MIMO-FM: A Solution to Estimate Target Elevation with Passive FM Radar

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***Abstract*—In this paper, we deal with the problem of estimating the target elevation in passive FM radar. Due to the large wavelength of such systems, accurate beamforming at the reception side would require unpractical large reception devices of several meter height. We instead propose to solve this problem by means of a MIMO-like system that exploits the vertical structure of large existing FM broadcasters transmitting different frequency subbands with antennas located at different heights. We provide the MIMO-FM ambiguity function in that context and details the specific reception processing enabling to retrieve the elevation parameters. The feasibility of such a MIMO-FM system is proved on real data experiment using transmitting antennas located on the Eiffel Tower in Paris.**

I. Introduction

A Passive Coherent Location (PCL) device, also known as passive radar, exploits civilian transmitters of opportunity in order to detect the surrounding targets [1], [2]. In the VHF-UHF frequency band, the civilian transmitters that can be exploited for passive radar purposes are either the analogue FM transmitters [3] around 100 MHz or the DAB-DVB (Digital Audio/Video Broadcasting) transmitters [4] around 200 MHz and 500 to 800 MHz.

In this paper, we consider the particular FM transmitter case. For such a frequency band, the corresponding wavelength is equal to 3 m. Thus an FM PCL reception device used to estimate the elevation of a target should present a height of several meters. Such a high system cannot always be considered for practical purposes, and thus target elevation estimation cannot be provided by a classic PCL receiver via reception beamforming.

Fortunately a different solution may be considered, inspired by the coherent MIMO radar methodology that has recently appeared in the literature [6], [7], [8], [9]. A coherent MIMO radar is an active device that transmits different waveforms through different transmitting antennas. For sufficiently orthogonal waveforms, the phase information carried by the different transmitted signals can be retrieved at the reception side by separating the signal contributions via a filter bank composed of the different transmitted waveforms. Angular estimation can thus be obtained at the reception from the sole coherent processing of the different transmitters, even with a single reception antenna. In particular, if these transmitters are located at different heights, then some information on the target elevation can be retrieved.

Based on this observation, we propose in this paper a new passive FM radar strategy that exploits the vertical structure of large existing FM broadcasters jointly with a specific MIMO processing in order to provide a direct estimation of the elevation of the surrounding targets: we will call MIMO-FM such a system. In particular, we will consider situations where antennas at different elevations broadcast signals at different frequency subbands, so that the transmitted signals can be considered orthogonal. Such a typical system can be observed at the top of the Eiffel Tower in Paris, and is presented in Figure 1. Interestingly a passive radar system exploiting several FM signals at different frequency subbands transmitted by colocated broadcasters has already been considered in the literature [10] but it did not exploit a difference in elevation of the different transmitters to recover the target elevation information.

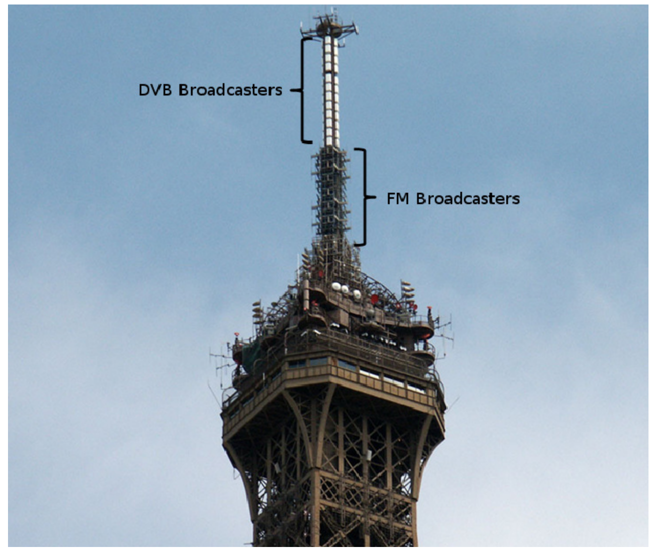

Fig. 1. FM and DVB broadcasters at the top of the Eiffel Tower [5].

