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DOA estimation of an Unmanned Aerial Vehicle with few sensors in the case of disturbing sources

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ABSTRACT

The increasing use of Unmanned Aerial Vehicles (UAVs) for several purposes can bring some concerns around sensitive sites. It is thus necessary to be able to locate drones when they become a threat. Thanks to many recent studies, the use of acoustical methods exploiting the sound emitted by UAVs enables to estimate the position or direction of the source. Sound produced by drones is still predominant and hence is a good way to compensate technological difficulties of other methods like optical, electromagnetic, or radar. Some sensitive sites could be situated around noisy environment where perturbing sources can be present. These perturbing sources can be produced by planes, cars, birds, etc. Experimental measurements have been conducted for this study to evaluate the performance of temporal beamforming coupling with the time-frequency representation of the focused signal. This enables us to take into account the UAV's acoustic signature. These measurements were carried out in an environment where some noise sources were present such as birds chirping and car passing. Beamforming with time-frequency representation has the advantage of providing a DOA estimation with only a few spectral contents considered, which can be particularly helpful in this kind of situations.

Keywords: Drones, Acoustic Source Localization, Beamforming, Microphone Array, Time-Frequency Representation

1 INTRODUCTION

During recent years, Unmanned Aerial Vehicles (UAVs) have been increasingly used to achieve various purposes. Among the multiple possible applications for these vehicles, some popular uses are: aerial filming, package deliveries, surveillance, inspection, and victim search and rescue. A recent study have shown several applications of UAV in the context of future smart cities[1]. These smart cities will use emerging technologies like Internet of Things, robotics, and others to get a better management of their cities. In this study, the contribution of UAVs along these technologies is addressed as well as the possible challenges that could appear. Besides the numerous benefits of UAVs, their use can also be threats in lots of ways. There could be safety threats on sensitive sites like airports [2] where an UAV could collide with an airplane. Nuclear facilities are also concerned by safety and privacy threats [3]. Two types of situations can occur with an UAVs' attack. In the first situation the drone is simply controlled by the pilot. But in the second situation, an ordinary flying UAV can be hacked and controlled by another pilot to perform an attack. In [4], the second situation is addressed as well as other issues with UAVs' security and privacy issues. In order to react to these threatening behaviors, it is necessary to know the UAV's position or direction of arrival. Many methods exist and can be used either separately or simultaneously[5, 6]. Optical methods use cameras to detect and track a drone but can be limited by meteorological conditions[7]. Electromagnetic methods use the detection of signals exchanged between the UAV and the controller but are not usable with autonomous drones[8]. Sound emitted by UAVs

can also be exploited by using a microphone antenna to obtain its direction of arrival (DOA) but these methods can be limited in noisy environment. A good way to enhance the possibility of locating a UAV is to combine multiple methods. In [9], an optronic system is combined with an acoustic system to perform the detection and the localization of drones using a deep learning approach. The work presented here will focus on an acoustic system to perform the UAV's direction of arrival estimation. Several studies have shown that UAVs produce a significant and particular noise [10, 11]. It is thus possible to use the acoustic signature to filter signals measured by a microphone array to enhance the DOA estimation [12]. An alternative presented here uses a time-frequency representation of a beamformer's output to select time-frequency bins associated to the UAV [13]. The aim of this work is to evaluate the performance of this process with perturbing sources like birds chirping or car passing.

The work is presented as follows: Part 2 presents Delay and Sum Beamforming and the use of the time-frequency representation approach. Part 3 describes the measurement set-up with the array geometry and the trajectories performed by the drone. Part 4 presents the results of DOA estimation for the situations considered. Part 5 conclude and presents some perspectives.

2 PRESENTATION OF THE DOA ESTIMATION METHODS

2.1 Delay and Sum Beamforming

Delay and Sum Beamforming (DSB) [14] is a well known method exploiting signals from a microphone array. Given the different positions of the microphones, the signal produced by the UAV will arrive at different times to the microphones. By realigning in time all these signals, it is possible to focus the signal in one direction. A reference microphone is chosen to calculate delays in regards to this reference. The 3D space is sampled with a spherical coordinate system, φ is the azimuth, θ is the elevation, and r is the distance between the origin and the source. In far field, a simplification can be made by considering a plane waveform. For this study, this plane wave model will be used which enables to search the source's DOA among the directions $\Omega = (\varphi, \theta)$. For one direction Ω , a set of delays is calculated and the focused signal is obtained by summing all the delayed signals. The DOA is given by the direction which gives the maximum energy of the focused signal.

