High-Resolution Wide-Swath ScanSAR: Opportunities and Trade-Offs of a Novel Exploitation of Radar Bandwidth and PRF

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Abstract

The multichannel extension of the conventional ScanSAR, combined with SCan-On-REceive (SCORE), is a preferential operational mode for future high-resolution wide-swath SAR systems. This paper investigates novel solutions to further improve the achievable performance of this mode and/or reduce the associated system complexity, based on an innovative exploitation of radar signal bandwidth and pulse repetition frequency (PRF). The rational of the proposed approaches is explained, the achievable performance numerically analyzed, advantages and trade-offs discussed.

1 Introduction

Future spaceborne Synthetic Aperture Radar (SAR) will be able to deliver images with overall improved quality if compared to the present systems. In particular, the relevance for the end user of the simultaneous availability of high-resolution and wide-swath images has motivated an intense research in the last decades, and brought to novel operational modes and algorithms [1]-[7]. A prominent concept, considered as candidate for future SAR missions, is the so called High-Resolution Wide-Swath (HRWS) SAR [2]. It is based on a planar phased array antenna with multiple digital receive (Rx) channels and Digital Beamforming (DBF) capability. Specifically, the azimuth multichannel reconstruction (MAPS) and SCan-On-REceive (SCORE) techniques are used to relax the SAR imaging constraints [3], [4]. As regards the operational mode, an extension for multiple azimuth channels of the conventional ScanSAR, combined with SCORE, the so called HRWS ScanSAR, is considered for imaging ultra-wide swaths with high resolution [5].

The HRWS ScanSAR demonstrates outstanding SAR imaging performance. Nevertheless, limitations and room for improvement are still recognizable [4]. In order to explain this statement, it is useful to recall that the number of bursts plays a fundamental role in view of the SAR instrument architecture and complexity, and the expected imaging performance. In fact, increasing the number of bursts allows imaging a wider swath, but requires also a larger number of azimuth Rx digital channels in order to achieve a desired azimuth resolution. This affects the complexity of the SAR instrument architecture, the data rate, the on-board memory and the downlink capacity. Moreover, a larger number of bursts is associated with a larger squint angle variation, and consequently with a performance degradation due to scalloping, ionospheric disturbance, line-of-sight velocity vector variations. It is therefore generally advantageous to keep the number of bursts as low as possible. Another problem is related with the spatial distribution of the transmitted power. In fact, on transmission (Tx), a broadening of the elevation antenna patterns is used to adapt the beamwidth to the imaged swath extension. Nevertheless, this could encounter practical restrictions and result in a poor SAR image quality.

In order to overcome the mentioned limitations of the HRWS ScanSAR, this paper investigates novel solutions based on an innovative exploitation of the radar signal bandwidth and the pulse repetition frequency (PRF).

2 Reference SAR System

Without loss of generality, the considered reference SAR system resembles the HRWS system, long assumed as baseline for the European Space Agency (ESA) mission, Sentinel-1 Next Generation (S1-NG) [2]. It is a C-band system (RF centre frequency 5.405 GHz) orbiting at a height of 700 km. The architecture is based on a planar phased array antenna, 1.18 m high and 12.8 m long, with multiple digital Rx channels (8 in azimuth and 7 in elevation) combined according to MAPS and SCORE. On Tx, the Phase Spoiling (PS) technique is used to broaden both the azimuth and elevation beams. The average Tx power is about 900 W. The system has full polarimetric capability. In particular, for the QP products, the Tx linear polarization is toggled from pulse to pulse; whereas for single- and dual-polarimetric (SP and DP) products a single linear polarization is transmitted.

The ESA HRWS system is expected to deliver SAR images with large coverage by operating in HRWS ScanSAR mode (in the following shortly denoted as WS). The timing diagrams considered for SP and QP in WS mode are shown in Fig. 1 (top and bottom, respectively). In both cases, the imaged swath is composed by 4 subswaths and is imaged in a single pass by using 4 bursts. In WS SP mode the imaged swath reaches an extension of 400 km, whereas in WS QP mode it covers the 280 km located in near range. The spatial resolution, both in ground range and azimuth, remains below 5 m.