The MIMO-FM ambiguity function obtained at the output of a classic matched filter processing presents some specificities. In particular, as for the classic active coherent MIMO radar [11] but to a much higher degree, the MIMO-FM ambiguity function presents a strong delay/angle coupling that will be discussed here, and that requires some specific processing. In short, the proposed processing consists first in performing target detection via a classic passive radar processing using a receiving array with several dislocated transmitting pylons, and then to apply, from time to time in a regular but not continuous fashion, a specific MIMO-FM processing in order to estimate the elevation for the detected targets by reallocating some of the pylon channels to a multi-frequency multi-antenna pylon. This approach enables to retrieve a rought estimation of the elevation parameter, and provides an additional interesting by-product in the form of an improvement of the range resolution due to the use of a much larger overall transmission bandwidth provided by the different frequency subbands used in the processing. The feasibility of such a MIMO-FM system is proved on a real data experiment using transmitting antennas located on the Eiffel Tower in Paris, and targets of opportunity provided by aircrafts landing at Orly airport in the South of Paris.

This paper is organized as follows: in section II, we present the expression of the received signal, carefully taking into account the difference of frequencies between the transmitters, and we derive the corresponding MIMO-FM ambiguity function. Then in section III, we present the proposed MIMO-FM processing that enables target elevation estimation. In section IV, we discuss the strong range/angle coupling observed in the MIMO-FM ambiguity function. Finally we provide experimental results in section V.

II. MIMO-FM PROCESSING

A. Received signal

Let us consider N_T FM transmitters located at different heights $(h_n)_{n\in\{0,\dots,N_T-1\}}$ on the same pylon, as presented in Figure 2. The position h_0 of the first transmitter will be used as the reference and we will denote by $\Delta h_n = h_n - h_0$ the relative height between the reference transmitter and the n^{th} transmitter. Let us then denote by $s_n(t)$ the baseband FM signal broadcasted by transmitter n and by f_n the corresponding carrier frequency, where $f_n \neq f_k, \forall n \neq k$, furthermore assuming that the different FM signal bandwidths do not overlap.

Let us now consider that the PCL reception device is an array composed of N_R antennas, located at positions $(\mathbf{x}_{R,m})_{m\in\{0,\dots,N_R-1\}}$ in Cartesian coordinates. Assuming a target located at a distance $d_{T,n}(t)$ from the n^{th} transmitter, the signal received by reception antenna m can be written:

$$s_{R,m}(t) = \sum_{n=0}^{N_T-1} s_n\left(t-\tau_{n,m}(t)\right) e^{j2\pi f_n (t-\tau_{n,m}(t))}, \quad (1)$$

where $\tau_{n,m}(t) = \tau_{T,n}(t) + \tau_{R,m}(t)$ represents the overall delay along the path between the n^{th} transmitter, the target and the m^{th} reception antenna. $\tau_{T,n}(t) = \frac{d_{T,n}(t)}{c}$ represents the delay between the n^{th} transmitter and the target, and c denotes the speed of light. Assuming that the target is located at an elevation angle θ_T defined with respect to the transmitter antenna and assumed constant during the integration time, the distance $d_{T,n}(t)$ can then be written as:

$$\tau_{T,n}(t) = \tau_{T,0}(t) + \frac{\Delta h_n \sin\theta_T}{c}. \quad (2)$$

On the other side, denoting by $\mathbf{u}_R$ the direction vector for the wave propagation between the target and the radar, the target-receiver delay $\tau_{R,m}(t)$ can be itself decomposed as:

$$\tau_{R,m}(t) = \tau_{R,0}(t) + \frac{\mathbf{x}_{R,m}^T \mathbf{u}_R}{c}, \quad (3)$$

