IMAGING A WIDE SWATH WITH FULL POLARIMETRY

Michelangelo Villano[(1)], Konstantinos P. Papathanassiou[(1)] , Gerhard Krieger[(1)] , Alberto Moreira[(1)]

*[(1)]German Aerospace Center (DLR), Microwaves and Radar Institute,
Oberpfaffenhofen, 82234 Wessling, Germany, Email: michelangelo.villano@dlr.de*

ABSTRACT

Several applications of synthetic aperture radar (SAR) require or at least benefit from full polarimetry. In the past, however, full polarimetry has been often discarded in the design of spaceborne SAR missions, as it implied a significant reduction of the swath width, already constrained by the requirement on azimuth resolution.

Innovative SAR techniques, based on digital beamforming on receive, allow nowadays high-resolution wide-swath (HRWS) imaging through multiple elevation beams, which simultaneously map multiple sub-swaths. Furthermore, a continuous variation of the pulse repetition interval, i.e., staggered SAR, can be introduced to get rid of the "blind ranges" between the multiple sub-swaths, due to the fact that the radar cannot receive, while it is transmitting.

This paper considers how the introduction of full polarimetry in HRWS imaging makes the design of the SAR system more challenging, but represents a viable solution for frequent and seamless high-resolution fully-polarimetric imaging of the Earth's surface.

1. INTRODUCTION

Synthetic Aperture Radar (SAR) is a well-established remote sensing technique, capable of acquiring high-resolution images of the Earth's surface independent of weather conditions and sunlight illumination [1], [2]. This makes SAR very attractive for the systematic observation of dynamic processes on the Earth's surface. However, conventional SAR systems are limited, in that a wide swath can only be achieved at the expense of a degraded azimuth resolution. In conventional stripmap SAR, in fact, the swath width constrains the pulse repetition interval (PRI): To control range ambiguities, the PRI must be larger than the time it takes to collect returns from the entire illuminated swath. On the other hand, to avoid significant azimuth ambiguity levels, a large PRI, or equivalently a low pulse repetition frequency (PRF), implies the adoption of a small Doppler bandwidth and limits the achievable azimuth resolution.

Several applications of SAR require or at least benefit from full polarimetry. The availability of a restricted subspace of polarizations (e.g. dual- and compact polarimetry), in fact, only allows the retrieval of some of the key parameters for most of the polarimetric models. In the past, however, full polarimetry has been often discarded in the design of spaceborne SAR missions. While dual-polarimetric SAR systems, in fact, are still able to keep the same swath width and azimuth resolution as single-polarimetric systems, provided that two separate antennas are employed on receive to record two distinct polarizations, fully-polarimetric SAR systems imply a further reduction of the swath width to keep the same azimuth resolution.

Fully-polarimetric SAR systems employ two orthogonal wave polarizations (e.g., horizontal and vertical) on both transmit and receive. On transmit the antenna alternately radiates pulses with horizontal and vertical polarizations, while on receive echoes are simultaneously recorded by two separate antennas with horizontal and vertical polarizations, respectively. In this case, in order to keep the same azimuth resolution of the single-polarimetric system, the same time span between two consecutive pulses transmitted in the same polarization has to be kept. This means that the effective PRF of the system becomes double, as the pulses from the other orthogonal polarization have to be transmitted as well, and the imaged swath is therefore halved. According to this limitation, a state-of-the-art SAR system such as ALOS-2 by JAXA can acquire fully-polarimetric data with an azimuth resolution of 6 m over a ground swath of 50 km [3].

2. HIGH-RESOLUTION WIDE-SWATH IMAGING

Future SAR missions may require a mapping capability much better than that of ALOS-2. A prominent example is DLR's-JAXA's Tandem-L/ALOS-Next, whose goal is the investigation of dynamic processes on the Earth's surface. For this, an extremely powerful SAR instrument is required, capable of mapping the whole Earth's surface twice per week, in full polarization and with a spatial resolution below 10 m. Other missions may require a higher spatial resolution, although without the need for such frequent coverage.

