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Suppression of distortions in signals received from Doppler sensor for vehicle speed measurement

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***Abstract*— Doppler sensors are commonly used for movement detection and speed measurement. However, electromagnetic interferences and imperfections in sensor construction result in degradation of the signal to noise ratio. As a result, detection of signals reflected from moving objects becomes problematic. The paper proposes an algorithm for reduction of distortions and noise in the signal received from a simple, dual-channel type of a Doppler sensor. The proposed method is based on examining phase relationship between I/Q channels of the sensor signal. A weighting function is calculated in order to suppress the distortions while preserving energy of the desired signal. Additionally, the proposed algorithm may select signals reflected by objects moving in a specific direction (e.g. towards the sensor). The processed signal may be further analyzed in order to detect signal frequency and compute the object velocity. The results of the experiments show that the proposed approach results in significant reduction of level of noise and interferences, allowing for detection and tracking of signals reflected from moving objects.**

Keywords-speed measurement; Doppler radar; noise suppression; traffic monitoring

I. INTRODUCTION

Traffic monitoring systems are important tools in maintenance of road networks. In order to obtain a detailed dataset on road traffic, a network of sensors measuring traffic parameters (such as number of vehicles, average speed, etc.) is necessary. Due to large number of sensors in such systems, low cost devices should be used in construction of monitoring stations. In order to ensure a sufficient level of accuracy, appropriate signal processing algorithms need to be employed. Radar sensors based on the Doppler effect are standard devices used for speed measurement. Low cost Doppler sensors, advertised as ‘motion sensors’, may be used for estimation of vehicles speed in the monitoring stations. While they are not as sophisticated as professional devices used e.g. for traffic law enforcement, they are able, with the help of digital signal processing algorithms, to provide sufficient accuracy of vehicle speed measurement for the purpose of collecting traffic data.

Various types of radar sensors are used for speed measurement [1]. Continuous wave (CW) sensors transmit a harmonic signal with constant frequency and amplitude. Only speed measurement is possible with these sensors. Pulse radars emit short impulses, they are often used in ranging applications. Newer frequency modulated continuous wave (FMCW) sensors [2] are able to measure range, speed and angle at the same time, at the cost of reduced resolution and maximum measured value. A variety of low cost sensors is available on the market. Alternatively, a custom sensor may be constructed. For example, Placentino et al built a custom CW sensor and used it for measurement of vehicle speed and length [3]. Nguyen et al used a pulse radar sensor and proposed an algorithm that calculates vehicle speed and length [4]. Processing signals from a Doppler sensor does not require significant processing power. Butterfield proposed a system composed from a CW motion detector, operating amplifiers, a sound card and a Raspberry Pi microcomputer, that is able to collect traffic data [5]. The processing algorithm may also be implemented on a low power digital signal processor.

Parameters of consumer motion sensor do not match those of professional equipment used e.g. by the Police. The most important problem is low signal-to-noise ratio, which makes the task of separating the useful signal from the background noise problematic. The usual approach is to compute a noise profile and to subtract this profile from the sensor signal. However, this method requires that signal parts containing only the noise are used for computing and updating the profile. Determining whether a signal frame contains components reflected from moving objects is problematic. In many cases, the algorithm takes blindly a number of signal frames, computes a profile and uses it for noise suppression [6]. If a reflected signal is present in the analyzed frames, the computed profile is incorrect. Additionally, subtracting the noise profile from the sensor signal also suppresses the reflected components. Another problem is that noise profiling works only for a stationary noise, it won’t help in case of noise resulting e.g. from wind blowing at the sensor. There is also a problem of electromagnetic interferences that may be present in the sensor signal and which are not successfully removed with the standard profile subtraction approach. Various advanced methods of noise suppression in a Doppler sensor were proposed. For example, Islam and Chong used a matched filter and wavelet analysis [7].

