Reconsideration of Ambiguities in Quad-Pol SAR

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Abstract

Merging the complex signals available from both cross-polarized (cross-pol) channels of a quad-polarimetric (quad-pol) synthetic aperture radar (SAR) may lead not only to a 3-dB gain in the signal-to-noise ratio (SNR), but also to a remarkable improvement in the azimuth and range ambiguity-to-signal ratios (AASR, RASR) of cross-pol data, especially if azimuth phase coding is employed. Staggered SAR operation is also addressed, for which a novel azimuth phase code is proposed. Range ambiguities in cross-pol data can also be reduced by adopting a hybrid-polarimetric architecture, but this may result in a degradation of the AASR of the cross-pol channels.

1 Introduction

The design of spaceborne high-resolution wide-swath (HRWS) quad-polarimetric (quad-pol) synthetic aperture radar (SAR) systems is often challenging due to severe range ambiguities in the cross-polarized (cross-pol) channels. If two linear polarizations, e.g., horizontal (H) and vertical (V), are interleaved on transmit (TX) and both H and V polarizations are simultaneously recorded on receive (RX), the signals of the cross-pol channels are contaminated by strong co-polarized (co-pol) range ambiguous returns from the interleaved pulses. This constrains the swath width over which the ambiguity requirements can be met, especially at large incidence angles.

While it is well known that, under the assumption of reciprocal backscattering coefficients, merging the complex signals available from both cross-pol channels leads to a 3-dB gain in the signal-to-noise ratio (SNR) of cross-pol data [1], the implications of such a merging on the azimuth and range ambiguity-to-signal ratios (AASR, RASR) have not been addressed so far. This paper thoroughly covers this topic and shows the performance for a spaceborne L-band HRWS SAR system with multiple elevation beams based on a 15 m reflector antenna, fed by a multi-channel array, as described in [2]. This system is able to achieve 7 m azimuth resolution over a 350 km ground swath in full polarization (simultaneous imaging of 5 subswaths separated by "blind" strips), if the pulse repetition interval (PRI) is kept constant, or a 175 km continuous swath, if the PRI is continuously varied (staggered SAR) [3]-[5]. Advantages and drawbacks of a hybrid quad-pol architecture [6], where left- (L) and right- (R) circular polarizations are interleaved on TX and both H and V polarizations are simultaneously recorded on RX, are furthermore discussed.

2 Conventional Quad-Pol SAR

2.1 Constant PRI SAR

For a conventional quad-pol SAR with constant PRI, the AASR of merged cross-pol data is equal to the value that would have been obtained for twice the pulse repetition frequency (PRF) of one channel. Figure 1 (a) shows the AASR for the aforementioned reflector-based L-band HRWS system and a PRF = 2800 Hz. As apparent, the gain from merging is significant.

The RASR of merged cross-pol data depends in general on the coherence γ and the relative phase φ of the two co-pol channels: As the odd range ambiguities consist of alternating HH and VV signals, the backscatter coefficient relative to the k-th odd ambiguity σ_k^0 to be considered for the odd range ambiguous contributions in the RASR evaluation [7] is given by

$$\sigma_k^0 = \frac{1}{4}\left(\sigma_{HH_k}^0 + \sigma_{VV_k}^0 + 2\sqrt{\sigma_{HH_k}^0 \sigma_{VV_k}^0}\,\gamma\cos\varphi\right) \qquad (1)$$

where $\sigma_{HH_k}^0$ and $\sigma_{VV_k}^0$ are the backscatter coefficients of the HH and VV channels. For the (non-merged) HV and VH channels σ_k^0 is equal to $\sigma_{HH_k}^0$ and $\sigma_{VV_k}^0$, respectively. The RASR gain from merging is null for γ=1 and φ=0, equal to 3 dB for γ=0, but can be considerable for γ=1 and $\varphi=\pi$ (backscatter model from [8]). Measurements on quad-pol L-band F-SAR data show that the RASR averagely improves by 1.7 dB [9].

