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Ph.D.
THESIS Summary

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A STUDY ON MULTISTATIC SAR CONFIGURATIONS

THESIS COMMITTEE

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Contents

1. Introduction

1.1 The field of the doctoral thesis

Multistatic SAR is an emerging technology with benefits hitherto unmatched by other remote sensing methods, providing “best-in-stock” sensing solutions that are weather and day-time independent such as real-time along and cross track interferometry for Digital Elevation Modeling, enhanced ocean analysis, enhanced resolution imaging, to name a few. Existing missions such as TanDem-X have already provided a glimpse into the possibilities provided by multistatic SAR, however, the small baseline of just a few km limits overall performance and multistatic capabiliteis. A future mission with larger baselines (>200km), called Harmony, is intended to premiere as the first spaceborne “true” multistatic Earth Observation SAR, to complement current remote sensing methods, and enable never before achieved real-time interferometric sensing capabilities. Harmony satellites will be equipped with passive SAR receivers and use the existing Sentinel satellites as an opportunistic transmitter.

1.2 The objectives of the doctoral thesis

This thesis is focused on bistatic SAR imaging using Sentinel 1 as an opportunistic transmitter and the COBIS [1] as a ground-based receiver. Multiple aspects are addressed, such as multiaperture stitching and gap extrapolation for improved cross-range resolution, permanent scatterer detection among sub-apertures, near-range multipath mitigation techniques to resolve undesired sync-to-imaging channel coupling, a UWB Voltage Controlled Oscillator (VCO) architecture for low-power and reduced size FMCW multistatic SAR systems with high range resolution, and various calibration techniques for phased arrays and transponders. Future work is to adapt the newly developed methods and techniques to fully spaceborne and airborne multistatic SAR systems, such as Harmony, or similar missions that may exist in the future.

The motivation behind choosing multistatic SAR as the main topic of my thesis was the significance of the topic. Multistatic SAR is an emergent technology which has been studied in depth at a concept level for the last two decades, but only recently introduced in practice/industry. Companion configurations that use a single high performant transmitter and multiple receive only companions are of special interest as they present an elegant and cost-effective solution of implementing a multistatic SAR system.

1.3 The original content of the doctoral thesis

The original work presented in this thesis can be classified into three parts.

The first part is a study on the possibilities of improving the cross-range resolution in a multistatic SAR system by capturing the signal leaked by the TX from antenna side-lobes and adjacent sub swaths. Experimental and analytical results prove the practicality of the proposed methodology. A novel CFAR detection algorithm is presented and applied as a permanent scatterer detection scheme for improving multi-aperture analysis.

The second part is a study on the effect of coupling found between the synchronization channel and the imaging channel of passive multistatic SAR receivers. A novel methodology is proposed using matched-adaptive filters as a means of time-domain deconvolution capable of cleaning the signal of such multipath. SAR systems generally use active targets for calibration, such as transponders, which are also susceptible to the same errors. The method is experimentally and analytically evaluated for both applications.

The third part is a study on the merger of multistatic SAR and the FMCW radar. A novel VCO architectures is presented designed to enhance multistatic FMCW SAR systems placed on UAV for high-resolution, close-range sensing. Next, an efficient radar-tailored Kalman filter is presented that may be used to enhance TX-RX synchronization, required for multistatic SAR. Finally, a near-field phased array calibration technique is presented that may be used to calibrate MIMO-SAR system on the field, without dismounting the radar sensor or any of the antennas.

2. Multi-Aperture Focusing in Bistatic SAR

In this chapter a methodology **[2]** is proposed for multistatic SAR systems, that performs azimuth focusing of spaceborne transmitter-stationary receiver bistatic synthetic aperture radar (SAR) data across multiple along-track apertures in order to increase azimuth resolution. The procedure uses as input several azimuth apertures (continuous groups of range compressed pulses) from one or more satellite bursts and comprises the following stages: antenna pattern compensation, slow time resampling, reconstruction of missing azimuth samples between neighboring sets of pulses using an auto-regressive (AR) model and back-projection focusing of the resulting multi-aperture range image. A novel, highly efficient method is proposed to estimate the optimal order for the AR model. It differs from the traditional approach that uses the Akaike Information Criterion to directly estimate the order, because the proposed method estimates the order indirectly by detecting the number of targets using principal component analysis. Spatial Smoothing is used to obtain a full rank Covariance matrix, whose eigen values are then analyzed using Minimum Description Length. The optimal order is an integer multiple of the number of targets, which depends on SNR. The approach is evaluated with real bistatic data acquired over an area of Bucharest city, Romania. An additional stable scatter detection **[3]** and novel CFAR detection scheme **[4]** are presented as a multi-aperture pre-processing method.

2.1 Multiaperture focusing

When Sentinel-1A/B operating in the terrain observation through progressive scans (TOPSAR) imaging mode is used as transmitter of opportunity, a stationary receiver captures pulses from the burst corresponding to the sub-swath in which the receiver is placed, and from bursts belonging to the other sub-swaths. In both cases, the received pulses can be pulses that were transmitted through the main beam or through the side lobes of the satellite's antenna. The available multi-burst data can be used in various ways for target characterization by exploiting the enhanced azimuth diversity. The envisaged geometry is presented in Fig. 2.1.

In the proposed bistatic SAR geometry the Azimuth Frequency evolution is almost linear, as shown in Fig. 2.2. The reason is that the range between the scene and the receiver is constant, and the rate of change in range between the receiver and the transmitter is very close to the rate of change between the transmitter and the scene. This allows us to approximate the signal as a sine-wave, which is a key assumption for our proposed signal reconstruction technique. The proposed methodology is presented in Fig. 2.3

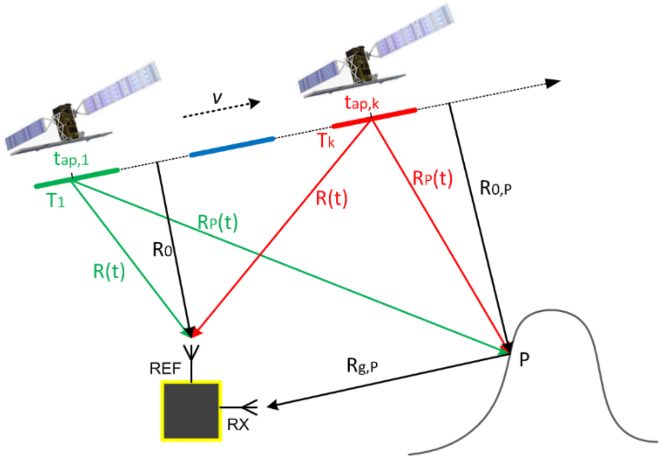
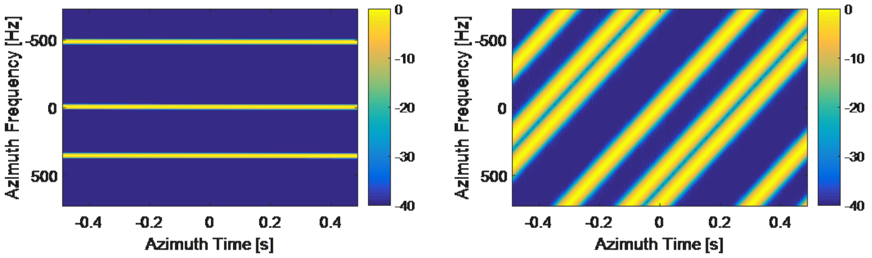


Figure 2.1 *Spaceborne transmitter-stationary receiver bistatic geometry.*



a). b).