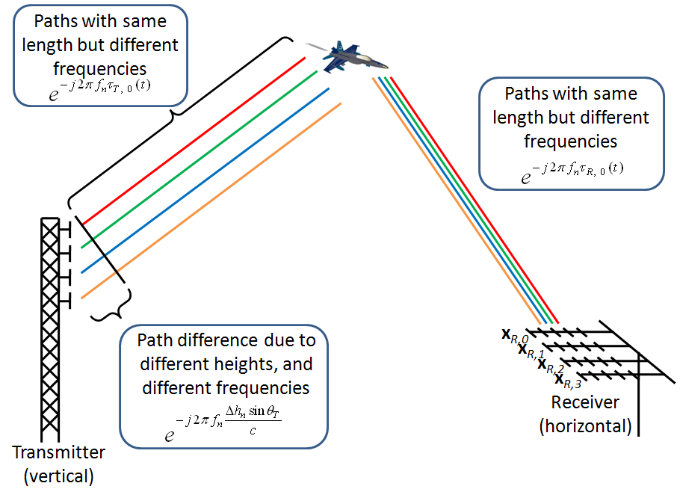

Fig. 2. Geometric configuration for the MIMO-FM passive radar. Since the path difference at the reception side is due to the horizontal positions of the different receiving antennas, it does not impact the elevation estimation and was not represented here.

where the second term $\mathbf{x}_{R,m}^T \mathbf{u}_R / c$ corresponds to the classic term allowing azimuth estimation according to the receiving site. Inserting these expressions in (1) with the reference delay $\tau_{0,0}(t) = \tau_{T,0}(t) + \tau_{R,0}(t)$ computed at the reference transmitter antenna $n = 0$ and reference receiver antenna $m = 0$,

$$\begin{aligned} s_{R,m}(t) &= \sum_{n=0}^{N_T-1} s_n\left(t-\tau_{0,0}(t)\right) e^{j2\pi f_n (t-\tau_{0,0}(t))} \\ &\quad \times e^{-j2\pi f_n \frac{\Delta h_n \sin\theta_T}{c}} e^{j2\pi f_n \frac{\mathbf{x}_{R,m}^T \mathbf{u}_R}{c}}, \end{aligned} \quad (4)$$

where the residual delays $\frac{\Delta h_n \sin\theta_T}{c}$ and $\frac{\mathbf{x}_{R,m}^T \mathbf{u}_R}{c}$ have been neglected in the baseband signal contribution since it is very small compared to the main delay contribution $\tau_{0,0}(t)$.

Finally, assuming that the target velocity is constant, the overall reference delay $\tau_{0,0}(t)$ can be written as:

$$\tau_{0,0}(t) = \tau_0 + \frac{v_0}{c} t, \quad (5)$$

where τ_0 and v_0 are the delay and the velocity of the target at the reference configuration $(n,m) = (0,0)$. Once again neglecting in the baseband signal term the doppler compression induced by $\frac{v_0}{c}t$, i.e. approximating $s_n\left(t-\tau_{0,0}(t)\right) \approx s_n\left(t-\tau_0\right)$, the received signal is finally provided by:

$$\begin{aligned} s_{R,m}(t) &= \sum_{n=0}^{N_T-1} s_n\left(t-\tau_0\right) e^{j2\pi f_n (t-\tau_0)} \\ &\quad \times e^{-j2\pi f_n \frac{v_0}{c} t} e^{-j2\pi f_n \frac{\Delta h_n \sin\theta_T}{c}} e^{j2\pi f_n \frac{\mathbf{x}_{R,m}^T \mathbf{u}_R}{c}}. \end{aligned} \quad (6)$$

B. MIMO-FM ambiguity function

The reception processing consists in applying a matched filter to the delay, target radial velocity and angle parameters. The output of such a processing for desired values τ, v, θ and $\mathbf{u}$ that correspond respectively to the delay, radial velocity, elevation and azimuth angle, provides the MIMO-FM ambiguity function. Exploiting the orthogonality of the

$$A(\tau, v, \theta, \mathbf{u}) = \sum_{n=0}^{N_T-1} \sum_{m=0}^{N_R-1} e^{-j2\pi f_n \frac{\Delta h_n(\sin\theta_T - \sin\theta)}{c}} e^{j2\pi f_n \frac{\mathbf{x}_{R,m}^T(\mathbf{u}_R - \mathbf{u})}{c}} \int s_n(t-\tau_T)\, s_n^*(t-\tau)\, e^{-j2\pi f_n(\tau_T-\tau)} e^{-j2\pi f_n \frac{v_T - v}{c} t}\, dt \tag{5}$$

signals transmitted in the different subbands, this MIMO-FM ambiguity function is given by (5) at the top of the page, and is illustrated in Figures 4 and 5 for two different configurations.