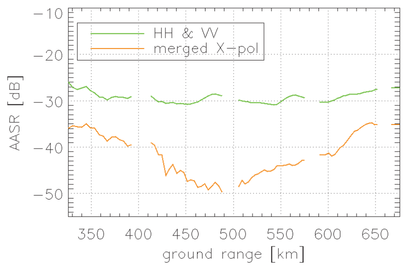
If azimuth phase coding [10] is employed and, in particular, the following code is used

TX Polarization	H V H V H V H V …
Phase	0 0 π 0 0 0 π 0 …

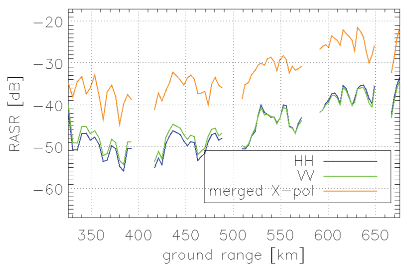
it can be shown that the backscatter coefficient of the ambiguity σ_k^0 is given by

$$\sigma_k^0 = \frac{1}{4}\left(\sigma_{HH_k}^0 + \sigma_{VV_k}^0\right) \quad (2)$$

independently of γ and φ. In this case, merging results in an additional 3-dB RASR gain when compared to the already improved RASR of the cross-pol channels with azimuth phase coding, leading to better ambiguity performance (Figure 1 (b)). The joint use of azimuth phase coding and merging is therefore strongly recommended not only for the design of future spaceborne quad-pol SAR systems, but also for the optimization of the imaging performance of quad-pol SAR systems currently in operation.



(a)



(b)

Figure 1: Ambiguity performance for a HRWS quad-pol SAR with constant PRI and multiple elevation beams, using azimuth phase coding and merging, for PRF = 2800 Hz. (a) AASR. (b) RASR.

2.2 Staggered SAR

Staggered SAR allows mapping a wide continuous swath rather than multiple disconnected subswaths by means of a continuous variation of the PRI [3]-[5]. The evaluation of the AASR and the RASR in staggered SAR is addressed in [7]. Moreover, azimuth phase coding is not straightforwardly applicable in the staggered SAR case, because the range ambiguous echoes are located at different ranges for different azimuth samples.

In the following it is assumed that staggered SAR data are resampled and decimated on-board prior to downlink and that the complex signals available from the HV and VH channels are available at the same time [5]. The AASR and RASR gain from merging (i.e. averaging) the complex signals available from both cross-pol channels can be evaluated by simulation. The AASR gain from merging is due to the non-stationarity of the azimuth impulse response of staggered SAR. As far as the RASR gain from merging is concerned, this depends on the coherence γ and the relative phase φ of the two co-pol channels. For γ=0, we have a 3-dB RASR gain, while for γ=1 the RASR gain as a function of φ is displayed in Figure 2 (black curve). If the azimuth phase code mentioned in Section 2.1 is employed, the RASR gain for γ=1 as a function of φ is just shifted compared to the previous one (red curve in Figure 2). Using the following novel azimuth phase code

TX Polarization	H V H V H V H V …
Phase	0 0 π 0 0 0 0 0 …

merging results in a 3-dB RASR gain, independently of of γ and φ (blue curve in Figure 2).

Figure 3 displays the AASR, the RASR, and the total ambiguity-to-signal ratio (ASR), defined as the sum of the AASR and the RASR, for the aforementioned HRWS SAR system operated in staggered SAR mode with a mean PRF equal to 3800 Hz. Merging cross-pol data in combination with a proper azimuth phase code leads to a 3-dB ASR gain and is therefore crucial to meet the ASR requirement (e.g. -22 dB) in a quad-pol staggered SAR system (Figure 3 (c)). Another possibility is to design the sequence of PRIs for staggered SAR, such that the closer near range ambiguity for the HV channel and the closer far range ambiguity for the VH channel are no longer located at different ranges for different azimuth samples. Simulations show that this allows a further RASR gain of approximately 1.5 dB.

3 Hybrid Quad-Pol SAR

Hybrid quad-pol SAR consists of interleaving L- and R-circular polarizations on TX and simultaneously recording both H and V polarizations on RX [6]. The conventional quad-pol channel data (HH, VV, HV, and VH) are then obtained by matrix transformation from HL, HR, VL, and VR. The main advantage of this architecture is the mitigation of range ambiguities in cross-pol data (critical) at the expense of an increase of range ambiguities in co-pol data (not critical) [6]. As discussed in the following, this improvement is, however, associated with a degradation of the AASR of the cross-pol channels.

