ERROR ANALYSIS AND CALIBRATION TECHNIQUES FOR MULTI-CHANNEL SAR INSTRUMENTS

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ABSTRACT

Future spaceborne Synthetic Aperture Radar (SAR) systems will be based on multiple transmit/receive channels and use Digital Beam Forming (DBF) technique and on board processing to provide high coverage and high resolution simultaneously. Due to the necessary on board processing and required alignment between the signals from different channels by the multi-channel operation, a big challenge in the system calibration arises. To manage that issue, new techniques have to be identified and verified. This paper presents the analysis of the effect of system and calibration errors on the SAR image quality for an example multi-channel spaceborne SAR system, which should give a starting point in the calibration accuracy considerations. Further, some ideas for the error correction in the data processing are given and computation results shown.

Index Terms— Multichannel Synthetic Aperture Radar, SAR, Error Analysis, Calibration

1. INTRODUCTION

Future spaceborne Synthetic Aperture Radar (SAR) systems should be able to provide high azimuth resolution and wide swath coverage simultaneously, which are, however, opponent requirements in conventional one channel SAR systems. This problem can be avoided by using High Resolution Wide Swath technique as presented in [1]. The basic idea is to use multiple receivers aligned in along track and combine their signals in a single channel signal with higher PRF. The processing is called reconstruction and is based on the theory of combining N independent representations of a signal, each sub-sampled with 1/N the Nyquist frequency that allow for the unambiguous reconstruction of the original signal from the aliased spectra of the N representations, see [2] and [3]. Moreover, to provide high receive (Rx) gain in the elevation, improve the range ambiguity suppression and minimize the losses at the swath border, the Scan on Receive (SCORE) technique should be used, which steers a narrow high gain receive beam in the elevation so that it follows the transmitted pulse on ground. This operation requires very fast and reliable on-board digital signal processing.

These characteristics pose new challenges to spaceborne SAR calibration. In fact, the correction of the errors at individual single channel level is not sufficient, it is also necessary to guarantee the alignment between the signals by the multi-channel operation. Moreover, the on-board calibration could be required, in order to ensure the negligibility of possible errors on SCORE, which will have a significant impact on the implementation complexity of the calibration. In order to minimize the calibration complexity, it is important to evaluate the impact of possible errors or residual calibration errors on the tasks done on board.

This paper provides an analysis of the effect of system and calibration errors in the SAR image quality performance for an example multi-channel satellite SAR system, which should give a starting point in the required calibration accuracy considerations. The analysis is focused on the range and azimuth performance in terms of ambiguities. The errors in the system and in the calibration are simulated by setting a phase and amplitude noise on the complex excitation coefficients of the Transmit/Receive Modules (TRMs) of the planar antenna used by the system. This can be seen as an error in the reference pattern and simulates all random types of errors that appear in the whole signal chain, like the errors in the distribution network to each single TRM, gain and phase error of the radiators or Rx signal distribution. Moreover some ideas of the correction of the errors in the on ground azimuth processing are given.

2. REFERENCE SAR SYSTEM

As a reference system a potential Sentinel 1 follower is taken, for which some ongoing studies are being carried. It is a C-Band ($f_{carrier}$ = 5.405 GHz) multichannel SAR system with eight channels in azimuth, which are required to provide high azimuth resolution (5 m) and wide coverage (400 km) simultaneously. The antenna is 12.8 m in azimuth, 1.18 m in the elevation and consists of 448 TRMs (16 in the azimuth, 28 in the elevation). To get 5 m resolution in azimuth, the transmit (Tx) pattern has to be wide, which cannot be normally achieved with that long antenna. To manage that issue, Phase Spoiling technique is used [4]. This technique applies a phase shift to each antenna element, so that the pattern is widened in comparison to the uniform excitation. All simulations were performed for the single polarization mode VV.

Fig. 1 presents the timing diagram for the simulations performed in this paper. The blue lines represent the transmit-events, green lines the nadir echo and the orange areas the sub-swathes. The system is driven in the ScanSAR mode with the swath width of 404 km and four sub-swathes (ssw1 to ssw4). To provide this wide coverage with high sensitivity, improve the range ambiguity suppression and minimize the losses at the swath border, the Scan-on-Receive (SCORE) technique in the elevation is used. The transmit elevation beam is also widened by Phase Spoiling for each sub-swath to provide this wide coverage.