This paper proposes an alternative approach to suppression of noise and electromagnetic interferences in the Doppler sensor signal. The algorithm works on any CW sensor with a dual channel, I/Q output. This approach is based on examining phase relationship between the two output channels. Both stationary and non-stationary noise, as well as electromagnetic interferences, may be reduced, without affecting the reflected signal. Additionally, this method is able to select only signals reflected from vehicles moving either towards or away from the sensor, which greatly simplifies the speed estimation. Additionally, an improved method of calculating the noise profile is also described. The details are presented in the following Sections.

II. PRINCIPLE OF DOPPLER SENSOR OPERATION

A CW Doppler sensor transmits an electromagnetic wave with constant frequency and amplitude. Most CW sensors in Europe use the K band and transmit signals with $f_0 = 24.125$ GHz frequency. Signals reflected by obstacles are received by the sensor antennas and amplified. Signals reflected by static obstacles have the same frequency as the transmitted signal. Objects in motion that reflect the transmitted wave cause the Doppler effect. As a result, frequency f_r of the received signal is higher than f_0 if the object approaches the sensor, and lower if the object moves away from the sensor. The transmitted and the received signals are multiplied in the mixer and low-pass filtered [1]. As a result, frequency f_d of the signal at the sensor output is equal to

$$f_d = \left| f_r - f_0 \right| = \frac{2}{\lambda} v_r = \frac{2 f_0}{c} v_r = S v_r \qquad (1)$$

where λ is the transmitted wave length, f_0 is the transmitted wave frequency, c is the speed of light, v_r is the radial velocity, i.e. the velocity vector component in the direction from the sensor to the moving object. Therefore, frequency of the received wave is related to v_r, with a constant scale factor S, equal to ca. 44.71 for $f_0 = 24.125$ GHz and speed expressed in kmph. It should be noted that the signal from the sensor output is within the audio frequencies, as vehicle speeds in range up to 200 kmph result in frequencies up to ca. 9 kHz.

Sensors with a single-channel output do not allow for determining the direction of movement. For this purpose, many Doppler sensors provide a dual-channel output in I/Q format. the first channel (I, in-phase) is the same as in the single-channel sensor, the second channel (Q, quadrature) is shifted in phase by 90 degrees. If the object moves towards the sensor ($f_d > 0$), phase difference between channels Q and I is equal to 90 degrees. If the object moves away from the sensor ($f_d < 0$), the sign in the Q channel is inverted and the phase difference Q-I is equal to -90 degrees. Therefore, it is possible to distinguish between the two directions of movement by examining phase difference between the channels.

It should be noted that the sensor measures only the radial component of the velocity vector. The relation between the actual object speed v and the measured velocity v_r is

$$v_r = v \cdot \cos(\alpha) \qquad (2)$$

where α is the angle between the line of the object movement and the line connecting the object with the sensor (Fig. 1). As a result, as the object moves closer to the sensor, the measured speed decreases. This is called a ‘cosine effect’ [8].

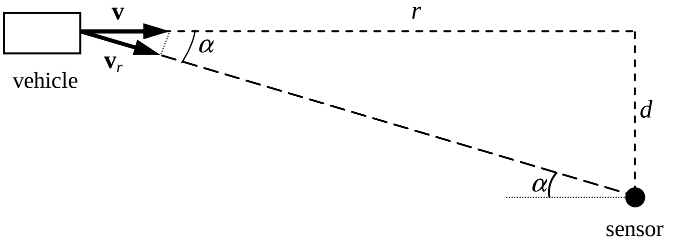

Figure 1. The actual object speed **v** and the radial speed **v**$_r$ measured by the Doppler sensor

This effect has an important influence on signals reflected from vehicles moving close to the sensor. As a vehicle approaches the sensor, the difference in angle α between the front and the back of the vehicle increases. As a result, difference in frequency of signals reflected from the front and the back of the car also increases, which results in widening of the spectrogram peak (Fig. 2). This effect my be utilized for estimation of vehicle length.