Figure 2.2 *Spectrogram of the azimuth chirps, a) 3 Hz/s for the present bi-static geometry, and b) 2400 Hz/s for mono-static.*

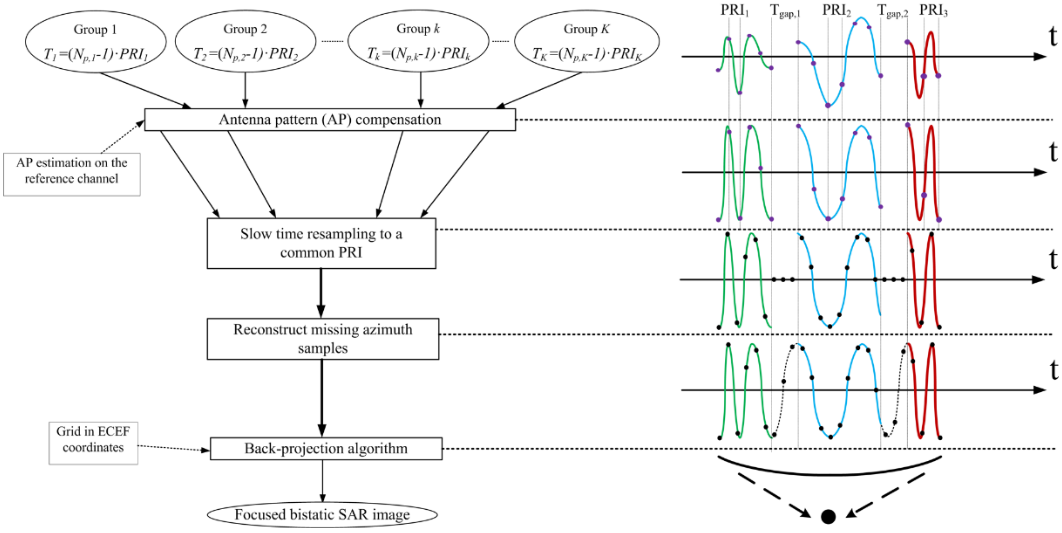


Figure 2. 1 *Multi-aperture bistatic focusing – flow diagram and signal representation.*

Algorithm 2. 1: Processing Chain of the Proposed Method

```
Input: $\boldsymbol{x}, SNR$
Output: $\boldsymbol{y}$
Choose $K$, $\alpha_{SNR}$ based on system requirements
$\widehat{\boldsymbol{R}}_s = FB\ Spatial\ Smoothing(\boldsymbol{x}, K)$
$\boldsymbol{\lambda} = EigenDecomposition\ \left(\widehat{\boldsymbol{R}}_s\right)$
$\widehat{N}_c = MDL(\boldsymbol{\lambda}, S)$
$\dim\left(\widehat{\boldsymbol{\theta}}\right) = \alpha_{SNR}\widehat{N}_c$
$\boldsymbol{y} = AR\left(\boldsymbol{x}, \dim\left(\widehat{\boldsymbol{\theta}}\right)\right)$
```

A highly sufficient approach was proposed is to estimate the number of target signatures within an iso-Azimuth line using Principle Component Analysis (PCA) and the Minimum Description Length (MDL) principle, and then construct a well-fitted model using the Burg method later used to extrapolate the missing samples in the multi-aperture. The MDL is a cost function consisting of two terms the likelihood function and a penalty term used to avoid overfitting the data.

$$MDL\left(\widehat{\boldsymbol{\theta}}\right) = -\log\left(\left[L\left(\boldsymbol{X}\middle|m\left(\widehat{\boldsymbol{\theta}}\right)\right)\right]\right) + \eta\log(S) \tag{2.10}$$

The first step of the proposed approach is to extract the eigen values of the covariance matrix. Since there is a single available snapshot spatial smoothing must first be applied to obtain a lower-rank but invertible matrix.

Afterwards the most significant eigen values are found using MDL as a thresholding method. The number of eigen values is interpreted as the number of spectral components required for reconstructions. It is shown on in Fig. 2.11 that the proposed model-estimation method provides better results than traditional order estimation methods, that may either under-fit or over-fit the data. Moreover, using the proposed approach results in a reduced complexity by a factor of approx. 1000 in practical use-cases. The cross-resolution gain provided by the multiaperture stitching methodology using the proposed signal processing techniques can be visually observed from Fig. 2.13, where it is compared to single-aperture focusing.