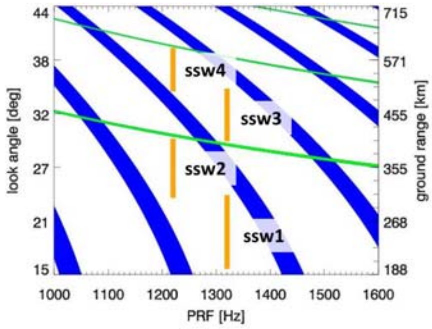

Fig.1: Timing diagram used for simulations.

Fig. 2 shows the reference azimuth and range performance in terms of azimuth and range ambiguities (Azimuth Ambiguity to Signal Ratio - AASR and Range Ambiguity to Signal Ratio - RASR) for the case of desired (noise free) adjustment of all TRMs. Due to ScanSAR processing the azimuth performance varies depending on the target position relative to the maximum of the azimuth beam. This dependency is taken into account through variation over center Doppler frequency.

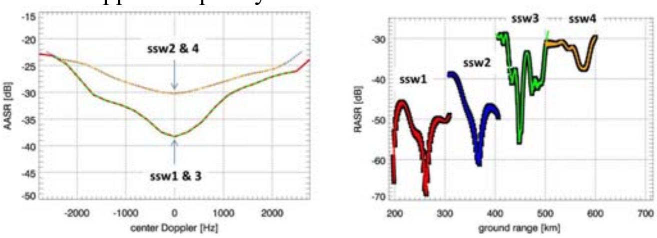

Fig. 2: Reference azimuth (on the left) and range performance (on the right) in terms of ambiguities.

3. ERROR ANALYSIS

3.1. Idea of the computations

As already mentioned, the errors in the system and in the calibration are simulated by adding a noise to the desired excitation coefficients of the TRMs and thereby changing the desired phase spoiled Tx or ideal uniform Rx patterns

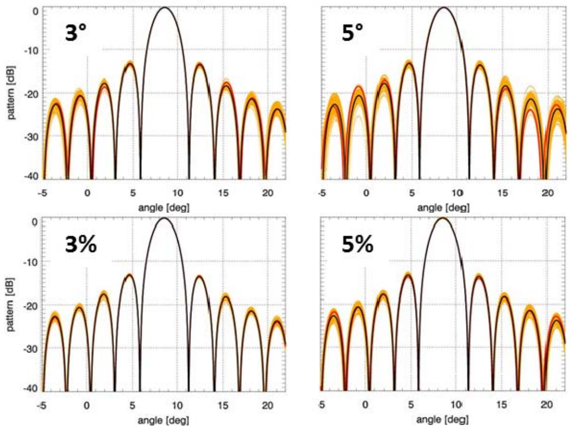

Fig. 3: Reference pattern (back), 100 noisy realizations (orange) and one chosen noisy realization (red) of the Rx elevation pattern of ssw4 with different standard deviations of the amplitude and phase of the excitation coefficients (patterns are normalized).

The antenna patterns with the noisy coefficients will be further called noisy patterns. This kind of the error analysis should simulate all possible random (since the noise at each single TRM is zero mean) errors in the system (like the errors in the distribution network to each single TRM on Tx, gain and phase error of the radiators or Rx signal distribution). With the comparison of the SAR imaging performance of the system with the noisy patterns with the performance of the noise free reference system, an analysis of the maximal level of allowable error (i.e. the calibration accuracy), for which the performance is still acceptable, can be performed.

The noise in the excitation coefficients was calculated as a zero-mean noise with an adjustable standard deviation (3σ) with Monte Carlo simulations. After calculating of the SAR imaging performance for each noisy pattern, the results were compared with the reference performance. Fig. 3 shows the reference Rx pattern for the ssw4 (black) and its 100 noisy realizations (orange) with different standard deviations of the amplitude (3% and 5%) and phase (3° and 5°) of the antenna excitation coefficients. The red line denotes one noisy realization. The values of 5% and 5° were chosen as realistic values of the achievable accuracy of modern hardware, 3% and 3° serve as a comparison. As can be seen, the main beam remains stable and is not shifted. The reason is a high number of the TRMs in the elevation (28) and no systematic error between them. Without a systematic error the difference between the TRMs is in average too small to introduce a strong distortion in the main beam, which is good news for the SCORE. In the side lobes the difference between the patterns is higher. Both the levels and positions of the side lobes differ between the separate noisy patterns. This will cause different range ambiguity levels which will be seen in the next section. The pattern seems to be more stable against the errors in the amplitude than in the phase. The phase spoiled patterns on the Tx (elevation and azimuth), which are not shown in this paper, also show more stability against the amplitude than the phase errors of the excitation coefficients. In the comparison to the uniform Rx patterns, they show less stability in the main beam against noise in the excitation coefficients. The gain level and shape of the main beam is more affected, especially for the case of noise in the phase of the excitation coefficients. The reason is the creation of the phase spoiled beam through the phase tapering of each single TRM. With an extra added phase noise, the pattern changes more than in the uniform case. As in the uniform excitation case the Half Power Beam Width of the phase spoiled patterns remains stable.