3 Exploiting Radar Bandwidth

The radar bandwidth can be used to improve the WS performance, according to the recently proposed multifrequency subpulse (MFSP) technique [6]. As ScanSAR, the MFSP is conceived for imaging wide scenes, but differs from the former due to the transmission within the same pulse repetition interval of multiple subpulses, occupying disjoint range bands. Specifically, each subpulse is used to illuminate a different subswath, so that, not only one, but multiple subswaths are imaged within a single burst. On Rx, the echoes arriving simultaneously from the different subswaths can then be separated based on their range frequency support. As a result, the MFSP mode allows for an improved swath extension and/or an improved spatial resolution if compared to a conventional ScanSAR mode, without the emergence of range ambiguities [6]. Moreover, as explained in the following Sections, further degrees of freedom in the system design become available, to achieve a desired SAR image quality.

3.1 Number of Bursts Reduction

Fig. 2 shows the timing diagram for a MFSP SP mode, where 2 subpulses are employed. In comparison with the WS SP (Fig. 1, top), the swath extension is unchanged, but the number of bursts reduces from 4 to 2.

The reduction of number of bursts makes a resource available, which can be exploited, for instance, by the following three design variations:

- Var#1: to improve the azimuth resolution;
- Var#2: to improve the overall azimuth performance;
- Var#3: to reduce the number of azimuth channels (i.e. system complexity and data rate).

More in detail, in Var#1, the MFSP exploits the same Doppler bandwidth and azimuth patterns of WS SP (cf. Fig. 3, top). Accordingly, the achievable azimuth resolution improves by a factor of about 3/5 with respect to WS.

In Var#2, the system is designed to achieve an azimuth resolution of 5 m. In this case the processed azimuth bandwidth is about 3/5 smaller than in case of WS. Consequently, a sharper Tx azimuth beam, with higher gain, could be used (Fig. 3, centre).

In Var#3, also the Rx beam becomes sharper, by reducing the number of azimuth channels from 8 to 5 (Fig. 3, bottom). The azimuth resolution is kept to 5 m.

The azimuth patterns and the processed Doppler bandwidth for the three design variations are shown in Fig. 3.

The achievable SAR imaging performance in WS and MFSP was numerically analysed for the presented variations, under the following assumptions:

- same chirp band extension for corresponding subswaths;
- same average Tx power;
- same SCORE beams scan corresponding subswaths;

Specifically, the following parameters were evaluated: swath extension; spatial resolution; azimuth and range ambiguity-to-signal ratio (AASR, RASR); noise equivalent sigma zero (NESZ); Scalloping. The obtained results are summarized in Table 1. They show that, compared with WS, the MFSP achieves a general improvement of the Scalloping and AASR, due to the lower number of bursts. The adjustment of azimuth patterns for Var#2 and Var#3 improves the AASR of more than 7 dB and 4 dB, respectively, and compensates the 3 dB loss of Tx power associated with each subpulse so that the NESZ is not degraded. RASR, as expected, is equal for all cases.

3.2 Subswath Extension Reduction

Fig. 4 shows the timing diagram for a QP mode based on the MFSP with 2 subpulses, as alternative to the WS QP (Fig. 1, bottom). In both cases the number of bursts is 4. Nevertheless, in MFSP the overall swath is covered by 8 instead than 4 subswaths; each subswath with an extension given by the half power beamwidth (HPBW) of the Tx elevation pattern. Accordingly, the subswaths can be

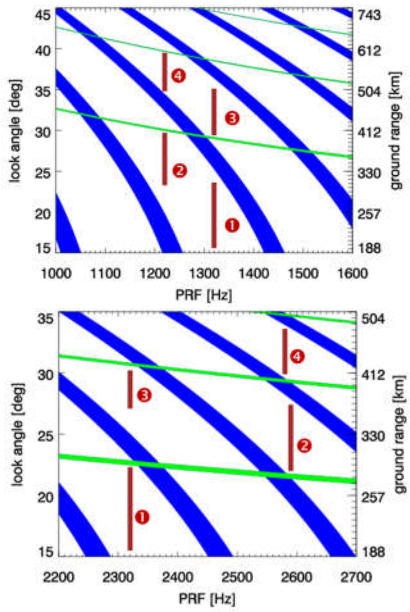

Figure 1 Timing diagrams for the WS SP (top) and WS QP (bottom) mode: the vertical segments denote the subswaths; the coloured stripes the blind areas associated with the Tx-event (blue) and the nadir echo (green); the ringed numbers the burst number.