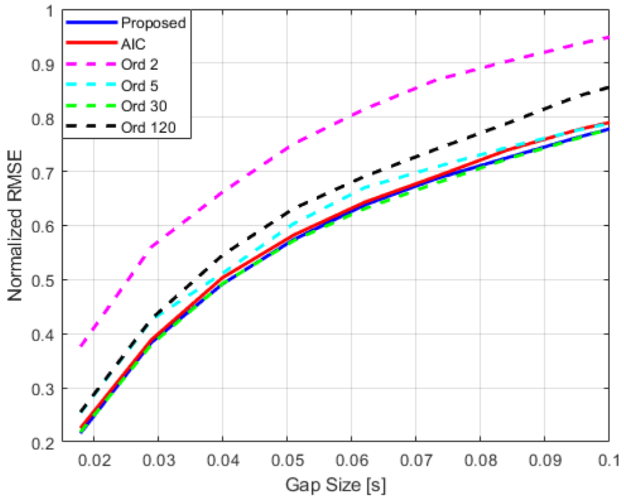
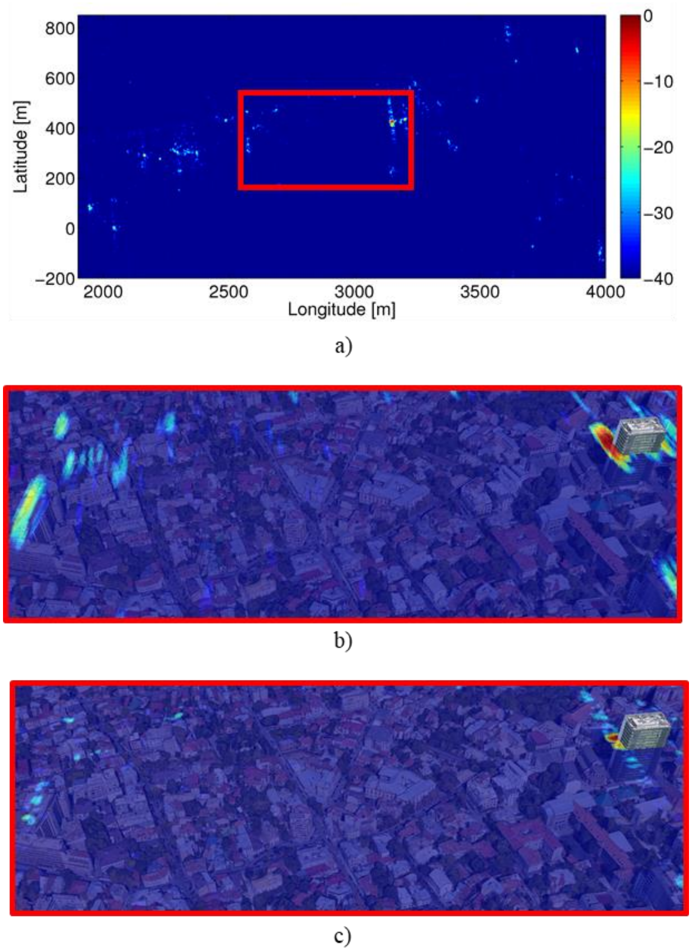


Figure 2.11 *RMS Error of the AR model when using different order estimating methods, normalized to the largest error.*



a)

b)

c)

Figure 2.13 *Resolution enhancement with multi-aperture focusing: a) high-resolution multi-aperture focused bistatic SAR image; single-aperture (b) and multi-aperture (c) images overlaid on Google Earth.*

2.2 Stable Scatterer Detection

Permanent and stable scatter detection [5] may provide insight on which areas may benefit from multi-aperture focusing. The scatterers that are stable and coherent among all sub-apertures will be focused with maximum resolution, while scatterers that can be seen only within some sub-apertures may produce undesired artefacts in the final SAR image if not processed correctly. The proposed permanent scatterer detection methodology is based on constructing CFAR bitmaps for each sub-aperture and applying logic AND. An example of CFAR thresholding is presented in Fig 2.16.

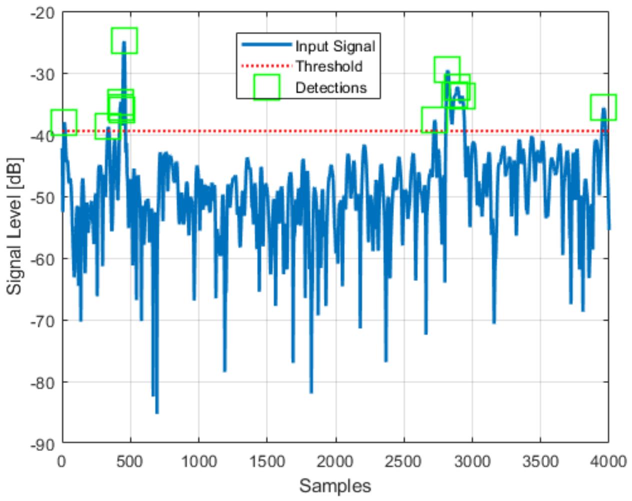
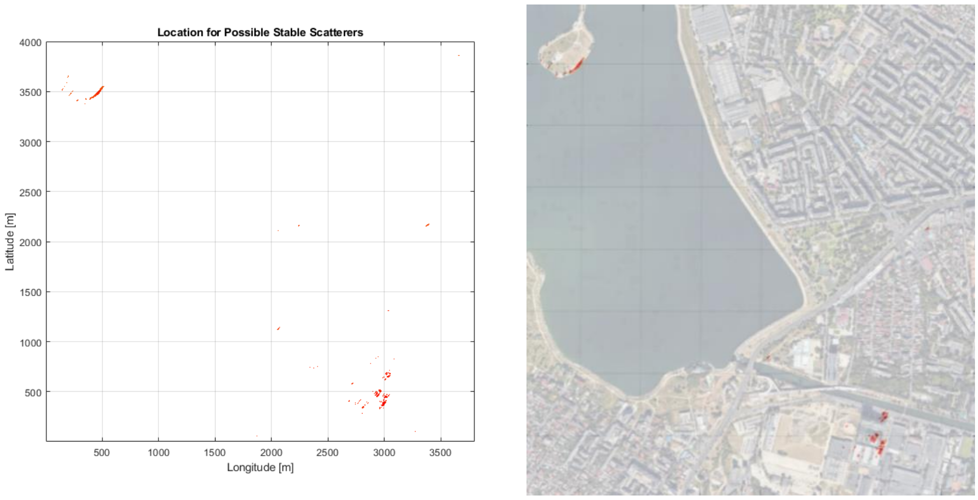


Figure 2.16 *Median-of-Means-CFAR applied to an arbitrary iso-range. Samples above the threshold are considered targets. Additional Peak Detection was applied for illustrative purposes.*

The permanent scatterer bitmap containing the common points within each sub-aperture CFAR bitmap is presented in Fig 2.17.



a) b)

Figure 2.17 *a) Stable Scatterer distribution after point-wise multiplying the four images in Fig.4. b) The Stable Scatterers are overlaid in red on the Google Earth satellite Image.*

The proposed Median of Means CFAR [4] is presented in Fig. 2.20. It was developed to provide high probability of detection even in dense enviornments, for a given probability of a false alarm. There are two novel aspects, the first was finding an analytical CA-CFAR threshold for log data, equation (2.30), and the second consists in the processing sequenze shown in Fig. 2.20.

Equation (2.30) presents the relationship between the distribution of a square-law detector noise signal, z, that is exponentially distributed, and that of a log-detector noise signal, λ.

$$\log\left(\int_0^\infty z\, p_Z(z)dz\right) = \int_{-\infty}^\infty \lambda\, p_\Lambda(\lambda)d\lambda + \frac{1}{2}\log(\pi) \tag{2.30}$$

Using equation (2.30), one can find the desired CA-CFAR threshold as a function of the desired probability of false alarm and window sizes as shown in equation (2.31).

$$T_{CA(log)} = \log\left(N\left[P_{FA}^{-1/N} - 1\right]\right) + \frac{1}{N}\sum_{n=1}^{N}\lambda_n + \frac{1}{2}\log(\pi) \tag{2.31}$$

Further on, using the central limit theorem one may use the median of means as a measure of noise power, while simultanously avoiding regions in the range profile containing target signatures, resulting in a very accurate estimate of the CFAR threshold.