If a single satellite is available, frequent and seamless coverage can only be achieved if a wide swath is imaged. In particular, a 350 km swath width on ground has to be imaged to map the whole Earth's surface twice per week.

Such a wide swath can be mapped using ScanSAR or TOPS, but the azimuth resolution would still be impaired.

New radar techniques have been then developed, which allow for the acquisition of spaceborne high-resolution

SAR images without the classical swath limitation imposed by range and azimuth ambiguities. These techniques are mainly based on digital beamforming (DBF) and multiple aperture signal recording [4]. A prominent example is the high-resolution wide-swath (HRWS) SAR, currently under development at Airbus with support from DLR [5]. This system uses DBF on receive to steer in real-time a narrow beam towards the direction of arrival of the radar echo from the ground, exploiting the one-to-one relationship between the radar pulse travel time and its direction of arrival (this is also referred to as scan-on-receive or Sweep-SAR). A large receiving antenna can hence be used to improve the sensitivity without narrowing the swath width. As the unambiguous swath width is limited by the antenna length, a long antenna is deployed to map a wide swath. Moreover, to improve the azimuth resolution, the receive antenna is divided into multiple sub-apertures, mutually displaced in the along-track direction and connected to individual receive channels. By this, multiple samples can be acquired for each transmitted pulse. The coherent combination of all signals in a dedicated multichannel processor enables the generation of a high-resolution wide-swath SAR image [6]. The need for a very long antenna represents the main limitation of the mentioned system: A 40 m antenna is, in fact, required to map a 350 km swath width on ground in stripmap imaging mode.
In order to keep the antenna length down, several new instrument architectures and modes have been proposed [7]. One example is the combination of displaced phase centers in azimuth with ScanSAR or TOPS mode (see top left of Fig. 1). 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 collecting radar echoes with multiple displaced azimuth apertures. A possible drawback of multichannel ScanSAR or TOPS approaches is the rather high Doppler centroid for some of the imaged targets, in case high resolution is desired. Moreover, high squint angles may also challenge co-registration in interferometric applications.

2.1. Multi-Beam Stripmap SAR

A viable solution is related to concepts based on simultaneous recording of echoes of different pulses, transmitted by a wide beam illuminator and coming from different directions. This concept, from now on referred to as multi-beam stripmap SAR, 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. 1 provides an illustration, where three narrow receive beams follow the echoes from three simultaneously mapped image swaths that are illuminated by a broad transmit beam. A sufficiently high antenna is needed to separate the echoes from the different swaths by digital beamforming on receive, while a wide beam can either be accomplished by a separate small transmit antenna or a combined transmit-receive antenna together with tapering, spectral diversity on transmission or sequences of subpulses.
An interesting alternative to a planar antenna is a reflector, fed by a multichannel array, as illustrated on the lower left of Fig. 1. 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 hence to only read out one feed element after the other to steer a high gain beam in concert with the arriving echoes. A drawback of the multi-beam stripmap SAR mode is the presence of blind ranges across the swath, as the radar cannot receive while it is transmitting.

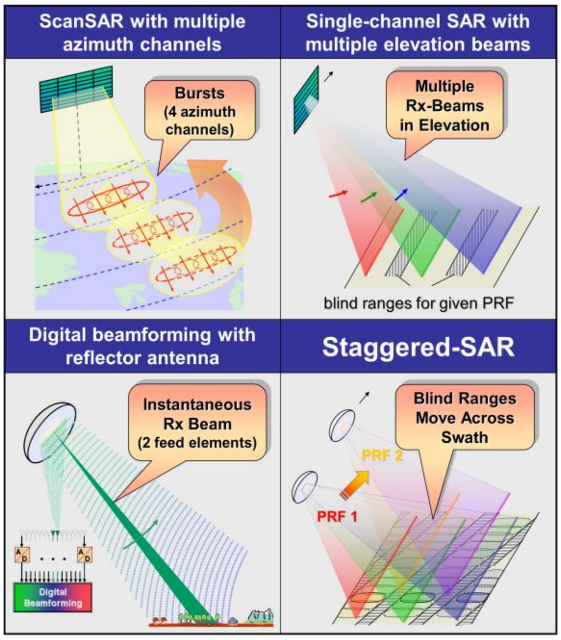


Figure 1. Advanced concepts for high-resolution wide-swath (HRWS) imaging.