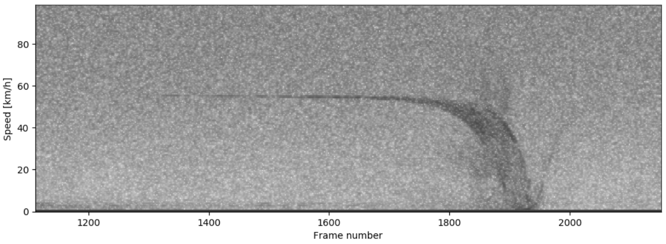

Figure 2. Recording from a Doppler sensor – signal reflected by a vehicle moving with a constant speed, the cosine effect is visible

III. WEIGHTING FUNCTION FOR NOISE SUPPRESSION

In an ideal dual-channel CW Doppler sensor, phase difference between I/Q channels of signals reflected from moving vehicles would be either +90 or -90 degrees. In practice, due to noise and interferences, the observed values deviate from the ideal ones. For example, the datasheet of the sensor used in the experiments shows possible range of ±30 degrees [9]. Nevertheless, this observation may be used in the noise suppression algorithm which is designed as follows. A weighting function is computed from the phase difference signal. Such a function has values from 0 to 1, indicating a probability that a given signal component is the desired signal. The signal components reflected from moving objects are expected to have phase difference close to ±90 degrees.

The distribution of phase difference for the noise was obtained by selecting signal frames containing only noise from the recording, computing spectra of both channels, computing the interchannel phase difference and constructing a histogram. The result is shown in Fig. 3. It can be observed that for the stationary noise, the distribution of phase differences is Gaussian, with mean close to zero. Therefore, most of the noise components are concentrated around zero phase difference and they are separated in phase from the reflected signal components.

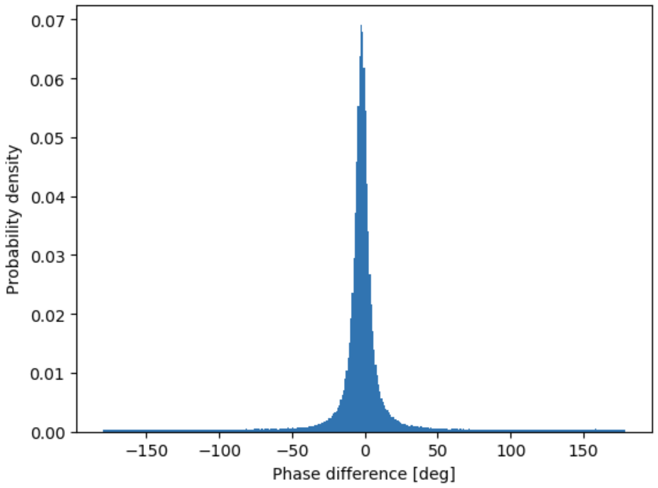

Figure 3. Histogram of phase differences in a noise recorded from the dual-channel Doppler sensor. Mean = -1.64, standard deviation = 38.15

The weighting function is calculated as follows. Signals $x_i(n)$ and $x_q(n)$, from the I/Q sensor output are digitized and transformed to the frequency domain, so that their spectral representations $X_i(f)$ and $X_q(f)$ are obtained. The phase difference function is computed as

$$\Delta_{\varphi}(f) = \arg\left(X_q(f)\right) - \arg\left(X_i(f)\right) \tag{3}$$

The function $\Delta_\varphi(f)$ is normalized to [-180, 180) degrees range by adding or subtracting 360 degrees where necessary. This function describes the Q-I phase difference for frequency components of the signal.

The weighting function $w(f)$ for detection of all moving objects is computed as

$$w(f) = 1 - \left| \frac{\left|\Delta_{\varphi}(f)\right|}{90} - 1 \right| \tag{4}$$

This function has values in range from 0 to 1.

