Passive Radar for Aircraft Situational Awareness Employing Airborne Air-to-Air Communication: A Feasibility Study

Alberto Arana Ragel
Institute of Communications and Navigation
German Aerospace Center (DLR)
Wessling, Germany
alberto.aranaragel@dlr.de

Miguel A. Bellido-Manganell
Institute of Communications and Navigation
German Aerospace Center (DLR)
Wessling, Germany
Miguel.BellidoManganell@dlr.de

Rodrigo Blázquez-García
Information Processing and Telecommunications Center (IPTC)
Universidad Politécnica de Madrid (UPM)
Madrid, Spain
rodrigo.blazquez@upm.es

Alexandra Filip-Dhaubhadel
Institute of Communications and Navigation
German Aerospace Center (DLR)
Wessling, Germany
alexandra.filip@dlr.de

***Abstract*—Currently, situational awareness capabilities in civil aviation are exclusively cooperative. To address this issue, in this work we propose a new non-cooperative situational awareness concept based on leveraging airborne air-to-air communication for passive radar sensing. In particular for this study we employ the LDACS A2A signals. We introduce the system advantages and limitations and perform an initial feasibility assessment of the concept. For this purpose, we evaluate the link budget and perform a detailed analysis of the ambiguity function (AF). The latter involves the characterization of the signal ambiguities that could impact the passive radar performance. Due to the presence of these ambiguities, we evaluate the effectiveness of employing a reciprocal filter for reducing their impact. Finally, the performance of the reciprocal filter is evaluated in simulation.**

***Index Terms*—Passive Radar, ISAC, non-cooperative situational awareness, LDACS A2A**

I. INTRODUCTION

Air target detection employing passive radar has gained increased attention over the last three decades [1]–[7]. The increasing number of flights as well as the increasing concern over drones operations has made the air target detection a focus point for many passive radar researchers. Specific to civil aircraft, there have been several research works approaching the problem from different perspectives, i.e., employing different Illuminators of Opportunity (IoOs). While many works focus on space-based illuminators like GNSS [1]–[3] or DVB-S [4], other works have employed terrestrial transmitters as DVB-T [5], GSM [6], or FM [7]. In this paper, we aim to evaluate the possibility of using a different link for the purpose of detecting air targets: an airborne air-to-air (A2A) communication link.

The importance of civil aircraft detection is motivated by the vulnerability of the current surveillance systems. In particular, civil aircraft situational awareness, especially outside of the continental area, is exclusively based on cooperative systems. Specifically, civil aircraft rely on the ADS-B and TCAS systems to detect other aircraft flying in the vicinity and, if needed, avoid a collision. This naturally leads to vulnerability concerns as cooperative systems are subject to outage in the case of transponder malfunction or performance degradation of the frequency band employed for the data exchange. The latter point becomes even more critical since both systems (along with several other surveillance systems) rely on the same congested 1090 MHz frequency band.

As such, in this paper we are interested to investigate the feasibility of employing a future airborne A2A communication link for non-cooperative situational awareness. This would realize a "passive" monostatic radar, as depicted in Figure 1, in the sense that no control over the transmitted signal is considered. In particular, we are interested to investigate the feasibility of employing the future A2A extension of the aeronautical communication link LDACS.

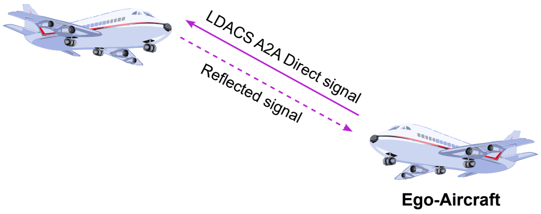


Fig. 1: Monostatic Passive Radar Geometry

In this work we present the first airborne air-to-air passive radar concept that leverages an onboard communication system and take several steps towards advancing its feasibility. We identify the advantages and potential limitations to be investigated, defining as a result the working principle of the concept, which is tailored to the intrinsic characteristics of the LDACS A2A system. We perform an initial feasibility assessment by evaluating the system link budget and the AF of the signal. The latter is a critical step accounting for the fact that LDACS A2A is an OFDM system with a limited bandwidth, such that the signal resolution and ambiguities play a crucial role in the concept feasibility. Additionally, the effect of employing a reciprocal filter (RpF) for this communication system is also studied in this work. Lastly, the first simulated radar data employing this system for a passive radar approach is presented and the performance of the RpF is evaluated.