2.2. Staggered SAR

The staggered SAR concept (Fig. 1 lower right) overcomes this drawback by continuously varying the PRI in a cyclic manner, so allowing the imaging of a wide continuous swath without the need for a long antenna with multiple apertures [8], [9].
In satellite SAR imaging, the antenna length and the required azimuth resolution impose an upper bound on the selected PRI. The PRI, in turn, limits the maximum continuous swath width in slant range, which is only slightly influenced by the uncompressed transmitted pulse length τ. The continuous time interval, where the radar echo can be received, in fact, is upper bounded by the time distance between the end of a transmitted pulse

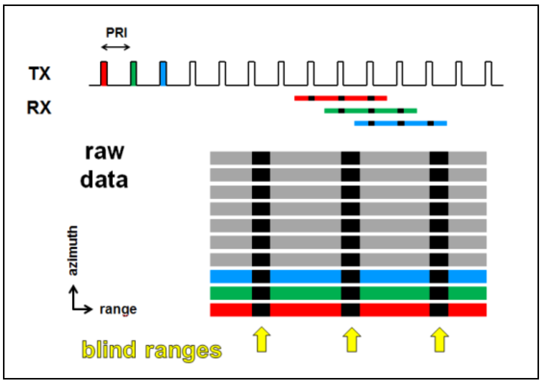
and the beginning of the next one, that is by $PRI - \tau$. Neglecting guard intervals, we have therefore intervals of duration $PRI - \tau$, where we receive the radar echo, separated by intervals of duration τ, where the radar echo cannot be received, because the radar is transmitting. In order to image a target with full range resolution, however, the echo of the full transmitted pulse of duration τ has to be received for that target and convolved with a conjugated replica of the transmitted signal. This means that only targets included within intervals of duration $PRI - 2\tau$, centered in the above mentioned intervals of duration $PRI - \tau$, can be imaged with full range resolution. After range compression, there will therefore be intervals of duration $PRI - 2\tau$, where targets can be imaged with full range resolution, separated by intervals of width 2τ, where targets can be only imaged with degraded range resolution, as only part of the echo of the transmitted pulse is received for those targets. The maximum value of the slant range swath width W_s is therefore obtained by multiplying the interval duration $PRI - 2\tau$ by $c_0/2$, where c_0 is speed of light in free space. If DBF on receive is used, multiple swaths, each of width W_s in slant range, can be simultaneously mapped using multiple elevation beams, but blind areas are present between adjacent swaths. The width in slant range $\Delta R_{0\ blind}$ of each blind range area is given by

$$\Delta R_{0blind} = c_0 \tau \qquad (1)$$

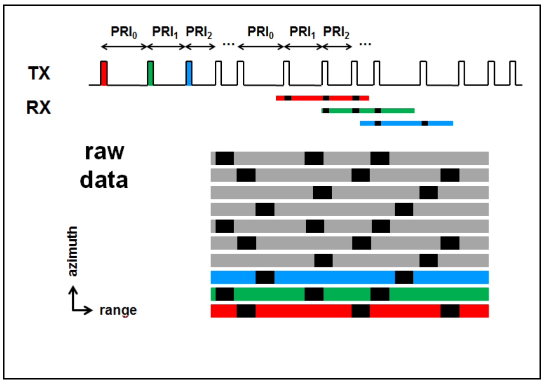
If the PRI is uniform, blind ranges remain unchanged along azimuth (Fig. 2 (a)). After compression in azimuth, the image will contain blind strips of width $\Delta R_{0\ blind}$.