The function given by Eq. 4 changes linearly. In order to increase attenuation of noise components and to preserve amplitude of the reflected components, a sigmoid function is applied to the original weighting function:

$$w'(f) = \frac{1}{1 + e^{-\gamma(w(f) - 0.5)}} \tag{5}$$

where γ is the parameter which defines ‘flatness’ of the curve at the extrema and sharpness of the function in the middle section. Values γ of in the range 10-20 were used in the experiments. Similarly to image processing, this additional weighting increases the ‘contrast’ between 0 and ±90 degrees phase differences.

The additional advantage of the proposed method is that it is possible to modify the function $w(f)$ in a way that only the objects moving towards the sensor are retained, and the objects moving away from the sensor are suppressed. Thanks to that, further analysis of vehicle speed detection is simplified. The weighting function for this case is

$$w_{in}(f) = 1 - \left| \max\left(\frac{\Delta_{\varphi}(f)}{90}, 0 \right) - 1 \right| \tag{6}$$

Fig. 4 shows plots of weighting functions for both cases, without and with the sigmoid function, for all objects and only for objects approaching the sensor.

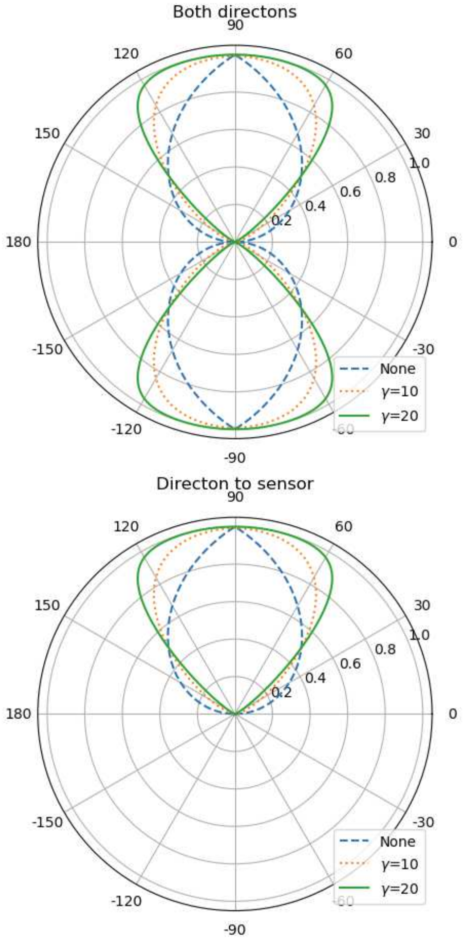

Figure 4. Weighting functions for all objects and only for objects moving towards the sensor, without using the sigmoid function (dashed lines) and with sigmoid function $\gamma = 10$ (dotted line) and $\gamma = 20$ (solid line)

Similarly, it is possible to select only objects moving away from the sensor, with weighting function

$$w_{out}(f) = 1 - \left| \max\left(\frac{-\Delta_{\varphi}(f)}{90}, 0 \right) - 1 \right| \qquad (7)$$

Electromagnetic interferences received by the sensor antennas will be added to the reflected signal, so in most cases, one of the directions of movement (usually away from the sensor) will be distorted. However, interferences inducted in the electronic circuits after the sensor output, or amplified by this circuit, are added to both channels, so their phase difference will be close to zero. These interferences may be suppressed with the proposed method, provided that their amplitude is comparable to the reflected signal amplitude.

After the weighting function is calculated, suppression of noise and interferences is performed by multiplying the amplitude or power spectrum of the signal frame by the weighting function. The result is used in detection of reflected signal components and for speed estimation.

IV. CALCULATION OF NOISE PROFILE

Subtraction of noise profile is the standard approach to noise suppression. The problem is that only signal frames that do not contain components reflected from moving objects should be used for profile calculation. The weighting function proposed in the previous Section may be used to determine spectral bins containing noise or signal components. In order to compute a profile for a given spectral bin, *N* values have to be collected. The proposed procedure works as follows. For each signal frame, amplitude spectrum and the phase difference processed by the weighting function (for all objects) are computed. For each frequency bin, the following operations are performed.