3.2. Range performance

Fig. 4 shows the RASR for the reference Rx noisy free pattern in the elevation (in black) and RASR of its 100 noisy realizations for different standard deviations of the pattern excitation coefficients in the amplitude and phase (in different colors) for ssw4. The sub-swath in far range was chosen as a worst case in the elevation.

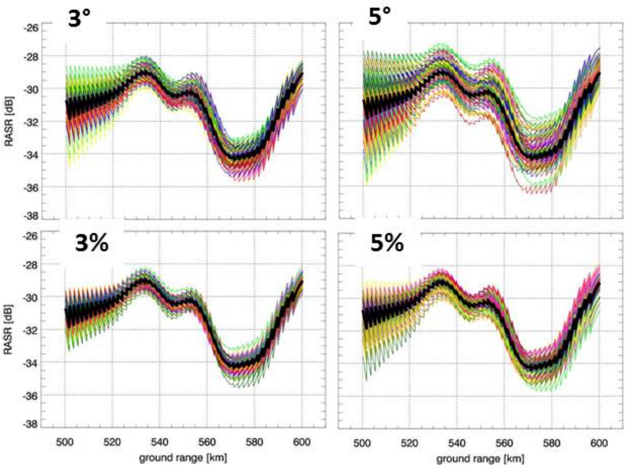

Fig. 4: RASR for ideal Rx-elevation pattern (in black) and 100 of its noisy realizations for different standard deviations in the amplitude and phase of its excitation coefficients (different colors) for ssw4.

As expected from the patterns in Fig. 3, the error in the phase causes more distortion in the performance as the error in the magnitude. The RASR performance can be, however, also improved – the degradation is not always the case. Tab. 1 presents the statistics of these 100 noisy pattern calculations. The mean degradation of the RASR performance stays under 0.4 dB, which is acceptable, since the reference value of the range ambiguities is sufficiently low. Also the standard deviation under 1 dB is acceptable. However, in the worst simulated case, the performance differs about 3 dB, which means 50 % (near range, 5° phase error) from the reference. This is not critical in the example system, but can be critical in another one, where the reference RASR performance does not leave much margin for further errors and losses.

Error	3°	5°	3%	5%
μ [dB]	0.015	0.216	-0.010	0.352
σ [dB]	0.548	0.860	0.013	0.523

Tab. 1: Mean value (μ) and standard deviation (σ) of the difference in the RASR performance for different levels of amplitude and phase noise in the pattern excitation coefficients for 100 noisy realizations for ssw4 and Rx pattern.

Another aspect is, that the errors in the phase and amplitude occur simultaneously, which means the distortion and/or improvement of the performance form phase and amplitude errors add together. That means in the worst simulated case, a degradation of about 4 dB (near range, 5° phase and 5 % amplitude error), which is sufficient. On the other hand, it is also possible, that the errors slightly or highly compensate the influence on the performance of each other. To avoid the worst case, the reference performance should provide some margin for further losses. In the average the RASR performance seems to be, however, stable.

3.3. Azimuth performance

The errors in the system and its calibration are expected to cause more problems in case of the azimuth performance. The reason is the combination/interleaving of the samples from different channels in the reconstruction algorithm to the signal with higher equivalent PRF. With the different phase and amplitude distortion of the adjacent samples (after the reconstruction) from different channels, a strong degradation in the performance is expected. Fig. 5 on the left shows the AASR for different phase and amplitude errors of the Rx-pattern excitation coefficients (for reference see Fig. 2 on the left). The performance for the targets with low center Doppler frequencies is more affected than the performance of the targets with higher center Doppler frequencies. This is feasible, since the differences in the affected patterns are higher at the centers of the main beam and side-lobes of the antenna pattern than “at the edges” (as in the Fig. 3 for the elevation pattern case – the azimuth case is similar). The AASR characteristic becomes flat and no strong dependency on the target center Doppler position is given.