2.2 Time-frequency Representation

In order to take into consideration the UAV's acoustic signature, the time-frequency representation (TFR) approach transforms the focused signal in one direction into a time-frequency plane. This time-frequency transformation is carried out with the Short Time Fourier Transform (STFT). It is then possible to select time-frequency bins associated with the UAV. The acoustic signature of UAVs have the particularity of having an harmonic structure. Two phenomena are present in this type of signals, the rotors' rotation which gives odd harmonics in the case of a two-blade drone, and the blade passing which gives even harmonics[12]. Because of the noise, only even harmonics are generally presents. A pitch tracking algorithm is thus used to detect the blade passing frequency of the drone. A number of even harmonics n_h is chosen to compute the energy of the corresponding time-frequency bins. To have more time-frequency bins, a bandwidth is defined to take bins around harmonics. This bandwidth is defined to be varying with the harmonic frequency such as $\Delta f = \frac{f_{detect}}{Q}$, with Q a factor determining the width, and f_{detect} the blade passing frequency. In this way, all the time-frequency bins in $[f_{detect} * i * (1 - \frac{1}{2Q}); f_{detect} * i * (1 + \frac{1}{2Q})]$ are selected, $i = 1, \dots, n_h$.

The pitch tracking algorithm chosen to detect the blade passing frequency is called the Spectral Harmonic Correlation (SHC)[15]. This algorithm calculates the correlation between one frequency and a chosen number of multiple of this frequency. It is thus possible to obtain multiple candidates of the blade passing frequency. The frequency that has the maximum harmonic correlation is the estimation of the blade passing frequency. However, in some cases, computing energy with the content selected using the SHC maximum does not ensure continuity between two estimations. In this case, another candidate is chosen until the continuity with the previous DOA estimation is reached.

3 MEASUREMENT SET-UP

3.1 Array Geometry

The microphone antenna used is a 10 microphone array designed in [12] to obtain a bandwidth of [220.5, 3430] Hz. Figure 1 shows the disposition of microphones and also the coordinate system used to position a source in the 3D space. The reference microphone is placed at the center and three microphones are distributed on three axes with three different spacings (Equation 1). The first spacing is $l_1 = 5$ cm which is linked to the high frequency limit. The second spacing is $l_2 = 20$ cm, and the last is $l_3 = 110$ cm which is linked to the low frequency limit.

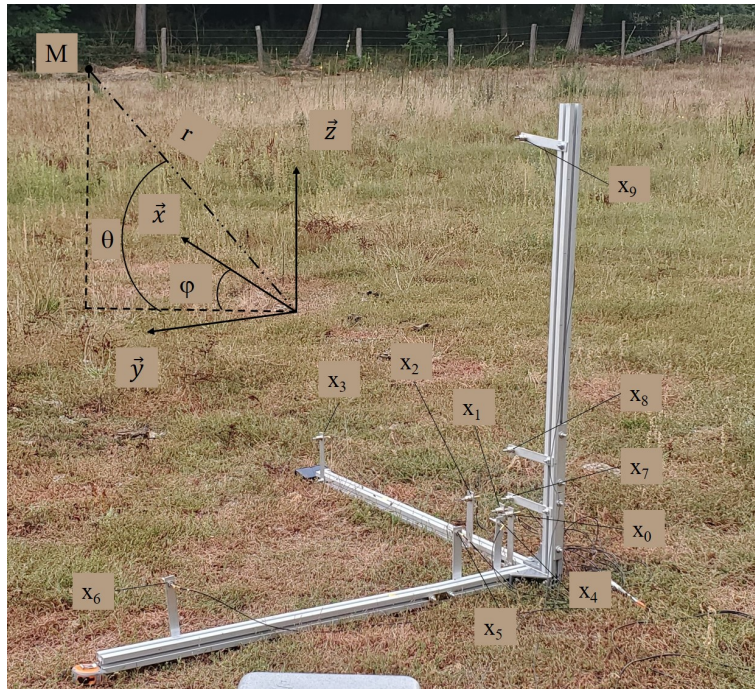


Figure 1. Microphone array disposition and coordinate system used.