Clearly the MIMO-FM ambiguity function presents very specific features that differs from the classic MIMO ambiguity function encountered in the literature:

- The reception processing, corresponding to the term $e^{j2\pi f_n \frac{\mathbf{x}_{R,m}^T(\mathbf{u}_R - \mathbf{u})}{c}}$, cannot be decoupled from the other parameters since it depends on the transmitted frequency. This means in particular that the reception beamforming must be performed before the transmission beamforming, whereas in classic MIMO radar, it can be performed either first at the output of the reception antennas or at the end of the processing chain.
- Similarly, the Doppler processing, that corresponds to the terms $e^{-j2\pi f_n \frac{v_T - v}{c} t}$, cannot be either decoupled from the other parameters since it also depends on the transmitted frequencies $(f_n)_{n\in\{0,\ldots,N_T-1\}}$. Thus it must be performed before the transmission beamforming. Of course, this Doppler processing can be classically performed by splitting the received signal into N_p subpulses of duration T_p and by simply compensating the phase due to the Doppler shift for each subpulse.
- However it is not possible to write this Doppler processing by replacing the target radial velocity with a corresponding Doppler frequency. Indeed since each transmitter is associated to a different frequency, this Doppler frequency differs from transmitter to transmitter. One must then perform the Doppler matched filter directly on the target radial velocity.
- The presence of many phase terms induces possibly strong coupling between the different parameters. This will be discussed thereafter.

III. MIMO-FM PROCESSING

The MIMO-FM ambiguity function provides a local delay resolution related to the overall bandwidth spanned by the different subbands, typically more than 1MHz in our experimental setting, which is much greater than the bandwidth provided by one classic FM channel (75kHz at the very most). This means first that the signal should be oversampled at a sampling frequency larger than this overall bandwidth in order to enable the elevation estimation - otherwise the phase information provided by the transmitter elevation would be lost due to the rotating phase of the delay - and second that this oversampling dramatically increases the computational load if performed on the full received signal, due to the strong increase in bandwidth when considering all frequency subbands.

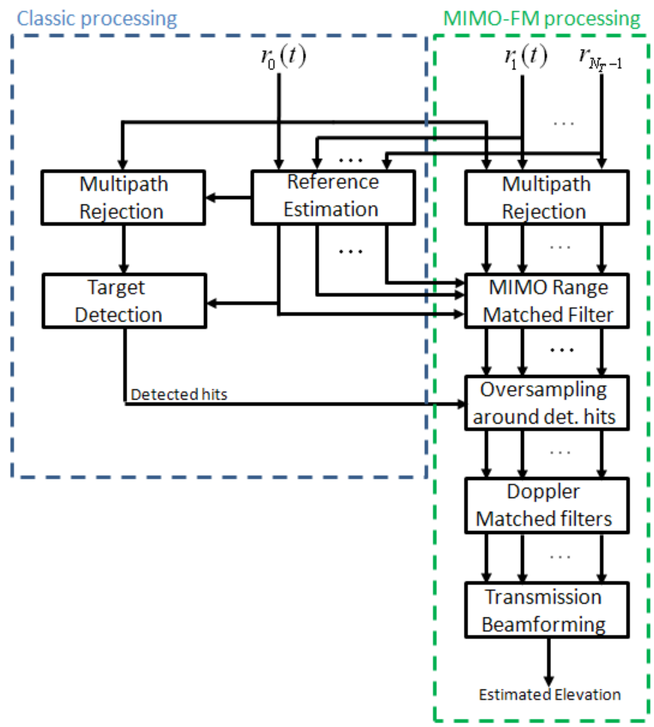

Fig. 3. Proposed MIMO-FM processing: first the classic processing is performed on one frequency to enable reference signal estimation, multipath rejection and target detection. Then for each detected hit, range matched filter to each signal corresponding to a considered frequency is performed, the output is oversampled around the estimated range, doppler matched filter is performed and transmission beamforming to obtain the elevation estimation. Here reception beamforming has been omitted for simplicity.