The remainder of this paper is organized as follows: in Section II the LDACS A2A airborne communication system is presented and the transmitted signal model is introduced. In Section III the envisioned passive radar system characteristics are introduced, the feasibility assessment is performed in Section III-A, with an initial link budget assessment in Section III-A1, and the analysis of the signal limitations in terms of ambiguities in Section III-A2. The signal processing is analyzed in III-B, the simulation results are shown in Section IV, and the paper is concluded in Section V.

II. LDACS A2A SYSTEM

The LDACS A2A data link has been developed as an extension of the current LDACS air-to-ground (A/G) system. However, while LDACS A/G has already been demonstrated in flight trials [8] and is being standardized, LDACS A2A has only been evaluated in simulations. The capability to perform direct aircraft-to-aircraft communications enables a series of new services and concepts of operation not feasible otherwise. For example, it will enable aircraft to fly autonomously without the support of the air traffic controllers, since situational awareness and any required conflict resolution will be managed directly via the LDACS A2A link. It will also allow for aircraft to fly in formations to reduce fuel consumption, which can be especially beneficial in long tracks such as the North Atlantic Corridor.

Although the medium access control layers of LDACS A2A and LDACS A/G differ significantly, the physical layer of LDACS A2A has been designed based on the LDACS A/G physical layer in order to ease its standardization and its compatibility with legacy systems. The current design of the LDACS A2A physical layer can be found in [9]. More specifically, LDACS A2A also employs OFDM with a subcarrier spacing of 9.765625 kHz and 25 active subcarriers on each side of the spectrum around the carrier frequency, leading to roughly 498.05 kHz of signal bandwidth. It employs the same windowing to attain the same transmit spectral mask as LDACS A/G reverse link. Important for this analysis, LDACS A2A reuses the same synchronization OFDM symbols defined for the reverse link of LDACS A/G. They comprise two OFDM symbols containing so-called CAZAC (constant amplitude, zero correlation) sequences. The duration of the cyclic prefix (CP) for LDACS A2A is 12.8 μs, shorter than the one used in LDACS A/G. An extensive analysis of the A2A propagation channel was conducted and the data link simulations showed that a shorter CP is beneficial for LDACS A2A [9], [10].

Two types of messages will be transmitted by LDACS A2A: beacons and point-to-point (P2P) messages. Beacons are transmitted by the aircraft to indicate their identity, position, trajectory, and related data required for active surveillance and situational awareness. In addition, beacons are used to organize the medium access control of the different aircraft using LDACS A2A. Beacons have a fixed length of 12 OFDM symbols with a total duration of 1.3824 ms. The first two OFDM symbols comprise the synchronization preamble while the remaining 10 OFDM symbols carry data and pilots for channel estimation. The synchronization preamble is depicted in Fig. 2, while the distribution of the pilot and data symbols within a frame is depicted in Fig. 3. The complete information can be found in [9].

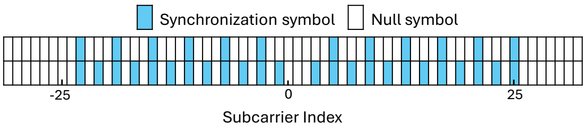


Fig. 2: LDACS A2A synchronization preamble

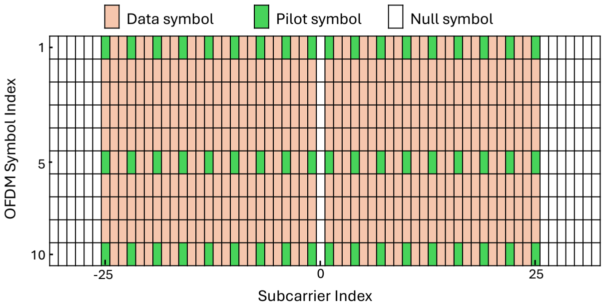


Fig. 3: LDACS A2A pilot and data symbols distribution

P2P communications do not have a fixed duration, since the required quality of service is previously negotiated between the stations. For the purpose of this work, we assume a transmit duration of 100 ms, although longer transmissions are not excluded in the LDACS A2A link. P2P transmissions start with the synchronization sequence of 2 OFDM symbols, followed by a variable number of OFDM symbols with data and pilots, which replicate the same pilot/data pattern of the beacons.