$$\begin{aligned}
 \|\mathbf{x}_1\| &= \|\mathbf{x}_4\| = \|\mathbf{x}_7\| = l_1, \\
 \|\mathbf{x}_2\| &= \|\mathbf{x}_5\| = \|\mathbf{x}_8\| = l_2, \\
 \|\mathbf{x}_3\| &= \|\mathbf{x}_6\| = \|\mathbf{x}_9\| = l_3.
 \end{aligned} \tag{1}$$

3.2 TFR Parameters and Trajectories

DOA estimation is performed on sections of 3000 points, using 2048 points for beamforming. Spatial sampling is carried out with a resolution of $(4^\circ, 2^\circ)$, which corresponds to the azimuth and elevation, and with a distance of $r=1$ m between the source and the reference microphone. SHC is performed with 8192 points and 5 harmonics for the correlations. TFR is operated by selecting 5 harmonics with a factor $Q=8$. Two trajectories have been performed by a DJI Phantom IV to evaluate the performance of the TFR approach. In the first configuration, the drone performs three horizontal flights at heights of around 6, 10 and 14 m. During this flight, many bird chirps can be heard. Figure 2 shows the spectrogram of the reference microphone for this trajectory. The harmonic structure of the drone is visible particularly below 2 kHz. Above 2 kHz, all the bird chirps are noticeable by vertical lines around 3 kHz and above. In the second configuration, the drone performs a small and a large circle above the antenna at a height around 15 m. Figure 3 shows the spectrogram of the reference microphone. Bird chirps are present in the same frequency range but are less noticeable. The spectrogram also

shows a car passing at the end of the trajectory.