We thus propose a different strategy, based on the idea that the MIMO-FM framework is only considered here for estimating an additional parameter that cannot classically be obtained and not for detection purpose. Thus, instead of performing the MIMO-FM processing over the whole received signal, it is more convenient to perform classic passive FM radar processing first, recover the detection hits, and then perform locally around the estimated delay of each detected hit the MIMO-FM processing. In that way, oversampling is required only on a limited range around the estimated delay. Note also that, as for the elevation estimation and once target detection has been performed, one can apply the processing only on the output of one single reception antenna (of course after rejection of the direct path and the multipaths), unless the subsequent SNR loss cannot be afforded.

The MIMO-FM proposed processing is summarized in Figure 3. We omitted here for simplicity the reception beamforming.

IV. RANGE/ANGLE COUPLING

If we decompose the n^{th} transmitted frequency with respect to the reference one f_0 as: $f_n = f_0 + \Delta f_n$, and denote $\Delta\tau = \tau_T - \tau$, then the phase terms depending on the delay difference in (5) can be rewritten as:

$$e^{-j2\pi f_n(\tau_T-\tau)} = e^{-j2\pi f_0 \Delta\tau} e^{-j2\pi \Delta f_n \Delta\tau}. \quad (7)$$

Inserting this in (5) enables to notice that strong range/angle coupling and ambiguities arise due to the combination of the following phases

$$\sum_{n=0}^{N_T-1} e^{-j2\pi f_n \frac{\Delta h_n(\sin\theta_T - \sin\theta)}{c}} e^{-j2\pi \Delta f_n \Delta\tau}$$

that mixes terms due to the target elevation, and terms due to the target delay. These ambiguities cannot be avoided and one must then cope with them, for instance by chosing the less penalizing set of frequencies. Indeed the ambiguity positions strongly depend on the repartition of the frequencies over the transmitting antennas/heights. Changing one single frequency may lead to a different ambiguity pattern. An exemple of such a coupling is presented in Figure 4. Clearly the range/elevation domain presents many strong ambiguities. However we can notice that the domain of interest for passive FM radar is located for low/medium altitude targets since high altitudes are not illuminated by the FM transmitters. Furthermore, passive components are considered as gap-fillers and consequently their potentiel interest is generally restricted to low altitude targets. Thus it is not necessary to consider elevations above a given altitude. In that limited domain of interest, most ambiguities are range ambiguities that occur at the same elevation. Thus, whereas the resulting range estimate may be ambiguous, the elevation parameter is correctly estimated. Still, in the example provided here, we notice that the width of the mainlobe does not permit a good elevation estimation accuracy, and also some additionnal ambiguities occur near the limit of the domain of interest, only around 1 dB below the maximum. Thus in such a configuration, errors on the elevation estimation may still arise.

Clearly, good performance of the MIMO-FM system will relie first on a carefully chosen set of heights and frequencies. We provide in the following different examples of such configurations. The first example, presented in Figure 5 is a simple example where the considered frequencies have been chosen so as to be quite linearly dependent with the transmitted height. Clearly such a choice should be avoided since it leads to a very strong range/angle coupling that would lead to a very poor elevation estimation. It appears also that a configuration with only 4 transmitted frequencies may hardly provide interesting outputs. In the experimental setting, we considered thus 6 frequencies.