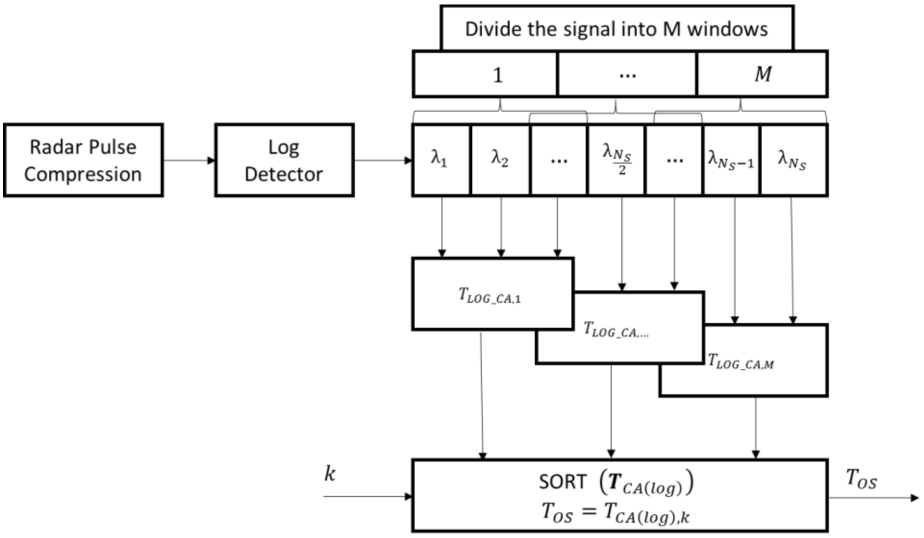


Figure 2. 2 Proposed *Median of Means CFAR processing flow.*

3. Near-Range Multipath Mitigation Methodology for Multistatic SAR Applications

This chapter presents a methodology based on matched-adaptive filters that is used to mitigate the effect of near-range multipath in multistatic SAR systems and transponders. It is challenging to physically construct a bistatic receiver such that the reference signal is not leaked into the received signal, either via coupling in the circuitry or via reflections off objects in the vicinity of the receiver. Due to its much larger amplitude, the reference signal can easily mask near-range targets with its side-lobes. A similar signal degradation is observed in active transponders that are used for calibrating radar systems, when objects exist in their vicinity. In this chapter we address these two issues: the coupling between the reference channel and the imaging channel, and the parasitic echoes present in the transponder response. A novel methodology is proposed that is capable of time-domain filtering the undesired components in real time. The novelty consists in combining matched and adaptive filters as a means of boosting performance and resolution estimation, resulting in an extremely accurate multipath elimination method. The proposed methodology is experimentally evaluated and optimized for each of the two aforementioned problems. The original work presented in this chapter has been previously published in: **[6] [7] [8]**

3.1 Near-Range Multipath Mitigation in Bistatic SAR

The envisaged geometry of a bistatic SAR system is illustrated in Fig 3.1. The undesired coupling and near-range reflections are represented in red. For this type of multipath mitigation the Matched-RLS filter is placed in a channel estimation configuration, such that the adaptive filter, $\boldsymbol{w}$, matches the RF Channel, $\boldsymbol{h}$. The block schematic of the proposed filter is shown in Fig. 3.5. Once the weights $\boldsymbol{w}$ have been estimated, than the reference signal is convolved with $\boldsymbol{w}$ and subtracted from the received signal. The new range-compressed SAR image is presented in Fig. 3.10. It is shown that the large near-range components are filtered, along with their associated side-lobes. It is experimentally proven that the proposed approach is both faster and more performant than the traditional approach using time-domain adaptive filters.

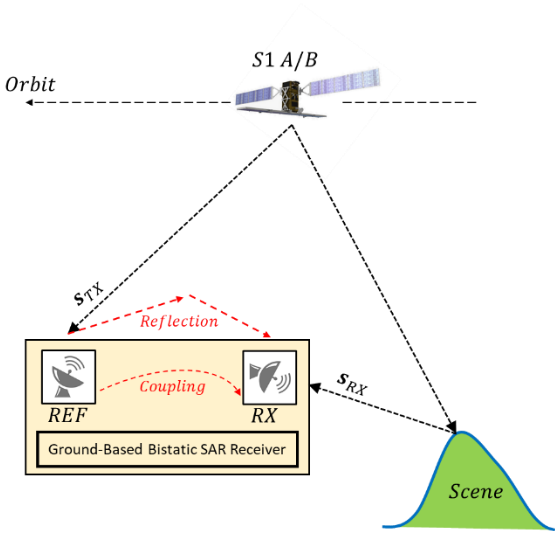


Figure 3.1 *Spaceborne transmitter - stationary receiver bistatic geometry. The addressed issue is depicted in red, as a parasitic coupling or reflection between the reference channel and the receive channel.*

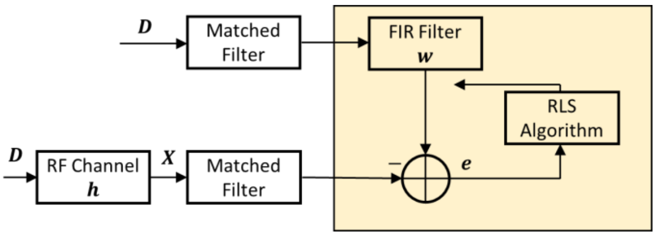
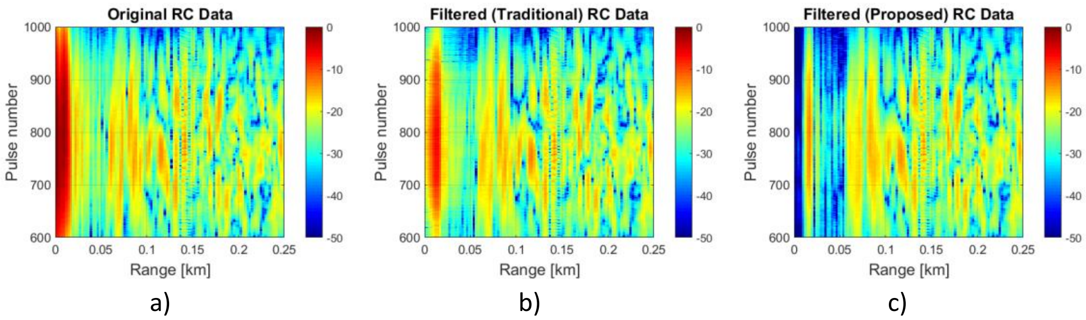


Figure 3.2 *Proposed matched-filtered channel-estimation configuration using the RLS adaptive algorithm.*



a) b) c)

Figure 3.10 *Range Compressed SAR image, a) of the raw data, b) of the near-range filtered targets using traditional approach, c) of the near-range filtered targets using proposed approach.*

3.2 Near-Range Multipath Mitigation in Transponders

Additional to the previous setup, a transponder may also be introduced in the ground-based system for calibration purposes, as shown in Fig. 3.2. And similarly, coupling and near-range reflections may cause performance degredation. The difference however, is that multipath within the transponder no longer follows a moving average model, but an auto-regressive model. To solve this, the proposed matched-adaptive filter is now configured as an echo-canceller, as shown in Fig. 3.6.