In hybrid quad-pol SAR the HV complex signal is obtained by combining the discrete and interleaved complex signals $s_{HR}(t)$ and $s_{HL}(t)$ of the HR and HL channels, given by

$$\begin{aligned} s_{HR}(t) &\approx s_{HH}(t)\sum_n \delta(t-nT) \\ &\quad - js_{HV}(t)\sum_n \delta(t-nT) \\ s_{HL}(t) &\approx s_{HH}(t)\sum_n \delta(t-nT-T/2) \\ &\quad + js_{HV}(t)\sum_n \delta(t-nT-T/2) \end{aligned} \tag{3}$$

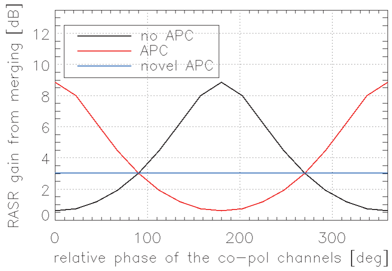


Figure 2: RASR gain from merging for a staggered SAR system as a function of φ and for γ=1.

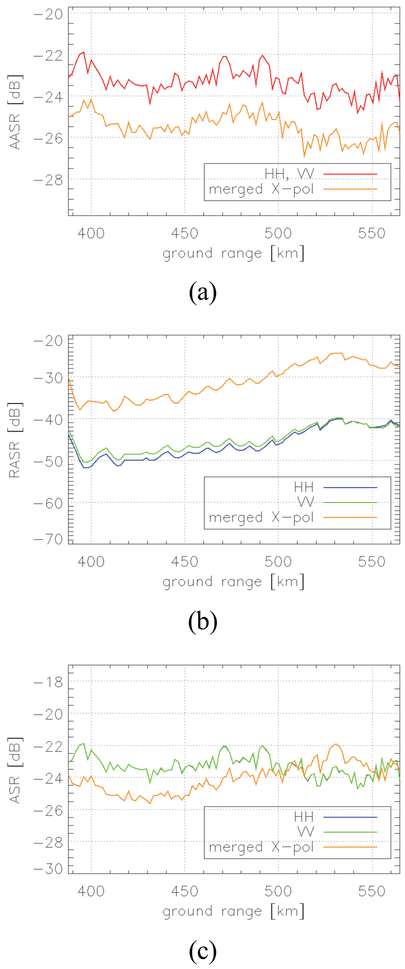


Figure 3: Ambiguity performance for a HRWS quad-pol SAR with PRI variation and multiple elevation beams for a mean PRF equal to 3800 Hz. (a) AASR. (b) RASR. (c) ASR. It is assumed that the novel proposed azimuth phase code is used together with merging of cross-pol data.

where $s_{HH}(t)$ and $s_{HV}(t)$ represent the ideal continuous time unambiguous signals of the HH and HV channels, and T is twice the reciprocal of the PRF. The synthesized discrete HV data $\hat{s}_{HV}(t)$ are then given by

$$\begin{aligned} \hat{s}_{HV}(t) &= js_{HR}(t) - js_{HL}(t) = s_{HV}(t)\sum_n \delta(t-nT/2) \\ &\quad + js_{HH}(t)\sum_n \delta(t-nT) - js_{HH}(t)\sum_n \delta(t-nT-T/2) \end{aligned} \tag{4}$$

and their spectrum $\hat{S}_{HV}(f)$ is given by

$$\begin{aligned} \hat{S}_{HV}(f) &= \sum_n S_{HV}(f-2n/T) + \sum_n jS_{HH}(f-n/T) \\ &\quad - \sum_n jS_{HH}(f-n/T)\exp(-j\pi n) \\ &= \sum_n S_{HV}(f-2n/T) + \sum_n jS_{HH}(f-(2n+1)/T) \end{aligned} \tag{5}$$

and represented in Figure 4 under the assumption that the azimuth signals are bandlimited to half the PRF, in which case the HH channel signal (red components in Figure 4) can be filtered out. As the azimuth signal is not bandlimited, the high frequency components of the HH channel signal contaminate the HV channel signal. The resulting AASR of the synthesized HV channel is