If, in place of a constant PRI, a sequence of M distinct PRIs, which then repeat periodically, is employed, there will still be blind ranges. The width of the blind range areas will be still given by (1), but the locations of blind ranges will be different for each transmitted pulse, as they are related to the time distances to the preceding transmitted pulses (Fig. 2 (b)). If the overall synthetic aperture is considered, it turns out that at each slant range only some of the transmitted pulses are missing. In particular, if a sequence of PRIs is chosen so that the blind range areas are almost uniformly distributed across the swath, it can be shown that the percentage of missing samples in the raw data is approximately equal to the mean duty cycle, i.e., the ratio of the uncompressed pulse length to the mean PRI.

If a relatively small percentage of pulses is missing, it is still possible to focus the data and obtain a SAR image over a wide continuous swath: The presence of large gaps in the raw azimuth signal, however, will determine the presence of rather high sidelobes in the azimuth impulse response. Another possibility is to design the sequence of PRIs such that in the raw azimuth signal two consecutive samples are never missed. In this case, if the mean pulse repetition interval is decreased, i.e., if the signal is averagely oversampled, it is possible to recover the missing samples by means of interpolation, so avoiding the high sidelobes in the azimuth impulse response. As a higher mean PRF is used, it will be necessary to increase the antenna height in order to keep the same range ambiguity-to-signal ratio (RASR).



(a)



(b)

Figure 2. Location of blind ranges. (a) Multi-beam stripmap SAR with constant PRI. (b) Staggered SAR.

3. DESIGN EXAMPLES FROM THE TANDEM-L/ALOS-NEXT STUDY

In the following some system design examples from the Tandem-L/ALOS-Next study are considered, concerning both the multi-beam stripmap SAR and the staggered SAR concepts. In particular, a reflector antenna, fed by a multi-channel array with forty-six feeds in elevation and six feeds in azimuth is considered, where the six feeds in azimuth are pairwise combined to form three azimuth channels. On transmit, all elevation feeds of the central pair of azimuth feeds are activated to illuminate the full swath. A set of phase-only weights is applied to the forty-six pairs of azimuth feeds on transmit to optimize the shape of the elevation pattern on transmit. On receive, different groups of four adjacent elevation feeds and all three azimuth channels are activated on receive to steer a high-gain beam in concert with the arriving echoes, as already described. It has to be stressed that this is not a system with multiple azimuth sub-apertures, as the twelve signals received by the three azimuth channels and four elevation feeds are combined on-board and only a linear combination of the received signals is digitized and stored for future processing. In particular, the twelve received signals are combined according to the minimum variance distortionless response (MVDR) or Capon beamformer weights, assuming an additive white Gaussian noise (AWGN) disturbance. Fig. 3 shows the normalized elevation patterns on transmit and on receive. The system and processing parameters are instead summarized in Tab. 1.

Table 1. System and processing parameters.

Parameter	**Value**
Radar wavelength	0.2384 m (L-band)
Orbit height	745 km
Minimum incidence angle	26.3°
Maximum incidence angle	46.9°
Tilt angle	32.7°
Antenna type	Reflector
Antenna size	15 m (diameter)
Feed elements in azimuth	6
Feed elements in elevation	46
Mean duty cycle	4%
Chirp bandwidth	80 MHz
Range sampling frequency	88 MHz
Processed Doppler bandwidth	780 Hz
Azimuth processing window	Hamming with α = 0.6
Compensation of the azimuth pattern	Yes
Range processing window	Hamming with α = 0.6
Backscatter model	D'Aria

3.1. Single and Dual-Polarimetric Modes

Fig. 4 shows the azimuth ambiguity-to-signal ratio (AASR) and the RASR for the multi-beam stripmap SAR system, for the single and dual-polarimetric modes, using a PRF of 1661 Hz. As is apparent, the AASR is better than -30 dB and the RASR is better than -32 dB.

Fig. 5 shows the AASR and the RASR for the staggered SAR system, always for the single and dual-polarimetric modes, using a mean PRF on transmit of 2700 Hz. As is apparent, the AASR is better than -27 dB and the RASR is better than -28 dB. The performance in terms of range and ambiguities is therefore satisfactory, provided that the signal is averagely oversampled in the azimuth direction.