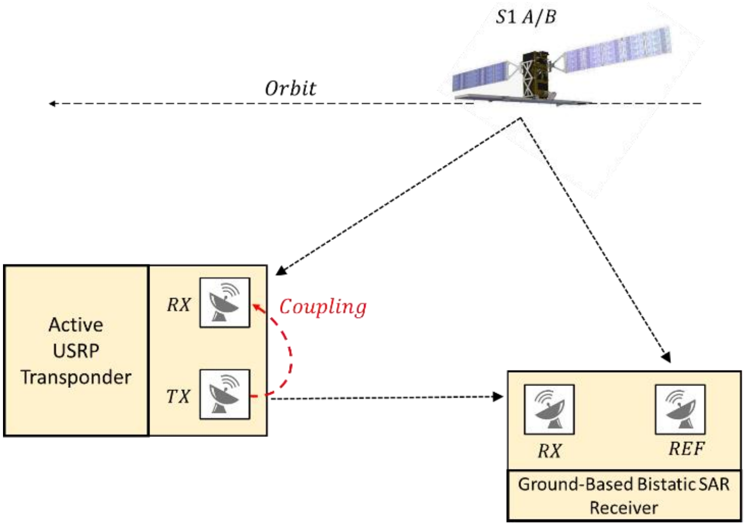


Figure 3.2 *A calibration transponder used for SAR applications, which is affected by parasitic couplings.*

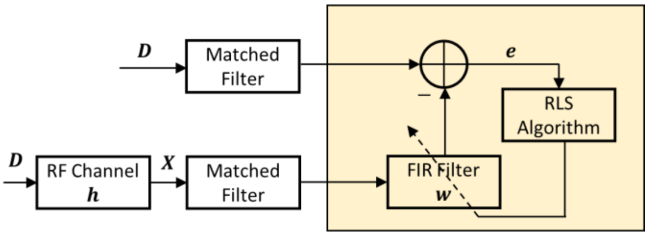


Figure 3.6 *Proposed matched-filtered echo-cancellation configuration using the RLS adaptive algorithm.*

The echo-canceller will rotate the phase of each pulse and set it to the phase of the reference signal, making it impossible to measure the pulse-to-pulse phase evolution required for SAR imaging. A solution to this is to configure the adaptive filter only for the first pulse, and hard-implement the coefficients for all following pulses as a static filter, as shown in Fig. 3.14.

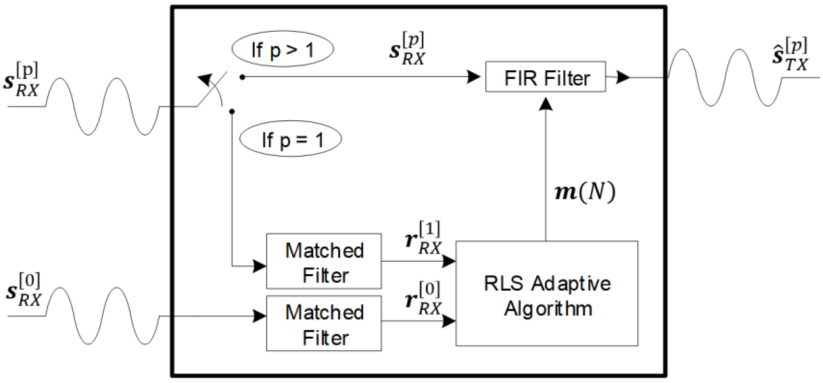


***Figure 3.14** Simplified block schematic of the proposed real-time method.* $\boldsymbol{s}_{RX}^{[p]}$ *is the input of the transponder and* $\boldsymbol{s}_{TX}^{[p]}$ *is the output.*

The method illustrated in Fig. 3.14 was implemented on the USRP-based active transponder, experimental results are shown in [8]. The undesired spurs were eliminated, as shown in the following figures. In Fig 3.15 the theoretical peak-to-spur ratio vs SNR is presented using multiple Monte Carlo simulated results.

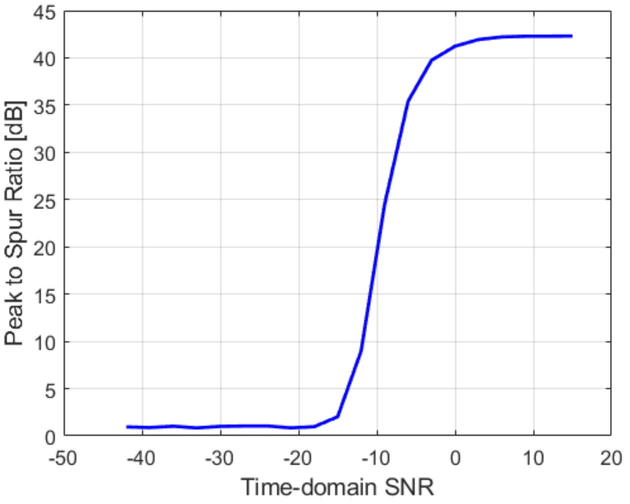


***Figure 3.15** Peak to Spur Ratio vs SNR.*

The experimental setup is presented in Fig. 3.18 and 3.19. The transponder response after SAR focusing, with and without the proposed method implemented, is shown in Fig. 3.24. The coefficients used to filter the data were processed one week prior, showing that the proposed approach does not require the coefficients to be often updated, making it highly efficient for remote bistatic receivers. Even with the one week old coefficients, the peak-spur ratio is improved by 10 dB compared to no filtering applied.