The airborne station of the LDACS A2A must share the same characteristics in terms of emissions with respect to the airborne station defined in the LDACS A/G standard. Importantly for this paper, this includes a maximum EIRP of 41 dBm. Also, LDACS A2A shall use the same frequency channels allocated to LDACS A/G. For the analysis in this paper, we can assume the highest LDACS frequency channel, i.e., 1156 MHz, to consider the case with the highest path loss.

III. LDACS A2A-BASED PASSIVE RADAR

The LDACS A2A passive radar system concept has a number of characteristics specific both to the scenario and to the LDACS A2A signal that need to be addressed. Whereas passive radar applications are typically associated with bistatic scenarios, in this case we face a monostatic passive radar geometry. This has several advantages, such as having direct access to the transmitted signal, as well as full knowledge of the transmitter position. Additionally, the range and Doppler retrieved are monostatic ones, which simplifies the complexity in comparison to a bistatic geometry.

Regarding the LDACS A2A signal, several remarks need to be made. Due to the two transmission types detailed in Section II, two different processing schemes can be envisioned. The short regular broadcast would allow for retrieving range information every second, however the short duration and low pulse repetition frequency would not allow for obtaining Doppler information. Even though this could be problematic in the presence of clutter, given the scenario under study, we do not foresee the clutter to be critical, as it would be mostly received through the sidelobes and well distributed across range. The regular range information could be enhanced with angle-of-arrival (AoA) information for localization of targets. This would follow a similar processing scheme to the one proposed in [11]. Additionally, due to the lack of Doppler, the velocity when employing this signal would be estimated in the tracking. In contrast, if a longer P2P data exchange were to take place, this would allow for Doppler processing and the retrieval of range/Doppler maps, along with bringing a higher integration gain due to the longer integration time. Given that the transmitter and receiver are located on the same platform, we assume that the surveillance system is constantly aware of the transmission protocol, i.e., whether the LDACS A2A system is transmitting a short beacon or a long P2P signal. As such, the surveillance system could adapt the processing to be performed to the type of transmitted signal.

Even though for this work the transmitter is not assumed to be cooperative, the concept presented here could evolve towards a more Integrated Sensing and Communications (ISAC)-like framework. Small changes in the waveform could be performed to enhance the radar performance, and the transmitter could be subject to on-demand transmission for radar purposes in specific cases. The analysis of these techniques lies, however, outside of the scope of this work.

A. *Feasibility Assessment*

1) Link budget: We start the feasibility assessment by performing a link budget study of the proposed system and evaluating the theoretical detection performance when taking into account the system parameters in Table I. In particular, we evaluate the maximum detection range, $R_{R_{\max}}$, as a function of the target RCS, given a desired detection probability, P_{d}, and a fixed probability of false alarm, P_{fa}. This relationship is defined by the radar equation and can be expressed as

$$R_{R_{\max}} = \sqrt[4]{\frac{P_T G_T G_R \lambda^2 \sigma T_{\mathrm{int}}}{(4\pi)^3 \mathrm{SNR}_{\mathrm{out,req}} L_R L_T k_B T_0 F_R}} \,, \tag{1}$$

where $\mathrm{SNR}_{\mathrm{out,req}}$ denotes the output SNR required to attain the desired performance, i.e., P_{d} at fixed P_{fa}, σ represents the target RCS, and T_{int} is the CPI duration [12]. Assuming a coherent detector and considering a Swerling 0 case given the short CPI, the relationship between P_{d} and P_{fa} follows as

$$P_{\mathrm{d}} = Q_m(\sqrt{2\mathrm{SNR}_{\mathrm{out,req}}}, \sqrt{2(-lnP_{FA})}) \,, \tag{2}$$

where Q_m represents *Marcum's Q function* [13].

