide swath is covered despite the high PRF.

The effect of doubling the PRF is threefold. First it results in a higher range ambiguity level [9]; this can at least partly be compensated by applying interference suppression techniques, i.e. elevation DBF. Second the high PRF basically means an oversampling of the azimuth Doppler spectrum; this allows the use of sub-pulse Azimuth Phase Coding (APC) which further eliminates part of the ambiguous energy [22]. Third, it causes an increase in the data rate; which can be reduced by applying on-board pre summing techniques. It should be pointed out that, apart from the APC, the above techniques which applied to compensate the various unwanted effects require an increase in the on-board digital processing capabilities.

VI. CONCLUSIONS

The paper treats multiple-input multiple-output synthetic aperture radar and its implementation through an example spaceborne instrument designs. By investigating the trade space of SAR, it is shown that MIMO extends the dimensionality of the same, when compared to conventional single channel SAR. As an example sub-pulse techniques open new perspectives for high resolution, single-pass interferometry, or full quad polarization SAR. The respective operation modes are described in the paper. It is understood that digital beamforming is essential for MIMO SAR, since without it the orthogonality of the signals can not be exploited, i.e. the signals could not be separated on-receive. Further, it offers improved interference (ambiguity) suppression and noise reduction. Clearly, the shift is towards systems with increase on-board digital processing capabilities.

REFERENCES


Fig. 7. Parameter and techniques trade map for the example MIMO SAR system.