$$\begin{aligned} AASR_{HV} \cong\ & \frac{\sum\limits_{\substack{m\,\text{even}\\ m\neq 0}} \int\limits_{f=-B_p/2}^{B_p/2} G^2\left(f+\frac{mPRF}{2}\right)H^2(f)df}{\int\limits_{f=-B_p/2}^{B_p/2} G^2(f)H^2(f)df} \\ & + \frac{\frac{\sigma^0_{HH}}{\sigma^0_{HV}} \sum\limits_{m\,\text{odd}} \int\limits_{f=-B_p/2}^{B_p/2} G^2\left(f+\frac{mPRF}{2}\right)H^2(f)df}{\int\limits_{f=-B_p/2}^{B_p/2} G^2(f)H^2(f)df} \end{aligned} \tag{6}$$

where $G^2(f)$ is the two-way power pattern in azimuth, $H(f)$ is the azimuth processing window, and B_p is the processed Doppler bandwidth. A similar formula can be derived for the synthesized VH data, where the high frequency components of the VV channel signal contaminates the VH channel signal. Cross-pol data are therefore contaminated by azimuth ambiguities from the co-pol data, which are characterized by a much stronger backscatter [8]. Figure 5 shows the AASR and the RASR for the aforementioned HRWS quad-pol SAR system, where L- and R-circular polarizations are interleaved on TX. Unlike in conventional quad-pol SAR, where, without merging, the AASR is the same for the co- and cross-pol channels and the RASR is much worse for the cross-pol channels (cf. Figure 1 (a) and (b)), in hybrid quad-pol SAR the RASR is approximately the same for the co- and cross-pol channels, while the AASR is much worse for the cross-pol channels. In the analysed system, the performance of the hybrid quad-pol SAR is slightly worse than that of conventional

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quad-pol SAR, mainly because hybrid quad-pol SAR cannot jointly exploit cross-pol data merging and azimuth phase coding.

Merging, in fact, results in a minor AASR improvement (the AASR expression is obtained by substituting the expression in (1) to σ^0_{HH} in (6)) and the cancellation of odd range ambiguities after merging mentioned in [6] only occurs, if the two co-pol channels have the same backscatter coefficients, are fully coherent, and in phase.

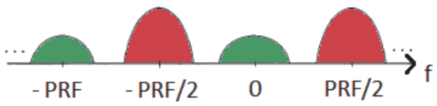
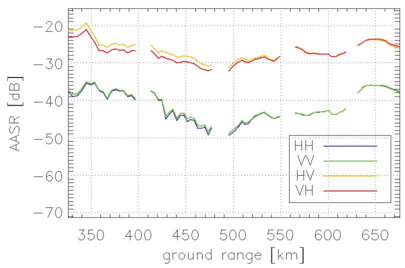
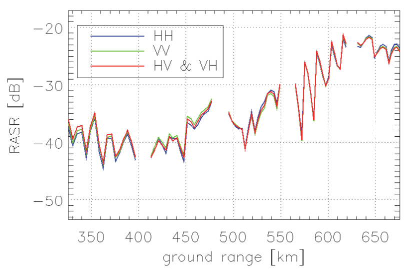


Figure 4: Spectrum of the synthesized HV data. The green components refer to the desired HV signal, while the red ones to the undesired HH signal.



(a)



(b)

Figure 5: Ambiguity performance for a hybrid HRWS quad-pol SAR with constant PRI and multiple elevation beams for PRF = 3320 Hz. (a) AASR. (b) RASR.

Azimuth phase coding in the context of hybrid quad-pol SAR can even be counterproductive, as shifting in frequency the range ambiguities of cross-pol data also shifts the contributions of the co-pol channel (red components in Figure 4) to baseband, while for conventional quad-pol SAR azimuth phase coding usually leads to a RASR improvement (cf. Figure 1 (b)).

Similar considerations regarding the contamination of the cross-pol channel signals by the co-pol channel signals are also valid for staggered SAR, where due to the non-stationarity of the azimuth impulse response, the effect is likely to be even worse.

4 Conclusions

Cross-pol data merging leads to significant range and azimuth ambiguity suppression in conventional quad-pol SAR, especially in combination with azimuth phase coding. The ambiguity performance of hybrid quad-pol SAR can be limited by the degraded AASR of the cross-pol channels and the ineffectiveness of azimuth phase coding. A more detailed and thorough analysis of the treated topics is provided in [9].

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