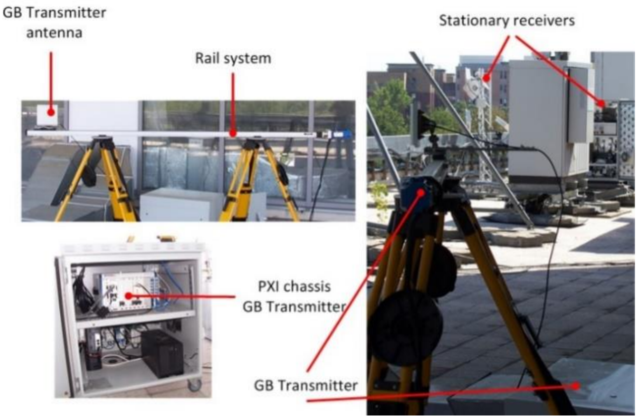


__Figure 3.18__ Ground based bi-static SAR system placed on the rectorate building of UPB.

Measure distance
Click on the map to add to your path
Total distance: 727.03 m (2,385.27 ft)

__Figure 3.19__ Transceiver, transponder and illuminated scene as seen from Google maps.

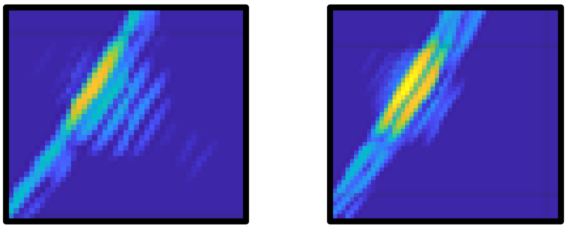


__Figure 3.24__ Transponder response with and without the implemented echo-cancelling filter.

4. Enhancing Multistatic FMCW Radar Applications

Frequency modulated continuous wave (FMCW) radar systems are generally used at close ranges, using low-power and cost-effective hardware architectures. Such radars can easily obtain larger bandwidths than pulsed radar systems, but are generally limited due to multiple constraints to operate within ranges under 10 km. They are mainly used in civilian applications, such as automotive and IoT, however, EO remote sensing has also made use of FMCW SAR equipped on airborne platforms [9]. This chapter presents a novel VCO design, an efficient Kalman Filter implementation, and a near-field phased array calibration method that may be used to improve FMCW SAR [10] systems, while considering a wide variety of applications. My original work presented in this chapter can be found in publications: [11] [12] [13] [14].

4.1 High-linearity UWB Push-Push VCO for FMCW Radar

In this section **[11]** a low-complexity push-push VCO is presented which achieves over 17% highly linear MHz/V tunable bandwidth. Unlike traditional VCOs, the proposed design does not require dedicated voltage sensitive reactance components such as varactors or other transistors. The frequency is controlled with the bias voltage of the SiGe transistors which are placed in push-push configuration. The VCO is implemented using discrete components and occupies 81 $\boldsymbol{mm^2}$ on PCB. The measured phase noise @1MHz is -103 dBc/Hz, the average power consumption is 18mW, the RF output power is -1dBm, and the supply voltage is 3.3 V. The tuning range is 5.15 GHz – 6.15 GHz, and the Figure of Merit with Tuning (FoMT) at center frequency is -170. The large tunable bandwidth is obtained without using voltages greater than the supply voltage. The linearity and tuning bandwidth are evaluated by implementing the design in a low-power C-band FMCW imaging radar.

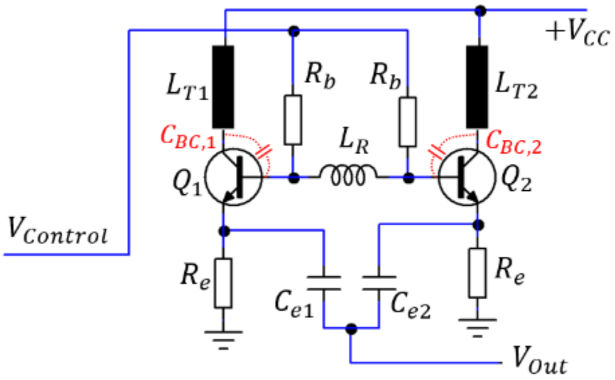


Figure 4.5 *Schematic of the proposed push-push VCO using SiGe transistors. The frequency is controlled by the DC voltage drop across* $C_{BC,1}$ *and* $C_{BC,2}$.

An imaging radar use-case is presented next. In Fig. 4.11 the two targets are plotted in Range [m] - Azimuth [deg]. The RX wide-band horn antennas used in the presented prototype are spaced at 85mm, resulting in a non-ambiguous field-of-view of ~80deg, and an angular resolution $\delta\varphi \cong \frac{0.89\lambda}{D\cos(\varphi)}$ of ~40deg. Two targets are placed at 2.2 and 3.2 meters, at 5 and -20 degrees, respectively.

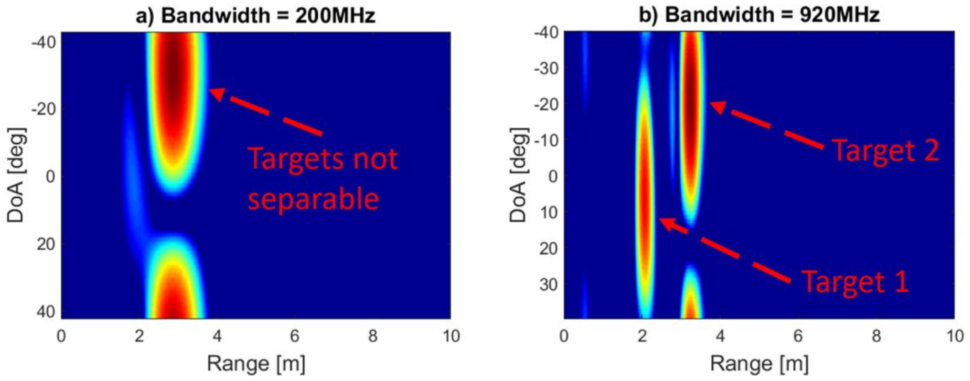


Figure 4.11 *Range-Angle representation of two targets for tuning bandwidths: a) 200 MHz (targets not separable), b) 920 MHz (targets are separable).*

4.2 Efficient Recursive Error Division Kalman Filter

This section **[13]** presents a time-domain analysis for digital Infinite Impulse Response filters used in tracking applications. It provides information on how such a filter may be used as discrete-time estimator, and even more so, offer valuable information on the rate of change of the input signal. Some examples where the proposed acquisition-synchronous filter may improve application performance, is in automotive radar-based driver assistance systems and multistatic FMCW radar system synchronization. The filter is responsible for estimating the velocity and acceleration of the tracked targets, which are then fed into a range only Kalman Filter (KF) Tracker. The proposed algorithm fusion not only reduces computational complexity, but also improves performance. Unlike alpha-beta-gamma filters, the present method can also be extended to non-Gaussian distributions for Extended Kalman Filters (EKF).