TABLE I: LDACS A2A surveillance parameters

Parameter	Value
Carrier frequency f_c	1156 MHz
Transmit power P_T	38 dBm
Transmit antenna gain G_T	3 dBi
Receive antenna gain G_R	15 dBi
Receiver loss L_R	2 dB
Transmitter loss L_T	3 dB
Receiver noise figure F_R	5 dB
Standard temperature T_0	290 K
Receiver Bandwidth B	498.05 kHz
Integration Time T_{int}	1.4 - 100 ms

For evaluating the link budget, we consider different transmission durations, i.e., different integration times associated with different transmission types. As mentioned in Section II, the shortest transmission of just one data packet corresponds to the regular broadcast, which is transmitted every second with a duration of 1.4 ms. Longer transmissions can be considered when assuming a P2P communication between aircraft, for which a maximum duration of 100 ms is considered here, corresponding to 87 data packets. Having defined the range of the integration time, we now evaluate (1) for four different integration times. We employ (2) for defining $\mathrm{SNR}_{\mathrm{out,req}}$ for a P_{d} of 0.9 and a P_{fa} of 10^{-6}. Following the parameters listed in Table I, the link budget result is depicted in Fig. 4. Assuming an RCS of 100 m^2 as commonly done in the literature, this result can be understood as a positive first assessment of the system capabilities. Employing the broadcast signal would allow for attaining a maximum detection range of 7 km, whereas when the longest signal is available, the maximum detection range could be extended to 20 km. Even when employing the beacon signal, the maximum detection range is significantly higher than the TCAS resolution advisory region (3.9 km), which gets triggered only within this range for avoiding a mid-air collision. This opens the possibility of considering this approach as a potential back-up for the current surveillance systems.

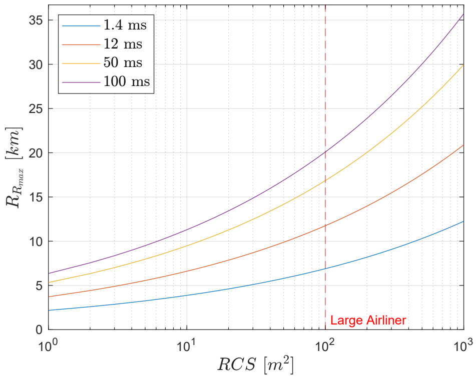


Fig. 4: LDACS A2A-based passive radar link budget

2) LDACS A2A ambiguity function: Another relevant step in evaluating the feasibility of employing the LDACS A2A signals as signals of opportunity is to analyze the signal resolution in delay/range and in Doppler, as well as the signal ambiguities arising as a result of the presence of deterministic elements in the transmitted signal. This is done by means of the AF, which is a two-dimensional function that measures the auto-correlation of a signal with delayed and Doppler shifted versions of itself. Its analytical expression can be written as

$$|\chi(\tau,\nu)|^2 = \left|\int_{-\infty}^{\infty} s(t)s^*(t-\tau)\mathrm{e}^{-\mathrm{j}2\pi\nu t}dt\right|^2, \tag{3}$$

where the superscript * represents the conjugate operation, $s(t)$ is the signal under study, τ represents the delay dimension and ν the Doppler dimension. The characterization in terms of resolution allows for demonstrating how effectively we can discriminate between objects at various ranges and velocities when employing a specific signal for sensing. Moreover, the characterization of the ambiguities reveals how critical these ambiguities are and how likely are they to mask weaker targets. The presence of deterministic elements in the transmitted signals is typical in OFDM systems. In the case of LDACS A2A, the deterministic elements that are expected to produce ambiguities are the OFDM cyclic prefix (CP), the pilot symbols, and the arrangement of both the synchronization and the pilots symbols within the transmitted frame. For this analysis, we need to differentiate between the two types of transmissions considered. The broadcast transmission would only allow for the acquisition of delay data during its short duration (1.4 ms) and its short repetition frequency (1 Hz) and thus only the delay dimension should be explored. The range compression response of the broadcast transmission is depicted in Fig. 5. The delay resolution when employing this signal results in 2 μs, which matches the theoretical resolution associated with a bandwidth of 498.05 Hz. A longer transmission such as the previously mentioned P2P one, would allow for the acquisition of Doppler data as well. For this analysis we focus on the longest signal considered (100 ms duration). By computing (3) for a subset of delay and Doppler values of interest, we retrieve the two-dimensional AF depicted in Fig. 6, where the relevant ambiguities can be seen.