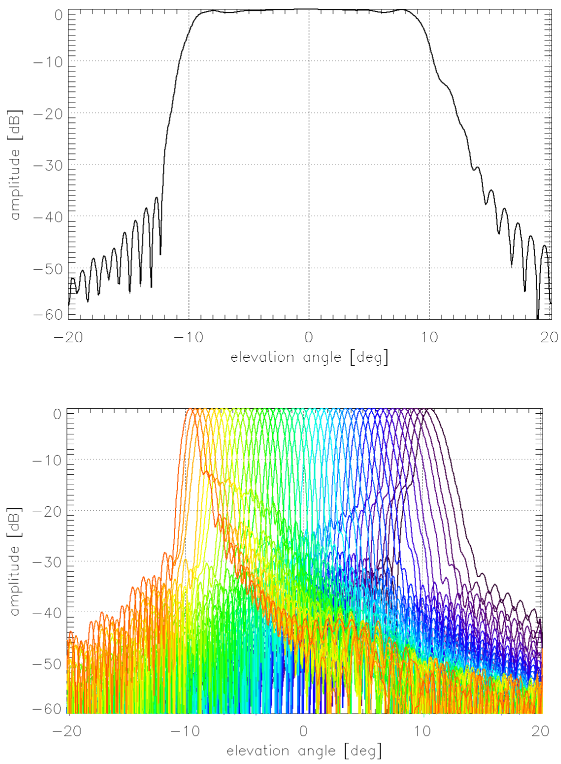


Figure 3. Normalized elevation patterns on transmit (top) and on receive (bottom).

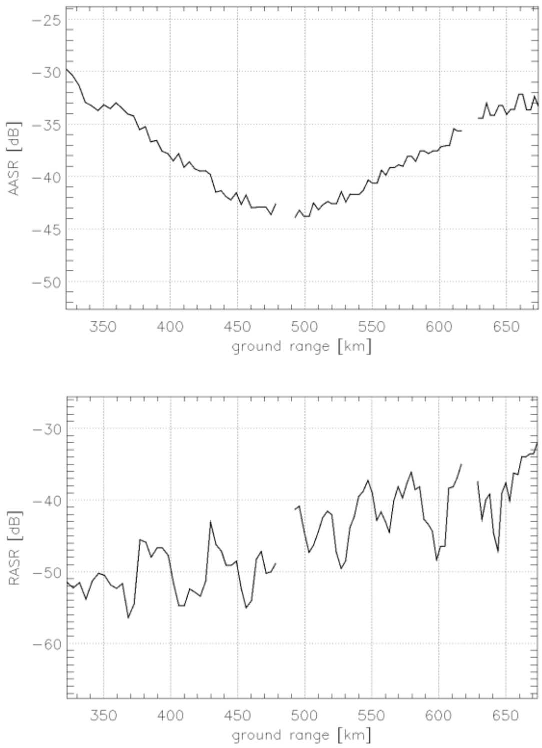


Figure 4. AASR (top) and RASR (bottom) for multi-beam stripmap SAR in single-pol and dual-pol mode.

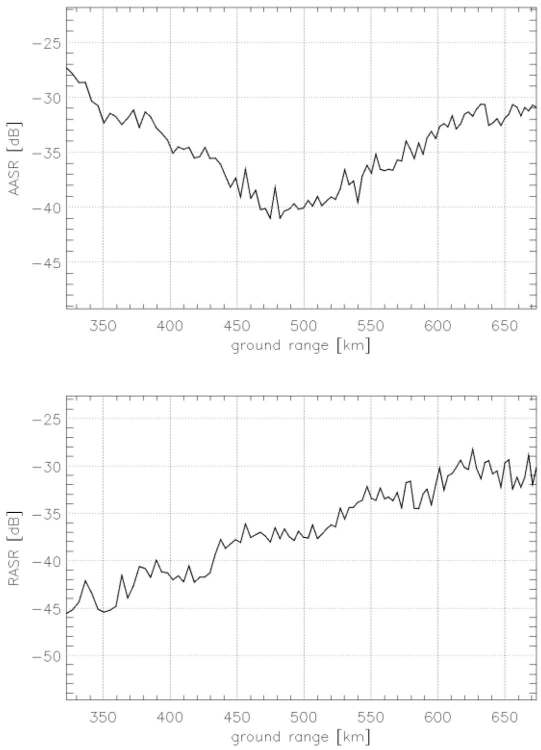


Figure 5. AASR (top) and RASR (bottom) for staggered SAR in single-pol and dual-pol mode.