- If the weighted phase difference is above a threshold T_n, the bin contains a signal component and is not processed further.
- If the number k of noise samples collected for the bin is $k < N$, add the value of spectral amplitude as another noise sample.
- If $k = N$, compute the noise estimate $e(f)$ as the arithmetic mean of the collected samples.
- If $k > N$, update the noise estimate:

$$e(f) = (1-\alpha) \cdot e(f) + \alpha |X(f)| \qquad (8)$$

where α is the learning parameter, $X(f)$ is the signal frame spectrum.

The noise profile is completed if $k \geq N$ for all spectral bins. The learning parameter is a small number, e.g. $\alpha = 0.05$.

V. EXPERIMENTS

The test system built for the experiments is based on a RSM2650 Doppler sensor operating with 24.125 GHz transmit frequency [9]. The output signal is processed with an amplifier. Initially, modules based on LM386 amplifiers were used. However, these modules introduced interferences into the analyzed signal, and the maximum gain (20×) was not sufficient. Therefore, they were replaced by a custom module based on a NE5532 amplifier (max gain 1000×). The amplified signal was digitized by a sound card and recorded on a computer. The recorded signals were processed offline with scripts written in Python. It was tested that the same scripts may be used for online analysis, running e.g. on a Raspberry Pi 3 microcomputer. Sampling frequency was 48 kHz, STFT analysis was performed with Blackman window of length 2048 samples, with 75% overlapping.

The recordings were made on a city street (vehicles moving with average speed of 30-50 kmph). The sensor was placed ca. 3 meters from the street, angled at ca. 45 degrees relative to the street. Fig. 5 shows the spectrogram of a fragment of the first recording, made with the original amplifier. Signal components reflected from moving vehicles are clearly visible. However, the noise level is high and there are constant frequency components at multiples of 1 kHz. The source of this interference was not found. It is possible that it is a result of USB frame synchronization, amplified in the circuit.

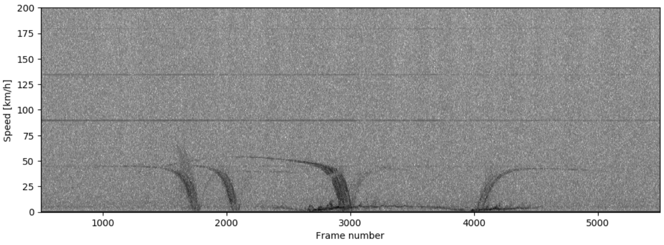

Figure 5. Spectrogram of a fragment of Recording 1

Fig. 6 shows phase difference (Q-I) for spectral components, black and white colors represent -90 and +90 degree phase difference, respectively. It can be observed that signals reflected from moving vehicles are marked mostly with black or white color, depending on the direction of movement. Electromagnetic interferences have phase difference close to zero (medium gray color). Phase difference of noise components is distributed as shown in Fig. 3.

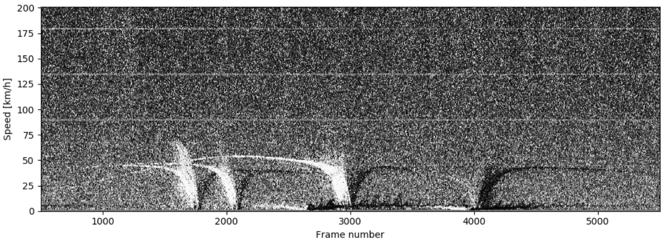

Figure 6. Phase difference Q-I of the signal shown in Fig. 5. Black and white colors represent phase difference -90 and +90 deg, respectively

Fig. 7 shows the spectrogram of a processed signal, after the weighting function is computed (for both directions, $\gamma = 20$) and multiplied with the amplitude spectrum of the signal. It can be observed that the interference components were successfully suppressed and that the noise level was significantly reduced, as the contrast between the signal components and the noise background is increased. Fig. 8 shows the result of applying a weighting function which selects only objects moving towards the sensor. Signal components reflected from vehicles moving away from the sensor are suppressed, the noise level is also decreased in comparison to the previous experiment.