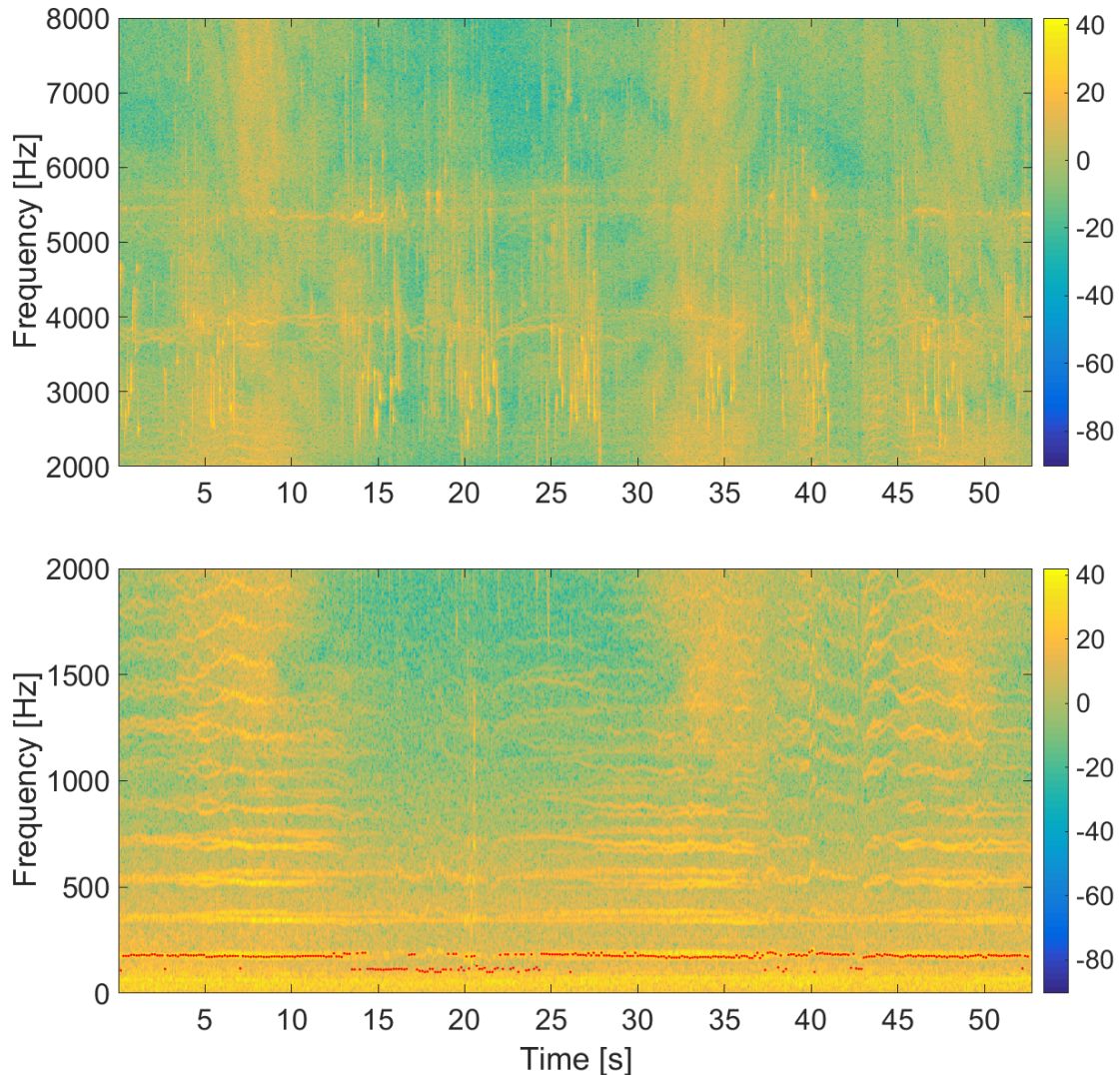


Figure 2. Spectrogram of the reference microphone for the first trajectory between 2 kHz and 8 kHz (top) and between 0 and 2 kHz (bottom) (red points are blade passing frequencies detected with SHC).

4 RESULTS

Azimuth and elevation vs time results are presented in Figure 4 for the first trajectory, with classical DSB and the TFR approach in comparison with a GPS embedded in the drone. Results in azimuth for classical DSB show several fluctuations around the GPS reference and particularly at the beginning, estimations are far from the GPS. Between 10 s and 30 s, estimations are fluctuating with a symmetry centered on 0. This symmetry is due to the fact that the main lobe and the secondary lobe are symmetric with respect to 0 and their level is very close. The TFR approach performs better than classical DSB with less fluctuations overall. However, the confusion between the two symmetrical lobes is still present between 10 s and 28 s. The GPS has an uncertainty around 3 meters which can explain the constant bias between the GPS and the results. In elevation, classical