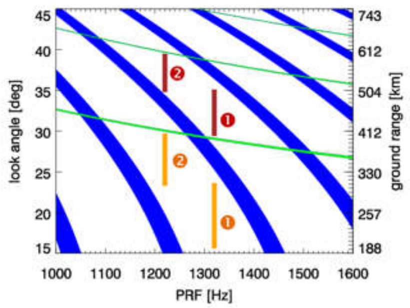

Figure 2 Timing diagram for the MFSP SP. The colour of each segment (subswath) denotes the subspulse number: brown for the first subpulse, orange for the second.

illuminated with uniform elevation Tx patterns. This solution allows for a better distribution of the Tx power and a better suppression of the range ambiguities, compared with the WS QP. In fact, the PS technique achieves poor performance for small broadening factors [8], as those used in far range (Fig. 5).

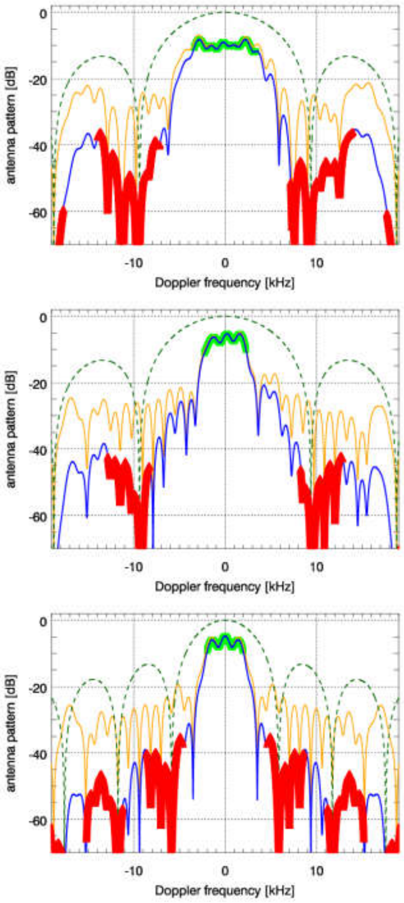

Figure 3 Azimuth patterns (solid orange line: Tx, dashed green line: Rx, solid blue line: 2-way); distribution of the useful/ambiguous signal (green/red) for uniform PRF.
WS SP and Var#1 (top); Var#2 (centre); Var#3 (bottom).

	WS SP	MFSP Var. #1	MFSP Var. #2	MFSP Var. #3
no. az. channels	**8**	**8**	**8**	**5**
swath width [km]	**400**	**400**	**400**	**400**
gr. resolution [m]	**5**	**5**	**5**	**5**
az. resolution [m]	**5**	**3.5**	**5**	**5**
RASR [dB]	**-26.5**	**-26.5**	**-26.5**	**-26.5**
AASR [dB]	**-22.3**	**-25.1**	**-30**	**-26.7**
NESZ [dB]	**-25.5**	**-22.5**	**-25.7**	**-25.7**
scalloping [dB]	**1.6**	**1.2**	**1**	**1.3**

Table 1 SAR imaging performance achieved over the imaged swath in WS and MFSP mode (the worst value).

It is worth to remark, that the constraint of having a swath extension given by the HPBW of the Tx elevation beam is relevant only in far range. Accordingly, the overall swath extension is not strictly determined by the HPBW.

The achievable SAR imaging performance was analysed under the same assumptions considered in the previous Section. The obtained results show a considerable improvement of the RASR performance for the MFSP mode compared with WS: about 9 dB in co-pol and 10 dB in x-pol. In particular, the x-pol RASR, generally a very critical performance, remains below -24 dB all over the imaged swath, in MFSP. Moreover, using uniform patterns instead than the PS allows for higher gain and better NESZ: with respect to WS, the NESZ at zero Doppler in MFSP shows an improvement of about 1 dB, even if in MFSP each subswath is imaged with half average power w.r.t. WS (the average Tx power for each subpulse is 450 W instead than 900 W). The other performance values are approximately equal for WS and MFSP.

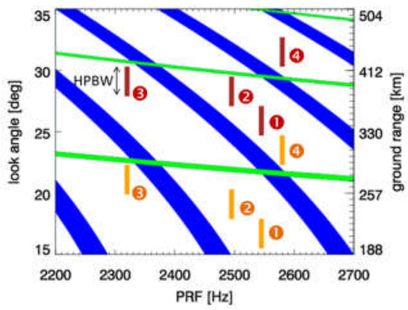

Figure 4 Timing diagram for the MFSP QP.