3.2. Fully-Polarimetric Mode

If the PRF of the multi-beam stripmap SAR system is doubled to achieve full polarimetry, the AASR remains the same as for the single and dual-polarimetric modes (but for the additional blind ranges, see upper plot of Fig. 6), while the RASR significantly degrades, in particularly for the cross-polarized channels, as the some of the range ambiguous echoes are characterized by the same polarization on transmit and receive and therefore by higher backscatters. The lower plot of Fig. 6 shows the RASR for the multibeam stripmap SAR system in fully-polarimetric mode, using a PRF of 3322 Hz. As is apparent, the RASR of the cross-polarized channels reaches -13 dB at far range. A similar and even worse situation occurs if the mean PRF on transmit of the staggered SAR system is doubled. In the latter case, in fact, the RASR for the cross-polarized channel reaches 0 dB at far range (Fig. 7). Better performance in terms of RASR is obtained, if a continuous swath of about 180 km (ground range ranging from 350 km to 550 km) is imaged. In that case, a RASR better than -20 dB, i.e., slightly better than the one displayed in Fig. 7, can be obtained, as a smaller swath has to be illuminated and range ambiguities from far range are characterized by a smaller power. Moreover, as the AASR is very low within this restricted range (better than -32 dB according to the upper plot of Fig. 5), the mean PRF on transmit could be decreased to further improve the RASR.