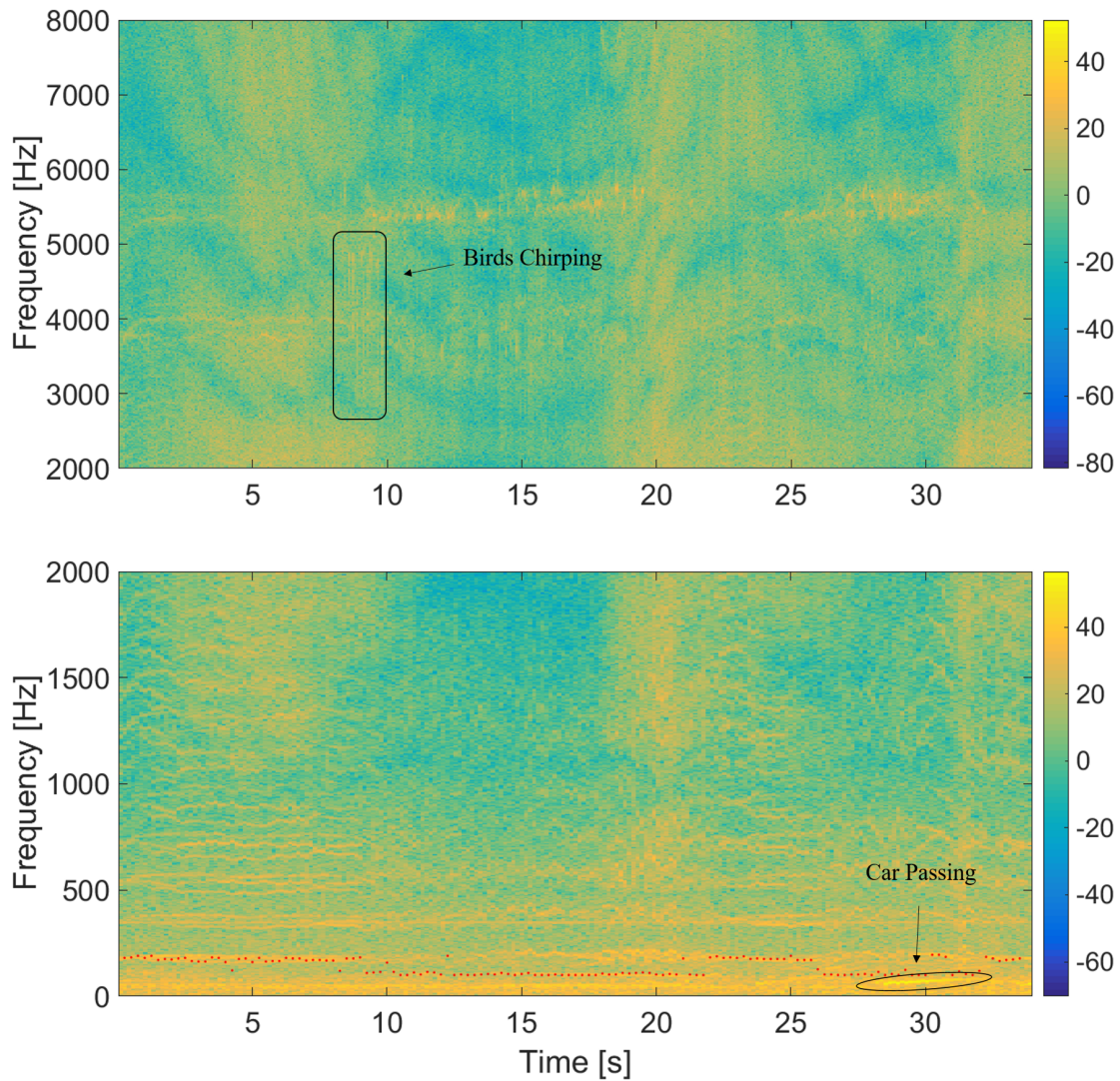


Figure 3. Spectrogram of the reference microphone for the second trajectory between 2 kHz and 8 kHz (top) and between 0 and 2 kHz (bottom) (red points are blade passing frequencies detected with SHC).

DSB performs better than in azimuth with still some fluctuations. The TFR approach gives better estimations globally with some fluctuations around 20 s and 40 s. As said before, bird chirps are above 2 kHz so taking harmonics between around 150 Hz and 1 kHz enables to select only content from the drone without the noise. According to the spectrogram in Figure 2, the signal is less strong in the intervals [10, 30] s and [38, 45] s so the signal to noise ratio is lower. This could explain the fluctuations for both methods.

Figure 5 shows the azimuth and elevation vs time for the second trajectory, for classical DSB and the TFR approach. Azimuth and elevation results for classical DSB show lots of bias but globally follow the trajectory until around 24 s. The TFR approach performs much better with only small fluctuations despite noise like bird chirps or car passing at the end of the trajectory. Car passing is below 100 Hz so as for the previous trajectory, taking harmonics above 150 Hz enables to select only content from the drone without the noise. Table 1 shows the mean errors and standard deviations for both trajectories and for the two methods used. Errors in elevation are lower than in azimuth and for both trajectories all values are lower with the TFR approach.

Table 1. Mean errors μ and standard deviations σ for classical DSB and TFR approach in azimuth and elevation for the two trajectories.

	First Trajectory				Second Trajectory			
	Azimuth (°)		Elevation (°)		Azimuth (°)		Elevation (°)	
	μ	σ	μ	σ	μ	σ	μ	σ
Classical DSB	85.9	69.7	12.6	12.1	63.7	42.7	29.1	21.4
TFR	49.7	30.3	8.3	6.9	53.3	14.5	8.9	4.9