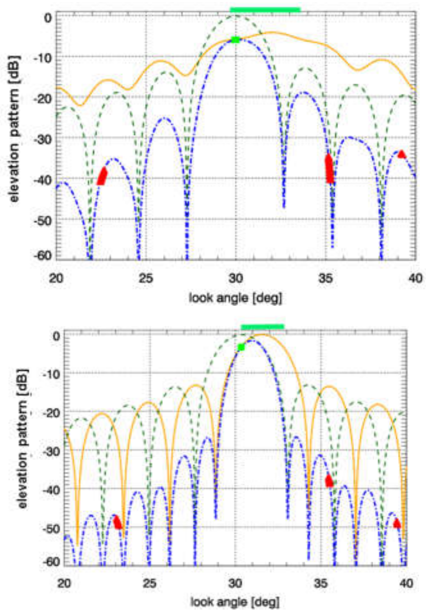

Figure 5 Elevation patterns for the WS QP (top) and MFSP QP (bottom). Orange solid line: Tx; green dashed: Rx; blue: two-way. Range ambiguities/signal marked by a red/green points. Subswath marked by the green segment on the top.

4 Exploiting PRF

As shown in the previous Section, imaging multiple subswaths within the same burst could be advantageous in terms of SAR image quality and system design. The solution based on the MFSP mode allows avoiding any interference between the simultaneously imaged subswaths [6]. Nevertheless, in general, the MFSP requires the implementation of multiple, simultaneous Rx beams, as well as the availability of additional radar signal bandwidth. These limitations can be overcome by properly exploiting the Tx PRF. The proposed approach is denoted as Generalized Beam Switch Wide Swath (GBSWS), recalling the relationship with the recently proposed BSWS mode for interferometrically compatible SP and QP SAR images [7].
With the mere aim of explaining the rationale of GBSWS, let us consider the timing diagram for SP in Fig. 6. In GBSWS, the Tx PRF increases by about an integer factor N with respect to the PRF conventionally used in SP (N=3 in Fig. 6). Groups of N subswaths are associated with the same PRF value, and imaged within the same burst. Specifically, these N subswaths are sequentially illuminated by switching the Tx beam pattern with frequency equal to the Tx PRF. Note that, for a constant average Tx power, if the Tx PRF increases by N, the power associated with each pulse decreases by N. A proper choice of the subswhats position along the slant range direction allows receiving the echo from the subswaths not simultaneously, but separated in N subsequent Rx-windows. Then, on Rx, a single beam allows recovering the echoes backscattered from the N subswaths, by scanning them sequentially from Rx-window to Rx-window. The so recorded echoes from N subsequent pulses (within the same burst) are elaborated separately: each one is used to image one of the subswaths, according to the conventional SAR processing, with a PRF N-times lower than the Tx PRF. It is worth to remark that the GBSWS could be sensitive to range ambiguities, due to the increased Tx PRF and the switch of the Tx pattern. In this case, it could be advantageous to combine GBSWS with a Multifrequency (MF) approach, to avoid or mitigate the interference between subswaths imaged within the same burst by exploiting the radar bandwidth of N subsequent pulses.

5 Conclusions

The MFSP and GBSWS, two burst modes for HRWS SAR imaging, exploit in an innovative way the radar signal bandwidth and the pulse repetition frequency, in order to image multiple subswaths within the same burst. As a result, w.r.t. a conventional approach, the number of bursts or the size of the subswaths can be reduced. This offers additional degrees of freedom in the systems design and/or allows for improved SAR imaging performance.

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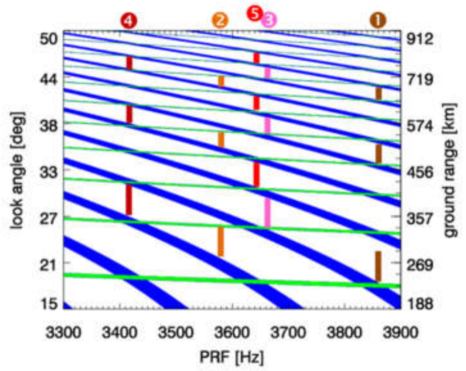

Figure 6 Timing diagram in GBSWS SP. The colour of each subswath denotes the burst number, which is remarked also by the ringed numbers on the top.