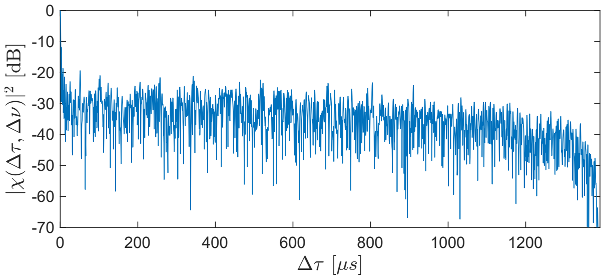


Fig. 5: Broadcast signal range compression response

By analyzing Fig. 6 and both cuts in Fig. 7, we can asses the criticality of the signal ambiguities. We start by analyzing Fig. 7a, where several ambiguities can be identified. First, the strong peak at 102.4 μs is associated with the OFDM CP. Second, the signal peaks appearing within the range $(0, 102.4)$ μs are related to the intra-symbol ambiguities. Lastly, the periodic repetition of the ambiguities appearing around 1152 μs and 2304 μs are associated with the inter-frame ambiguities. As regards to Fig. 7b, no relevant ambiguities appear in the range of interest. The long P2P signal is associated with a theoretical delay resolution of approximately 2 μs and a theoretical Doppler resolution of 10 Hz, which is confirmed by the AF cuts in Fig. 7. The analysis of the AF and its associated cuts reveals the presence of critical ambiguities produced by the regularity in both time and frequency of the signal structure. Thus, an appropriate counter-measure needs to be implemented in order to use this signal for radar purposes.

B. Signal processing

Given the characteristics that such a system should have, as presented in Section III, a dedicated signal processing scheme needs to be designed. This framework should allow for processing both the beacons and P2P transmissions, adapting the processing to the transmitted signal. Additionally, and similar to the work in [11], AoA information, obtained for example with a digital array on reception, would be needed to localize the targets. As such, a signal processing scheme is proposed in Fig. 8. Assuming such a processing scheme, we turn now our attention to the range compression block within the diagram. We consider the surveillance reflected signal $r(t)$ to be range compressed by the reference signal $s(t)$. Given the evidence shown in the previous section, performing such compression with a matched filter (MF) would lead to high power ambiguities. A well-established alternative to the MF is the RpF, first introduced in [14]. This scheme aims at removing the effect of the transmitted signal periodicity in the result of the range compression, thus generating a range compressed result that is independent from the transmitted waveform. This is done at the expense of an SNR loss. Assuming $R(f)$ and $S(f)$ to be the Fourier transformed signals $r(t)$ and $s(t)$, respectively, the MF range compression operation can be expressed as $\chi_{MF}(f) = R(f) \cdot S^*(f)$. In contrast, the RpF range compression is defined as $\chi_{RpF}(f) = R(f)/S(f)$. As such, we are interested to evaluate the effectiveness of the RpF in removing the ambiguities when employing an LDACS A2A signal. For this purpose, we compare the range compression result when employing the MF and the RpF when using the long P2P signal. This comparison is shown in Fig. 9 where, in line with the results shown in [15], we see that the range compression with the RpF results in a sinc. As such, we see that the RpF can effectively eliminate the ambiguities, leading to a range compression response that it is independent from the signal structure. However, employing an RpF for the range compression leads to a loss in the target SNR with respect to the MF, which needs to be evaluated with simulation results to ensure that it is not critical. This effect is even more noticeable when employing a non-OFDM fragmentation, which can give rise to spectral notches and thus resulting in a noise enhancement. When employing the LDACS A2A signal, we need to use a non-OFDM fragmentation in order to increase the instrumented range. More specifically, we assume a pulse repetition interval of 3 OFDM symbols. Improved versions of the RpF like the thresholded RpF (TRF) help reduce the impact of this effect. A specific implementation called the saturated TRF defines a minimum value for the amplitude of the spectrum samples, which reduces the impact of the spectral