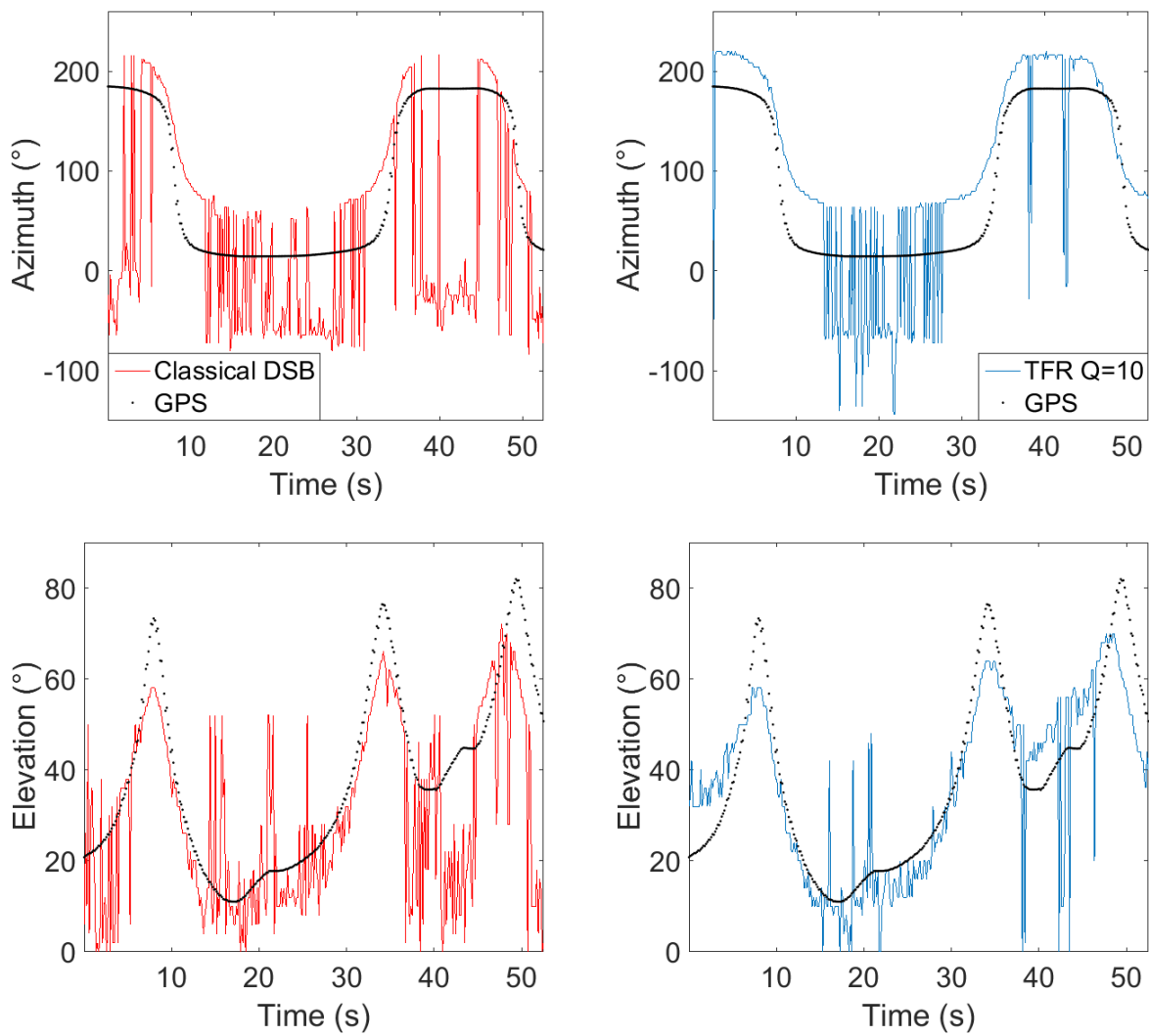


Figure 4. Azimuth and Elevation vs time for classical DSB and TFR method with $Q=10$, for the first trajectory.