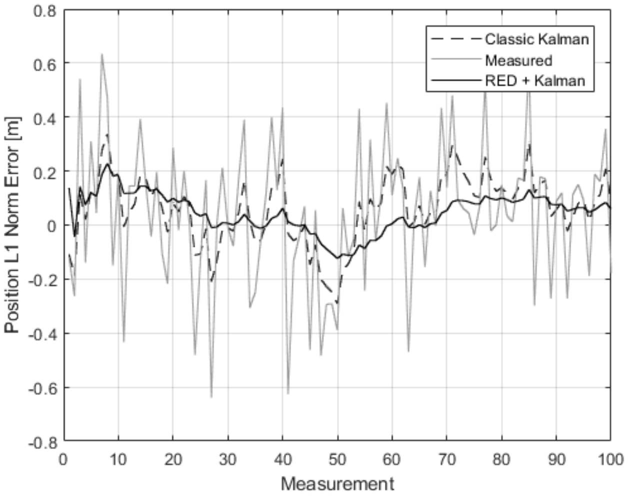


Figure 4.18 *Simulated results presenting the L1 error of the position.*

4.3 Near-Field Phased Array Calibration

This section [14] addresses the issue of calibrating receive phased arrays, compensating element coupling and gain or length mismatches between the channels. Far-field measurements are always preferred, however, it is rarely possible to take such measurements due to the very large spacing required between the source, or reflector (for radar), and the receiving phased array. Hence, most calibrations in practice are made in the near-field of the array. This requires specialized positioning/optical equipment to correctly estimate the spherical wave-front for proper phase compensation.

The received signal: $\boldsymbol{z} = \left(\boldsymbol{C}(\boldsymbol{x} \odot \boldsymbol{A})\right) \odot \boldsymbol{g} \odot \exp\left(j2\pi \frac{\boldsymbol{r}}{\lambda}\right)$

where **x** is the ideal signal, **A** is the antenna element gain and phase mismatch, **g** is the trace gain mismatch, **r** is the trace length mismatch, and **C** is the coupling matrix.

The calibrated signal is found by compensating the estimated parasitic errors:

$$\boldsymbol{x} = \widehat{\boldsymbol{C}}_{\boldsymbol{cal}} \left(\boldsymbol{z} \odot \frac{1}{\widehat{\boldsymbol{g}}} \odot exp\left(2\pi j \frac{-\widehat{\boldsymbol{r}}}{\lambda}\right)\right)$$

The procedure is illustrated in Fig. 4.21 and the results are shown in 4.25.

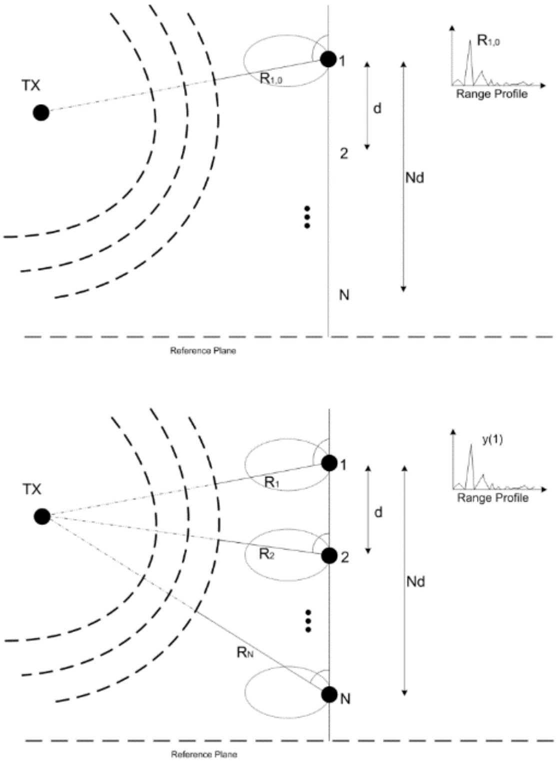


Figure 4.21 *Mutual coupling calibration procedure.*

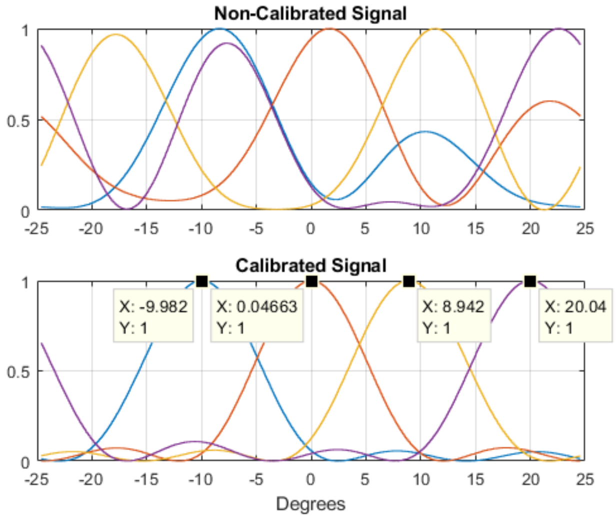


Figure 4.25 *Far-field simulation using the calibration vector and matrix obtained during near-field measurements.*

5. Conclusions

Multistatic SAR is an emerging technology capable of providing exceptional performance compared to traditional SAR systems. There is however a large series of challenges regarding synchronization, calibration, and system design that must be addressed for such a system to function properly. The ever-growing computational power and semiconductor performance has reduced costs for multistatic SAR, resulting in more and more applications and industry fields benefiting from the technology. Of all applications, EO remote sensing is currently the most active in multistatic SAR development, mainly because of the scale of the geometry, consisting in spaceborne, airborne and ground-based sensors, which enables large baselines to be used, and profit at a maximum from multistatic information sensing and processing.

In this thesis a study of mulistatic SAR was presented. Original techniques and methodologies from various fields of engineering, including signal processing, detection, estimation, tracking, phased arrays, RF system architectures, active microwave circuits, and more, were developed to address the multiple challenges affecting multistatic SAR systems.

A resolution enhancement technique using multi-aperture focusing for space-borne transmitter – ground-based receiver bistatic SAR was implemented and experimentally evaluated using the COBIS platform. The results were promising and show that using leakage from antenna side-lobes and adjacent sub-swaths that has been captured by an bistatic receiver, a much larger synthetic aperture may be constructed, resulting in enhanced cross-range resolution. Additionally, the missing gaps between the sub-apertures must be filled in order to avoid powerful spurs that may impact the focused SAR image significantly. An order estimation and extrapolation technique is proposed to fill these gaps efficiently in real-time. Further on, a permanent scatterer detection scheme was developed using a newly introduced CFAR algorithm that may be used to further enhance multiaperture processing by only processing the targets present in all sub-apertures.

A common issue affecting bistatic radar systems in general is coupling between the sync or reference channel and the primary receive channel. A method capable of time-domain multipath and feedback mitigation is developed using a new matched-adaptive filter technique. It is shown that the proposed methodology provides a highly superior performance and reduced computational cost, simultanously, when compared to prior art. The method is experimentally evaluated for two different applications using UPB's system of active transponders and ground-based Earth Observation (EO) passive SAR receivers sycnronized to ESA's Sentinel 1 EO-SAR satellite system.