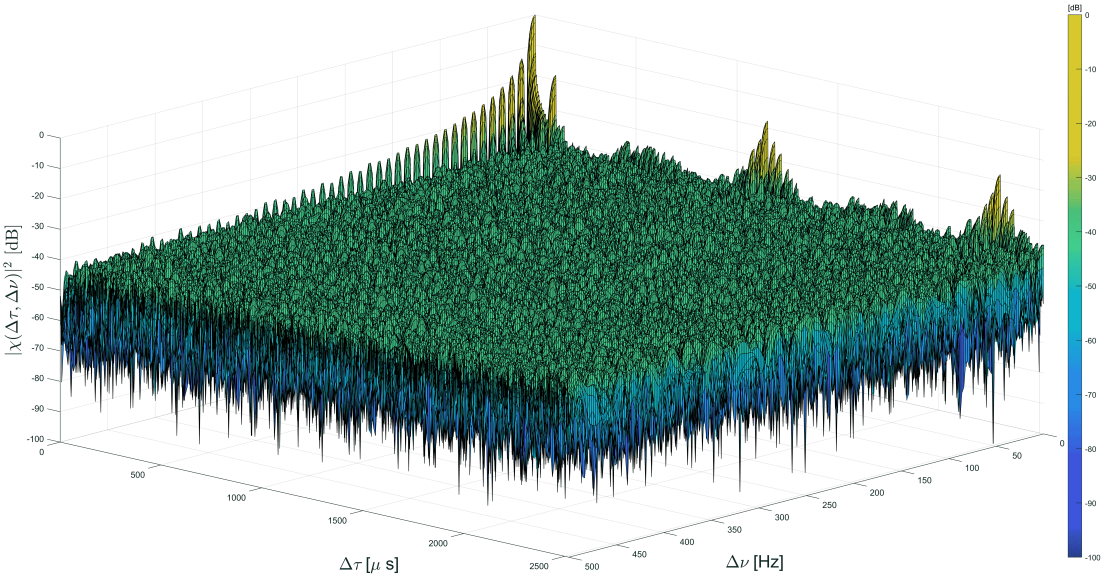
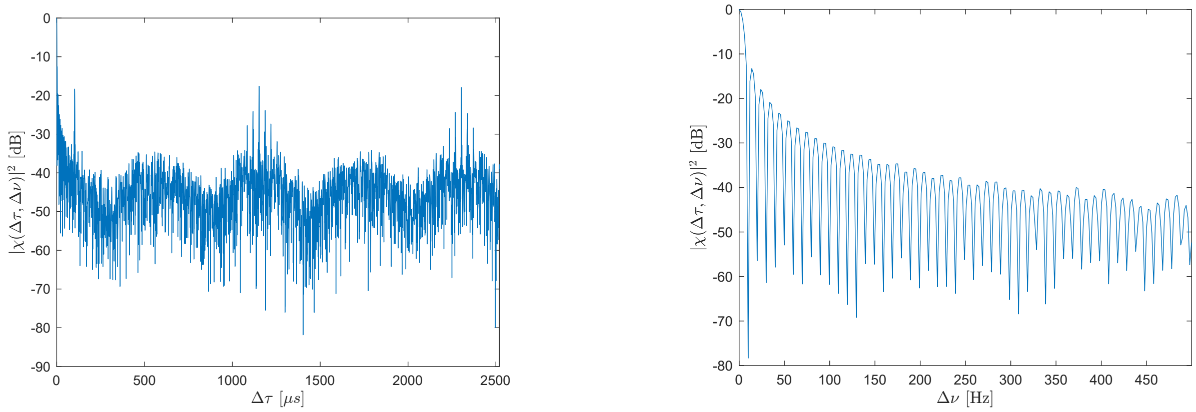


Fig. 6: LDACS A2A two-dimensional AF



(a) Zero-Doppler cut

(b) Zero-delay cut

Fig. 7: LDACS A2A two-dimensional AF cuts

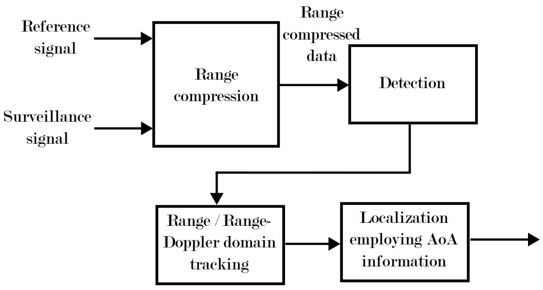


Fig. 8: Proposed signal processing high-level view

notches [16]. The overall sustained SNR loss when employing the saturated TRF is evaluated in the next section.