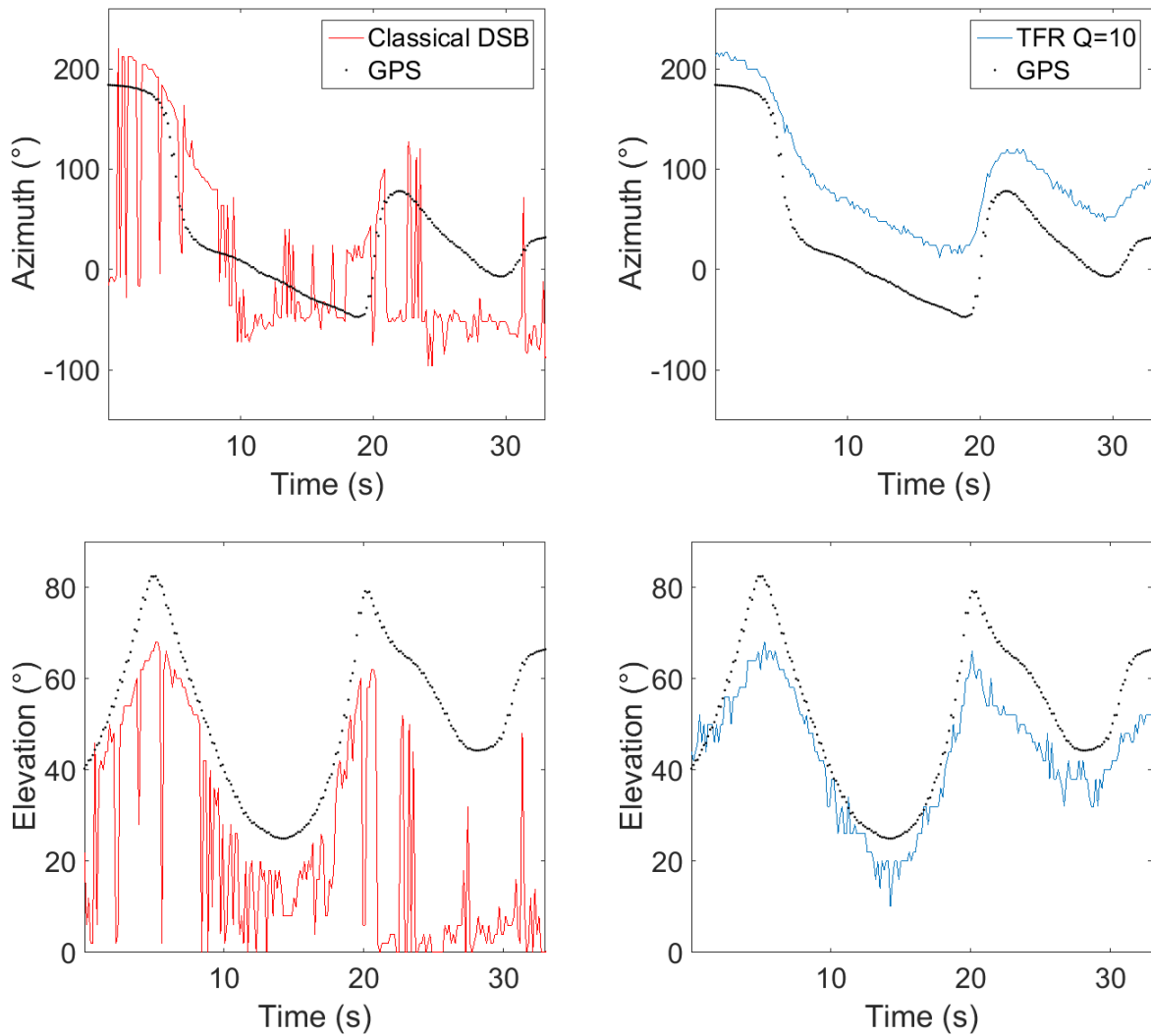


Figure 5. Azimuth and Elevation vs time for classical DSB and TFR method with $Q=10$, for the second trajectory.

5 CONCLUSION

The purpose of this work is to evaluate the performance of a method exploiting a time-frequency representation of beamforming's output in a noisy environment. Two measurements were carried out, one with birds chirping and another with also a car passing. The time-frequency approach was compared with the classical delay and sum beamforming. The former approach enables to select time-frequency bins corresponding to the UAV to enhance the signal to noise ratio. Results show that for both trajectories, the time-frequency approach gives better DOA's estimations. Indeed, the content selected for energy calculation is not in the frequency range of the types of noise considered which increases the signal to noise ratio and enhances the performance of beamforming. There are still some bias for particular very noisy signal's sections, thus it could be useful to apply some filters like a Kalman filter to smooth those bias. It could also be interesting to know what is the limit signal to noise ratio where the time-frequency approach can still performs well.

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