V. EXPERIMENTAL DATA

Our MIMO-FM experimentations have been performed during Spring 2017. The FM transmitting antennas recorded during the experiment were located on the Eiffel tower, at different heights (see 1). 6 frequency subbands were selected for the recorded data; these frequencies were 102.7, 103.1, 102.3, 101.9, 103.9 and 103.5 MHz. The corresponding heights of the FM antennas are 291, 294, 299, 304, 294 and 304 m

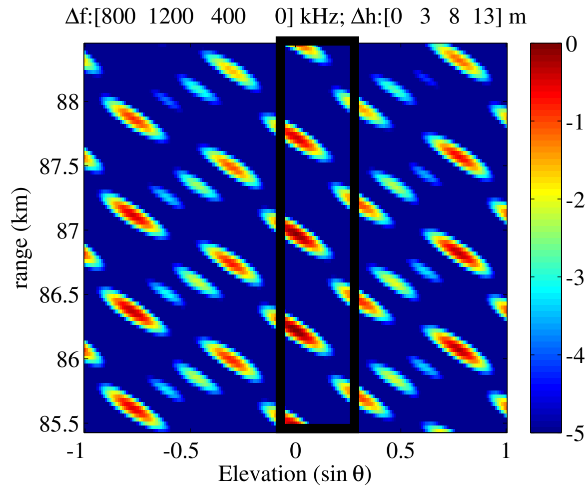

Fig. 4. Ambiguity function for $N_T = 4$ transmitters located at heights $[291, 294, 299, 304]$ m, and transmitting respective frequencies $[102.7, 103.1, 102.3, 101.9]$ MHz. The target is present at range 86.22 km and elevation 0. The range domain considered corresponds to the range cell of the target. The black rectangle represents the domain of interest, i.e. low altitude targets.

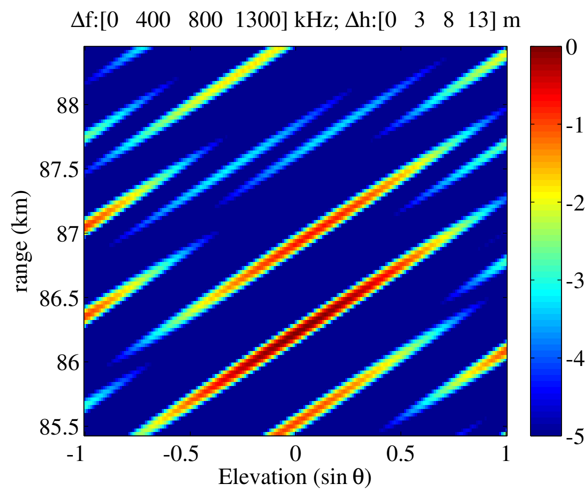

Fig. 5. Ambiguity function for $N_T = 4$ transmitters located at heights $[291, 294, 299, 304]$ m, and transmitting respective frequencies $[101.9, 102.3, 102.8, 103.3]$ MHz. The target is present at range 86.22 km and elevation 0. The range domain considered corresponds to the range cell of the target.

above ground, thus providing a transmitter length of 13m. , thus providing an overall bandwidth of 2 MHz.

The reception array was composed of 6 antennas located on the top of one building on the ONERA site at Palaiseau near Paris and near the Orly airport (see Figure 7). Antennas were disposed so that the Eiffel tower was roughly in the normal of the array while the Orly airport was roughly in the axis of the array. Only four of the six antennas were used for the processing. Due to a limited sensitivity, the reception device only enabled to detect close airplanes. However it enabled to detect airplanes landing at Orly airport. One ADSB receiver was used to obtain the ground truth for these airplanes.

For the data set under consideration in this article, 7

Fig. 6. Reception device of the experimental setting. Although the reception array was composed of six antennas, only four were used for the processing.