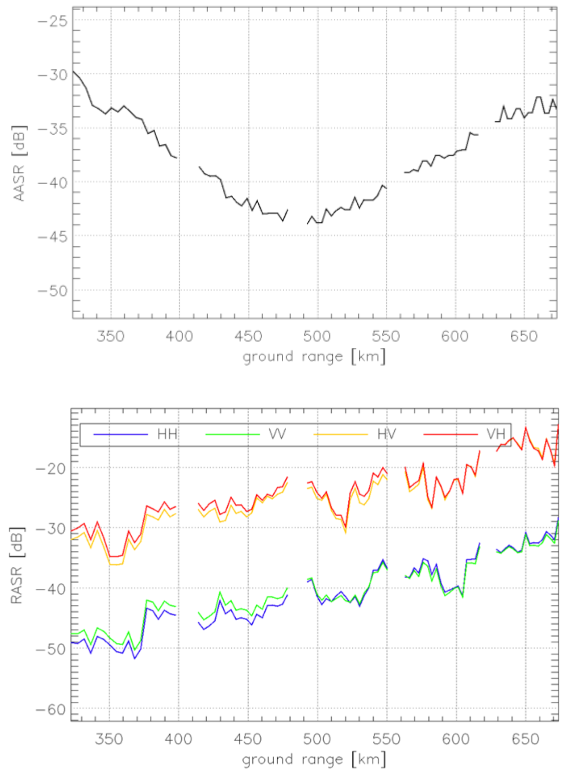


Figure 6. RASR for multibeam stripmap SAR in fully-pol mode

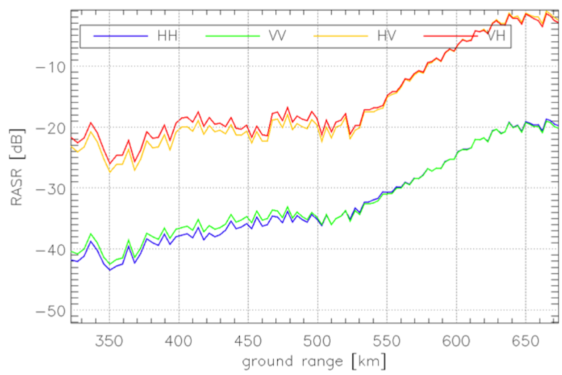


Figure 7. RASR for staggered SAR in fully-pol mode

4. INNOVATIVE METHODS FOR RANGE AMBIGUITY SUPPRESSION

One possibility to achieve a better RASR in fully-polarimetric system is to employ a hybrid-polarity SAR architecture, with left- and right-circular transmit pulses interleaved and orthogonal linearly polarized reception (e.g., H and V), but this makes the design of the SAR antenna challenging [10], [11].

Other alternatives for range ambiguities suppression under investigations within the Tandem-L/ALOS-Next study are the use of azimuth phase coding and cross elevation beam range ambiguity suppression (CEBRAS).

4.1. Azimuth Phase Coding

Azimuth phase coding consists of applying an azimuth phase modulation to the transmitted pulses and a corresponding demodulation to the received pulses [12]. By this, some of the ambiguous returns can be significantly suppressed. In [13] an interpulse signal coding is suggested for the suppression of some of the ambiguous returns in a fully-polarimetric system. Rather than using the sequence of phases on transmission proposed in [13], we use the following sequences of phases:

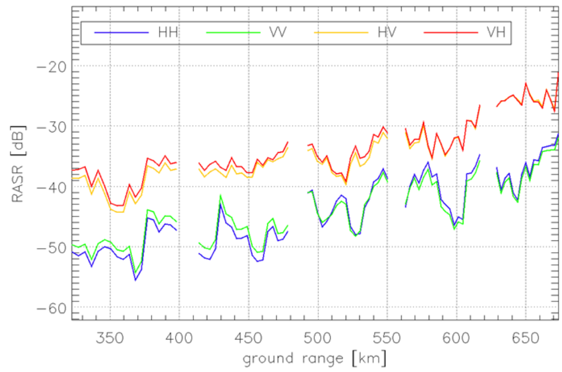
Transmitted Polarization	H V H V H V H V H V H V…
Phase	0 0 π 0 0 0 π 0 0 0 π 0…

The latter sequence of phases, in fact, is particularly effective for a HRWS fully-polarimetric system, because it allows the suppression of all odd range ambiguities, leading to a significant improvement of the RASR of the cross-polarized channels. The RASR of the co-polarized channels improved only slightly, but this is not a problem, as the RASR of the co-polarized channels already fulfils the typical requirements for a spaceborne system.

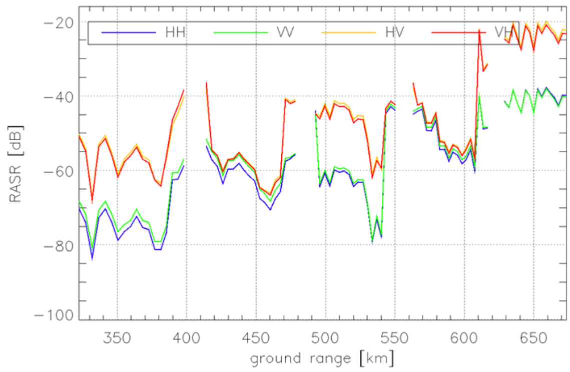
Azimuth phase coding unfortunately cannot be straightforwardly applied to staggered SAR system, as the range ambiguous echoes are located at different ranges for different range lines, as the time distance to the preceding and succeeding pulses continuously varies. A proper selection of the transmitted sequence of PRIs can suppress only the first near or far range ambiguity in the cross-polarized channels. Fig. 8 (a) shows the RASR achieved in the fully-polarimetric design example by employing azimuth phase coding in multi-beam stripmap SAR. The comparison with Fig. 6 (b) shows that the worst RASR across the swath improves from -13 dB to -23 dB.