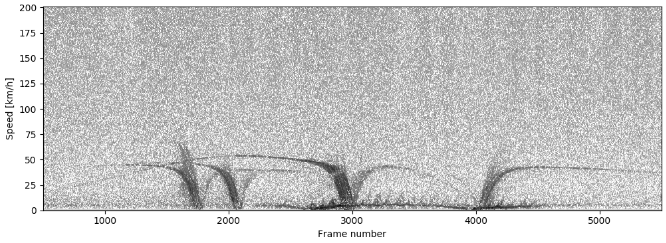

Figure 7. Spectrogram of a fragment of Recording 1, after noise suppression with the proposed algorithm (weighting function for all vehicles)

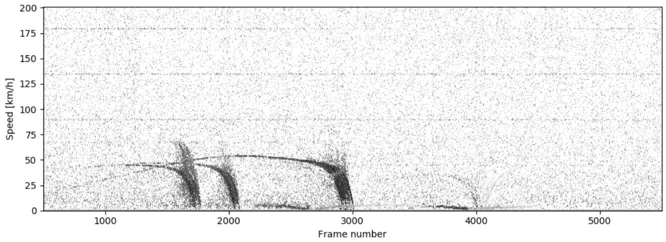

Figure 8. Spectrogram of a fragment of Recording 1, after noise suppression with the proposed algorithm (weighting function only for vehicles moving towards the sensor)

Fig. 9 shows noise profiles computed from the same recording. The standard profile is the amplitude spectrum averaged over the first 100 frames (no reflected signals were present in these frames). The ‘proposed’ profile was computed using the method described in the previous section, with $N = 100$. Both profiles are similar, but the second profile may also be computed in presence of reflected signals, as they are excluded from the profiling. Electromagnetic interferences are clearly visible in the profile plot. The third (‘processed’) profile is obtained after noise suppression with the procedure described earlier (the weighting function for both directions was used). It can be seen that the noise level was reduced significantly, by ca. 20 dB. Peaks from interferences, as well as the direct component (resulting from signal reflections from static obstacles), are suppressed, making further signal analysis (speed estimation) easier.

Because of electromagnetic interferences visible in the recorded signals, the amplifier circuit was replaced with another one. In the second recording, made with this setup, interferences were significantly reduced, but the noise level has increased. Noise profiles calculated for this recording are presented in Fig. 10. The proposed algorithm for noise suppression reduced the overall noise level. The observed gain in signal to noise ratio is higher than in the first recording.