Apart from EO remote sensing, multistatic radar imaging and multistatic SAR is also used in close-range applications such as those using UAVs. Generally, the FMCW radar architecture is adapted in such systems for its much larger range resolution and lower power consumption. A novel VCO architecture for low-cost, low-power, reduced size FMCW radar applications was presented. The novelty consists in using the oscillator bias as a tuning voltage, eliminating the need of using separate resonator tank. This significantly reduces circuit complexity, consumption, and also improves the VCO's transfer function linearity. Additionally, an highly efficient tracking algorithm is presented, that is based on the Kalman Filter, and may be used to enhance localization for multistatic radars placed on UAVs or other platforms. Such a filter is useful for compensating the frequency off-sets between the different local oscillators in multistatic SAR systems during the synchronization step, procedure that is required for interferometry.

Bistatic receivers such as the COBIS may also be used to obtain real-time elevation, or height, information. This requires using a rather large phased array that must be accurately calibrated. In many applications, calibration must be done periodically, and dismounting the array is not always an option. A new near-field calibration technique is presented for wireless communication and radar phased array calibration, that solves trace length mismatch and element coupling, does not require anechoic chamber measurements or precise positioning.

5.1 List of original publications

My original contributions presented in this thesis are fully available within my list of publications and patents from section 5.2. The contributions are as follows: [J] = Journal paper, [C] = Conference paper, [P] = US Patent Application.

5.1.1 Journal Papers

[J1] F. Rosu, A. Anghel, R. Cacoveanu, B. Rommen and M. Datcu, "Multiaperture Focusing for Spaceborne Transmitter/Ground-Based Receiver Bistatic SAR," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 13, pp. 5823-5832, Oct. 2020.

[J2] F. Rosu and I. Rosu, "SiGe Push–Push VCO for Low-Power C-Band FMCW High-Resolution Radar Applications," in IEEE Microwave and Wireless Components Letters, vol. 31, no. 10, pp. 1150-1153, Oct. 2021.

[J3] F. Rosu, A. Anghel, S. Ciochina, R. Cacoveanu, M. Datcu, "Near-Range Multipath Mitigation Methodology for Multistatic SAR Applications using Matched Adaptive Filters," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 15, pp. 3204-3214, Apr. 2022.

5.1.2 Conference Papers

[C1] F. Rosu, A. Anghel, R. Cacoveanu, S. Ciochină and M. Datcu, "Deconvolution Method for Eliminating Reference Signal Coupling/Reflections in Bistatic SAR," 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, 2021, pp. 2715-2718.

[C2] F. Rosu, A. Anghel, R. Cacoveanu, M. Datcu, "Stable Scatterer Detection in Multi-Aperture Spaceborne-TX / Ground based-RX Bistatic SAR", CENTERIS SARwatch, Procedia Computer Science, Volume 181, 2021, Pages 255-260.

[C3] F. Rosu, A. Anghel and S. Ciochina, "Sub-Resolution Multipath Mitigation in Radar Transponders by Range Compression and Adaptive Filtering," 2019 International Symposium on Signals, Circuits and Systems (ISSCS), 2019, pp. 1-4.

[C4] F. Rosu, "Cartesian Tracking for Advanced Driver Assistance Imaging Radar Systems," 2020 13th International Conference on Communications (COMM), 2020, pp. 37-41.

[C5] F. Rosu, "Recursive Error Division Kalman Filter for Advanced Driver Assistance Radar Systems," 2020 13th International Conference on Communications (COMM), 2020, pp. 31-35.

5.1.3 Patent Applications Filed at US Patent House

[P1] Rosu, Filip Alexandru (Bucharest, RO), Bogatu, Tudor (Bucuresti, RO) 2022 CALIBRATION OF A PHASED ARRAY United States NXP USA, Inc. (Austin, TX, US) 20220128654

[P2] Rosu, Filip Alexandru (Bucharest, RO) 2022 CELL-AVERAGE AND ORDERED-STATISTIC OF CELL-AVERAGE CFAR ALGORITHMS FOR

LOG DETECTORS United States NXP USA, Inc. (Austin, TX, US) 20220120855

[P3] F. A. Rosu, "STOP CRITERION FOR GREEDY TARGET DETECTION ALGORITHMS IN RADAR APPLICATIONS USING SPARSE PHASED ARRAYS". United States NXP USA, Inc. (Austin, TX, US) Patent 17/226397, 04 09 2021.

5.3 Perspectives for further developments

Further developments consist in optimizing the solutions developed/evaluated for the ground-based RX – space-borne TX multistatic SAR setup for fully spaceborne or airborne multistatic SAR such that they may benefit future missions such as Harmony.

While SAR is historically known to be used in the fields of aerospace and EO, it has been just recently introduced in other applications, such as ADAS. With a whole new set of constraints and challenges, there is massive space for innovation required to adapt the technology for self-driving applications. Perhaps the main challenge is designing and implementing a SAR system capable of running in real-time on a typical automotive radar microcontroller unit (MCU) or microprocessor unit (MPU). Unlike EO and Aerospace, where the use of billion-dollar hardware and offline processing is generally acceptable, the automotive industry has very strict standards regarding real-time capabilities, and the entire radar system is generally priced under a few hundred USD. My goal is to contribute with new algorithms and system designs to enable multistatic MIMO-SAR within the context of self-driving, mainly autonomous and valet parking.

In the past decade UAV systems have received more attention than ever, with more and more applications making use of them. Autonomous flying is generally not possible if the UAV is relying solely on optical sensors and GNSS data, especially during night-time or harsh weather conditions. Radar could significantly boost the application up-time during these periods, and even enhance flight robustness. UAV-oriented radar applications are one of the directions I intend to further investigate and contribute towards. Another direction that is of interest to me is multistatic-SAR imaging using fleets of UAVs equipped with active or passive receivers, for surveillance or defense purposes, such as mine detection or medium-range through-wall imaging.

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[12] F. Rosu, „Cartesian Tracking for Advanced Driver Assistance Imaging Radar Systems,” în *2020 13th International Conference on Communications (COMM)*, Bucharest, Romania, 2020.

[13] F. Rosu, „Recursive Error Division Kalman Filter for Advanced Driver Assistance Radar Systems,” în *2020 13th International Conference on Communications (COMM)*, Bucharest, Romania, 2020.

[14] „"Rosu, Filip Alexandru (Bucharest, RO), Bogatu, Tudor (Bucuresti, RO) 2022 CALIBRATION OF A PHASED ARRAY United States NXP USA, Inc. (Austin, TX, US) 20220128654".”.

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