4.2. Cross Elevation Beam Range Ambiguity Suppression (CEBRAS)

A significant improvement of the range ambiguity suppression can be obtained by noting that the most annoying range ambiguities for one imaging beam/swath are indeed the desired signals for the other imaging beams/swaths [14]. Since the signals from all imaging beams are anyway downloaded to the ground to map multiple swaths, it is possible to use this additional information *a posteriori* to mutually suppress range ambiguities. In its most simple form, one may mitigate the range ambiguities for one swath/beam by appropriately weighting and subtracting the signals from the other beams. This innovative concept for range ambiguity suppression, applicable to staggered SAR as well, is from now on referred to as CEBRAS.



(a)



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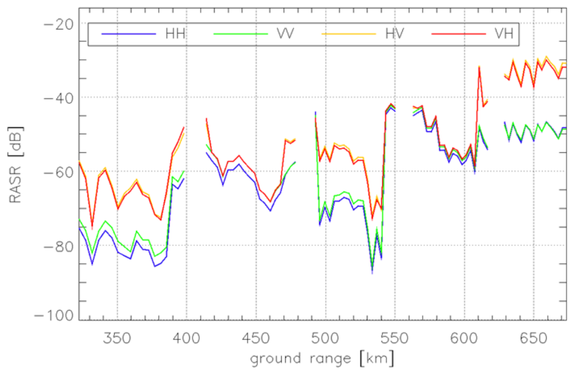

(c)

Figure 8. RASR for multibeam stripmap SAR in fully-polarimetric mode using advanced techniques for range ambiguity suppression. (a) Using azimuth phase coding. (b) Using CEBRAS. (c) Using azimuth phase coding and CEBRAS.

The accurate subtraction requires, however, a precise knowledge of the ambiguities for each beam. Since the strength of these ambiguities depends mainly on the sidelobes of the imaging beam under consideration, it may be difficult to know the (potentially complex) weighting factors *a priori* with sufficient accuracy. As an alternative, one may estimate the weighting factors and unambiguous signals directly from the recorded signals.

Fig. 8 (b) shows the RASR achieved in the multi-beam stripmap fully-polarimetric SAR design example by employing CEBRAS and assuming that all range ambiguities within the transmit beam are perfectly suppressed. The comparison with Fig. 6 (b) shows that the worst RASR across the swath improves from -13 dB to -20 dB. The performance is across the swath much better than the worst RASR, but degrades at far range (ground range comprised between 610 km and 670 km). The acquisition of a further elevation beam, to be used uniquely for range ambiguity suppression, could therefore further improve the RASR performance.

Moreover, for a multi-beam stripmap SAR, CEBRAS can be also combined with azimuth phase coding. Fig. 8 (c) shows the RASR achieved. It can be noticed that the worst RASR is now even better than 30 dB.

Finally, Fig. 9 shows the RASR for the staggered SAR fully-polarimetric design examples, which is better than 30 dB for a 300 km swath width. Even in this case, the acquisition of a further elevation beam, to be used uniquely for range ambiguity suppression, could therefore further improve the RASR performance at far range, if a swath width larger than 300 km is required.

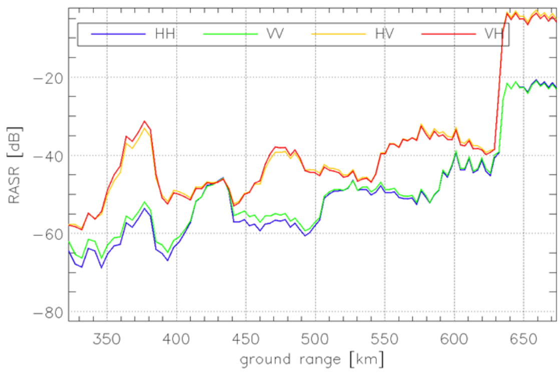

Figure 9. RASR for staggered SAR in fully-pol mode using CEBRAS.

5. CONCLUSION

Some SAR architectures have been considered, namely multi-beam stripmap SAR and staggered SAR, which together with innovative methods for range ambiguity suppression, such as azimuth phase coding and CEBRAS, are very promising to achieve fully-polarimetric high-resolution imaging over a wide swath.

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