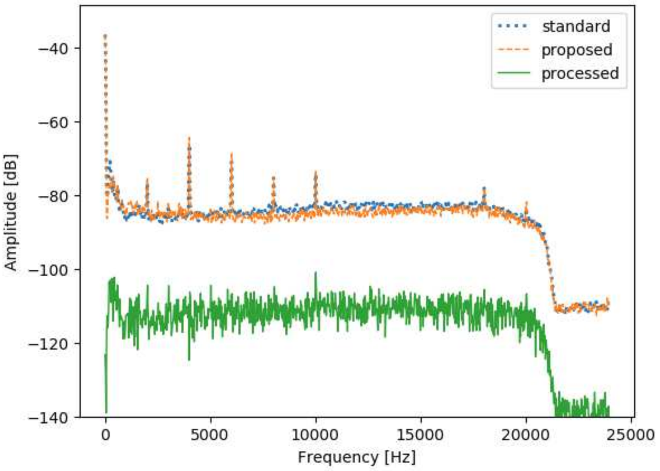

Figure 9. Noise profiles computed from Recording 1, using various methods

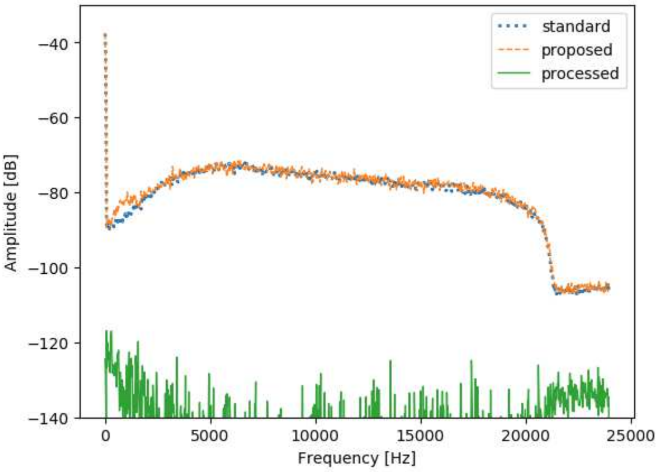

Figure 10. Noise profiles computed from Recording 2, using various methods

Table 1 summarizes the results of the proposed algorithm in terms of the measured noise level, for both tested recordings. Average noise level was computed as a mean of the noise profile values in the frequency range 500 Hz – 10 kHz. Each recording was processed with a weighting function calculated first for both directions (two-dir.), and then only for the direction towards the sensor (one-dir.). Three cases were tested: without the sigmoid function and with the sigmoid function and two different γ values. The obtained results confirm that the proposed algorithm efficiently decreases the noise level. This reduction is more prominent if only one direction is selected for the analysis. Sigmoid weighting of the phase difference enhances the noise suppression in most cases. In one case (Recording 2, no sigmoid weighting) it was not possible to complete the noise profile calculation (due to insufficient number of frames), but with the help of sigmoid weighting, it was possible to calculate the profile.

The observed noise levels (-84 dB to -76 dB) may seem low, but the signal to noise ratio in the Doppler radar system built from low cost components is very low. The observed levels of signals reflected from moving vehicles were in the range from -80 dB to -50 dB, depending on distance to the object and the object size. Therefore, increasing the gap between the signal and the noise levels is vital for efficient speed measurement. The standard approach based on noise profile subtraction reduces the amplitude of both the signal and the noise. The proposed method applies strong attenuation to the noise while keeping the suppression of signal level at a reasonably low level.

TABLE I. NOISE LEVEL [dB] MEASURED FOR THE SIGNAL (500 Hz – 10 kHz) PROCESSED WITH THE PROPOSED ALGORITHM

Algorithm	**Recording 1**		**Recording 2**	
	two-dir.	***one-dir.***	***two-dir.***	***one-dir.***
Original signal	-84,1	-84,1	-75.8	-75.8
No sigmoid	-100.2	-118.6	—	-105.1
Sigmoid, $\gamma = 10$	-105.3	-118.9	-113.5	-114.9
Sigmoid, $\gamma = 20$	-111,7	-131.0	-139.6	-143.1

VI. CONCLUSION

Commonly used noise suppression methods, e.g. based on subtracting a noise profile, are suboptimal for processing Doppler sensor signals, as they do not utilize phase relationship between I/Q channels and they do not provide satisfactory efficiency in low signal-to-noise ratio conditions. The proposed algorithm detects signal components that are expected to represent signals reflected from moving objects, based on phase difference between the two channels. The remaining components are considered to be noise ad they are efficiently suppressed. The proposed algorithm performs much better than the profile subtraction approach in case of presence of electromagnetic interferences. An important advantage of the proposed method is that objects moving in opposite directions (e.g. on two lanes) may be separated from each other using the appropriate weighting function. As a result, speed measurement may be performed separately for each direction. Moreover, selecting only one direction allows for more efficient noise suppression. Additionally, if a noise profile is required, the proposed algorithm is able to extract the profile from a signal that may contain useful components, so it does not require selection of noise-only signal frames.

The main intended application of the presented algorithm are traffic monitoring networks composed of a large number of monitoring devices. The presented noise suppression algorithm is intended to be used in a pre-processing stage of an algorithm for vehicle speed measurement. Thanks to digital signal processing, it will be possible to construct a network of a large number of simple, low cost sensors, providing an effective and economic solution for traffic monitoring.

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