IV. SIMULATION RESULTS

In order to evaluate the signal processing loss associated with the use of the RpF and in particular the TRF, in this section we perform an initial simulation study. For this study, the same scenario as the one in [3], [17] is selected for comparison, which is based on real measurement campaign trajectories.

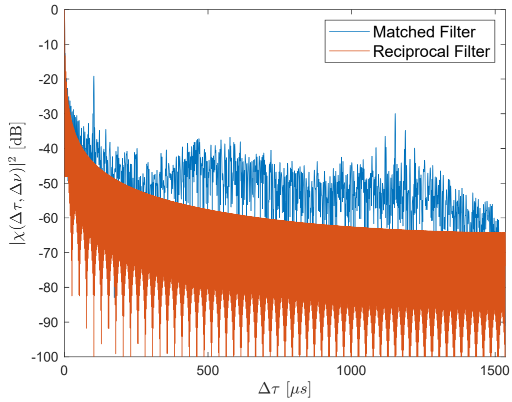
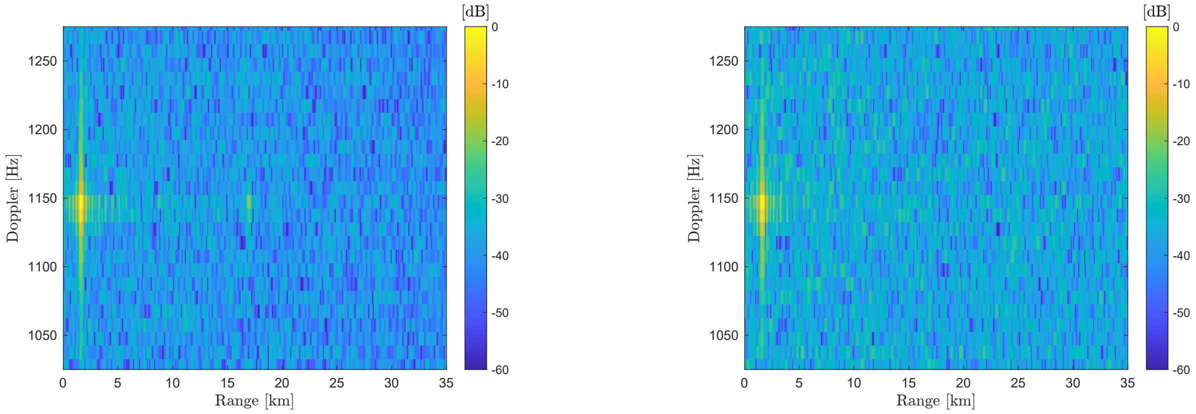


Fig. 9: Range compression response (zero-Doppler)

The scenario involves two non-accelerating aircraft separated by 1.64 km and flying towards each other at an airspeed of 300 $\mathrm{km/h}$. The Doppler shift generated by this geometry is 1.14 kHz accounting for the two-way path. The long P2P signal, associated with an integration time of 100 ms, is used in this



(a) MF

(b) RpF

Fig. 10: Range-Doppler map result

simulation for depicting both range and Doppler.

The result of the range compression stage in range-Doppler domain is shown in Fig 10, where the MF is depicted in Fig 10a and the RpF in Fig 10b. In Fig 10a, the signal ambiguities are visible above the noise floor, which further motivate the need for the use of the RpF in the range compression stage. The result, in Fig 10b, on the other hand, presents a higher noise floor, which is directly related to the SNR loss associated with the RpF. In particular, the use of the TRF results in an SNR loss of 7.5 dB, whereas it is able to eliminate the signal ambiguities. Given the high SNR loss, the impact of the RpF in the detection performance will be evaluated in future work, in addition to researching different alternatives to deal with the ambiguities that result in a lower SNR loss Lastly, we confirm that no target energy migration is present in the range-compressed result, despite evaluating such a dynamic scenario, thereby avoiding the need for migration compensation techniques.

V. CONCLUSION AND FUTURE WORK

In this work, we present a new airborne monostatic passive radar concept for providing a back-up for civil aircraft situational awareness. We evaluate the theoretical feasibility of the approach and point out the main challenges to be overcome. More specifically, we perform a link budget analysis and evaluate the characteristics of the signal AF. Our analyses show that the proposed concept presents strong maximum detection range capabilities, but strong ambiguities arise as a result of the signal structure. As such, the RpF is evaluated as a method to overcome this ambiguities, which is demonstrated to be a potential solution. Initial simulation results depict the SNR loss associated with the RpF.