If the errors between the channels are known, they can be compensated in the reconstruction algorithm. This compensation can be provided as a multiplication of the system channel function of each channel in frequency domain with the difference between its pattern and the pattern of one channel taken as a reference. If this operation is taken, the AASR performance will be close to the reference performance, which is shown in Fig. 5 on the right. The biggest difference to the reference performance is

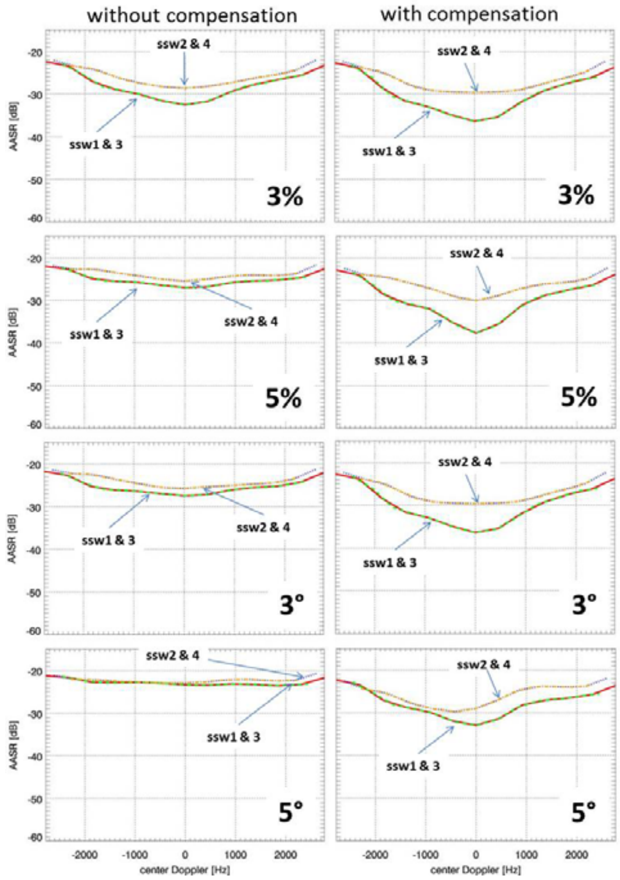

Fig. 5: AASR performance for different phase and amplitude errors of the excitation coefficients of the Rx azimuth pattern without (on the left) and with compensation (on the right) in the reconstruction algorithm.

about 0.5 dB (for 5° phase error) for the targets with the maximum center Doppler frequency, which is acceptable. For all other simulated cases for the maximum center Doppler frequency there is no degradation at all. As in the case of no consideration of antenna patterns in the reconstruction, the highest degradation affects the targets with the zero Doppler center frequency. This degradation reaches from prox. 2 dB for 5% amplitude and 5 dB for the 5° phase error, which is not critical for the overall performance, as the reference AASR for targets at zero Doppler is much smaller than at the edges. As in the RASR case, this applies only to systems, where a margin in the AASR performance exists.

This yields to a more practical question how to measure the differences between the receive patterns in azimuth. The first idea would be to compare the echoes form the azimuth channels in frequency domain and balance them before the reconstruction. Unfortunately, the spectra will be aliased, which makes this approach hardly possible. The solution could be to measure the differences in real-time on board of the satellite with special calibration pulses, but this is also not trivial. A solution to that issue has to be still investigated.

4. CONCLUSION

This paper presented the influence of the random system and calibration errors on the SAR imaging performance in terms of range and azimuth ambiguities for an example multichannel SAR system. The random errors were modeled by setting a noise to the complex antenna excitation coefficients of the TRMs of the planar antenna. As the error values 3°/3% and 5°/5% were taken. The accuracy of 5°-6° in the phase and 5%-6% in the amplitude seems to be achievable with the modern hardware. The range performance seems to be stable for the simulated cases – the mean value and standard deviation of the performance degradation do not affect the reference performance in a significant way. However, in the worst simulated case the degradation reaches 4 dB (worst case in the amplitude and phase error at the same time). This is not critical in the example system in the paper, but it can be critical for other systems, dependent of how much margin in the reference performance is left for the errors and losses.

The azimuth performance can be strongly affected by even small errors, especially for the targets with small center Doppler frequencies. This degradation can be, however, almost fully compensated in the reconstruction algorithm, if the errors are known. However, the practical measurement of the small discrepancies between the channels seems to be complicated and the final solution still has to be found.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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