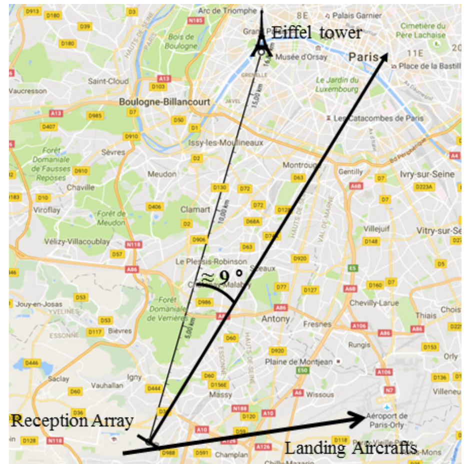

Fig. 7. Geometry for the experimental setting. The reception device is located in south of the Parisian suburban area, at a few kilometers west from the Orly airport. The transmitter (Eiffel tower) is located in a direction of approximately 9 with respect to the normal of the reception array. Aircrafts landing at the Orly airport pass in the South near the reception device.

planes were detected. 5 of these planes were landing at Orly airport while the two others were flying at higher altitudes. These differences between the targets enabled to check the validity of the elevation estimation. The application of the proposed MIMO-FM processing provided the estimation results in doppler, range and elevation that can be seen in Figures 8, 11 and 10, that are compared to the ground truth provided by the ADSB receiver. It can be seen on these results that:

- the Doppler parameter is well estimated, as expected for an FM passive receiver using an integration time of 1s.
- the range parameter is very accurate, especially when compared to the range estimation provided when applying a classic processing only on one subband as provided in Figure 9: clearly the proposed MIMO-FM processing enabled here to benefit from the overall bandwidth provided by the four recorded FM channels. The output range resolution is much higher than what can be expected for an FM passive receiver
- the elevation parameter is not very accurately estimated, which was expected from the experimental setting (the transmission antennas are only 13m apart but the target located at almost 20km from the transmitter) but is still quite interesting: indeed we can observe that the estimated parameters are very coherent with the approximate ground truth provided by the ADSB data. Extracted hits corresponding to the five landing aircrafts provide elevation estimates between 1 and 2, which corresponds indeed to very low altitudes. On the contrary, extracted hits from the two other targets present elevation estimates much higher, and also very coherent with the ADSB data. A slight estimation bias may be observe for all these estimates, but it may be explained by the poor quality of the altitude estimation provided by the ADSB receiver itself, which is based on atmospheric pressure measurements and not on absolute altitude measurements. Overall the proposed MIMO-FM enabled us to get a rough estimation of the aircraft altitude without the need for building a very high reception antenna!

VI. Conclusion

In this article, we have proposed a passive MIMO-FM system that enables target elevation estimation by exploiting the different heights of several transmitters broadcasting signals at different frequencies. The MIMO-FM ambiguity for such a system is derived, and a MIMO-like processing is considered so as to perform transmission beamforming and retrieve the target elevation according to the transmitting pylon. Although this MIMO-FM ambiguity function provides strong range/angle coupling, it nevertheless enables to retrieve a rough estimate of the target elevation. The feasibility of the system is demonstrated on real data experiment set using transmitters located on the Eiffel Tower. In this experiment, not only the elevation parameter could be retrieved, but also the range parameter estimation could be improved thanks to the exploitation of the total bandwidth provided by the four frequency subbands considered.

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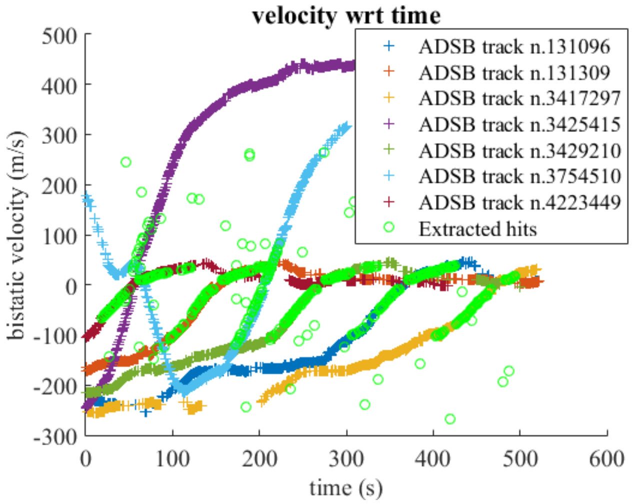

Fig. 8. Evolution of the target velocity with respect to time, as provided by the ADSB measurements, and corresponding extracted hits estimated from the MIMO-FM processing.