Future work will focus on the full signal processing chain implementation, as well as investigating alternatives for the range compression stage. Lastly, the viability of performing an experimental measurement campaign will be evaluated.

REFERENCES

[1] V. Koch and R. Westphal, "New approach to a multistatic passive radar sensor for air/space defense," *IEEE Aerospace and Electronic Systems Magazine*, vol. 10, no. 11, pp. 24–32, 1995.

[2] K. Gronowski, P. Samczyński, K. Stasiak, and K. Kulpa, "First results of air target detection using single channel passive radar utilizing gps illumination," in *2019 IEEE Radar Conference (RadarConf)*, 2019.

[3] A. Filip-Dhaubhadel and A. A. Ragel, "GNSS-Based Non-Cooperative Air Traffic Situational Awareness," in *2023 IEEE International Radar Conference (RADAR)*, 2023.

[4] A. Arcangeli, C. Bongioanni, N. Ustalli, D. Pastina, and P. Lombardo, "Passive forward scatter radar based on satellite TV broadcast for air target detection: Preliminary experimental results," in *2017 IEEE Radar Conference (RadarConf)*, 2017, pp. 1592–1596.

[5] M. K. Bączyk, P. Samczyński, and K. Kulpa, "Passive ISAR imaging of air targets using DVB-T signals," in *2014 IEEE Radar Conference*, 2014, pp. 0502–0506.

[6] H. Sun, D. K. P. Tan, and Y. Lu, "Aircraft target measurements using a GSM-based passive radar," in *2008 IEEE Radar Conference*, 2008.

[7] J. Brown, K. Woodbridge, A. Stove, and S. Watts, "Air target detection using airborne passive bistatic radar," *Electronics letters*, vol. 46, no. 20, pp. 1396–1397, 2010.

[8] M. A. Bellido-Manganell, T. Gräupl, O. Heirich, N. Mäurer, A. Filip-Dhaubhadel, D. M. Mielke, L. M. Schalk, D. Becker, N. Schneckenburger, and M. Schnell, "LDACS flight trials: Demonstration and performance analysis of the future aeronautical communications system," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 58, no. 1, pp. 615–634, Feb. 2022.

[9] M. A. Bellido-Manganell, "Aircraft-to-aircraft communications: Channel modeling and data link design," Ph.D. dissertation, University of Ulm, 2025. [Online]. Available: https://oparu.uni-ulm.de/items/86a90a19-c0dd-4afe-a2e9-9833fb7442fa

[10] M. A. Bellido-Manganell and M. Walter, "Non-stationary 3D M2M channel modeling and verification with aircraft-to-aircraft, drone-to-drone, vehicle-to-vehicle, and ship-to-ship measurements," *IEEE Transactions on Vehicular Technology*, vol. 73, no. 5, pp. 6045–6060, May 2024.

[11] Y. Zhang and J. Qiao, "ADS-B radar system," U.S. Patent 7 414 567.

[12] M. I. Skolnik, *Introduction to radar systems.* McGraw-Hill Education, 2002.

[13] M. A. Richards, *Fundamentals of Radar Signal Processing, Third Edition*, third edition ed. New York, N.Y: McGraw Hill LLC, 2022.

[14] M. Glende, "PCL-Signal-Processing for Sidelobe Reduction in Case of Periodical Illuminator Signals," in *2006 International Radar Symposium*, 2006, pp. 1–4.

[15] P. Wojaczek, F. Colone, D. Cristallini, and P. Lombardo, "Reciprocal-Filter-Based STAP for Passive Radar on Moving Platforms," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 55, no. 2, pp. 967–988, 2019.

[16] J. T. Rodriguez, F. Colone, and P. Lombardo, "Supervised reciprocal filter for ofdm radar signal processing," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 59, no. 4, pp. 3871–3889, 2023.

[17] A. A. Ragel and A. Filip-Dhaubhadel, "Multistatic Data Fusion for GNSS-Based Air-to-Air Passive Radar," in *2024 International Radar Conference (RADAR)*, 2024, pp. 1–6.