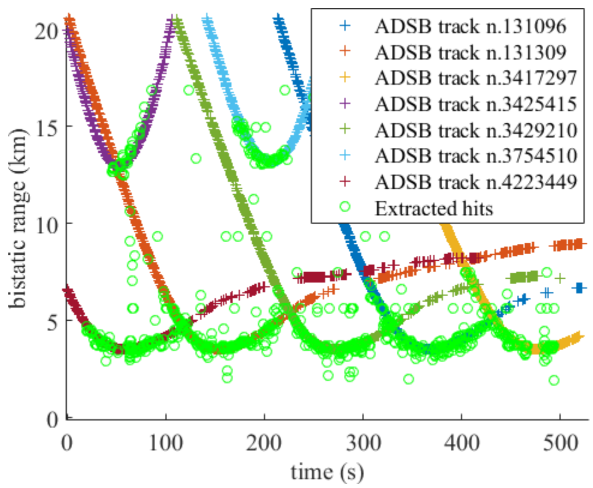

Fig. 9. Evolution of the target range with respect to time, as provided by the ADSB measurements, and corresponding extracted hits estimated from the classic FM processing. In that case, the range estimation is worse than in the MIMO-FM case (see Figure 11), which is expected since only one subband with small bandwidth is used for the estimation.

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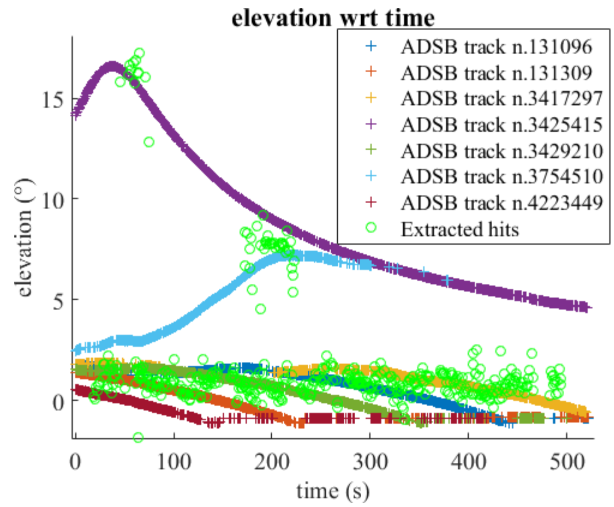

Fig. 10. Evolution of the target elevation with respect to time, as provided by the ADSB measurements, and corresponding extracted hits estimated from the MIMO-FM processing. The elevation estimation presents a relatively high variance, but clearly the MIMO-FM processing enabled to discriminate targets landing at Orly airport from other targets flying higher.

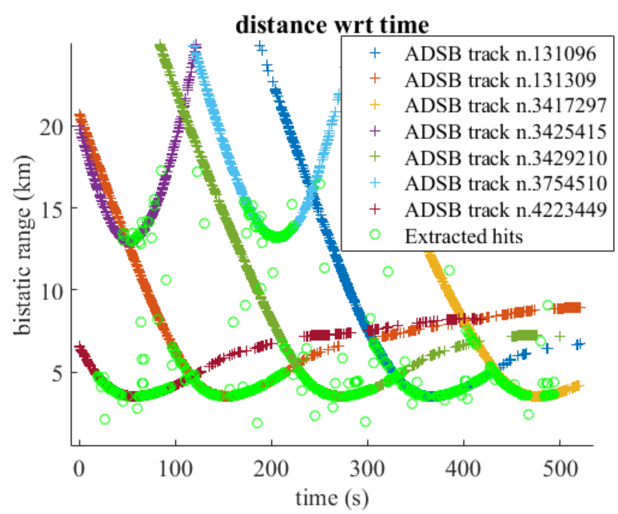

Fig. 11. Evolution of the target range with respect to time, as provided by the ADSB measurements, and corresponding extracted hits estimated from the MIMO-FM processing. The range parameter is very accurately estimated, taking benefit from the overall MIMO-FM bandwidth.