Doppler Effect Measurements with SDR

2 authors:

Matej Bažec
University of Ljubljana
14 PUBLICATIONS **21** CITATIONS

Franc Dimc
University of Ljubljana
38 PUBLICATIONS **83** CITATIONS

DOPPLER EFFECT MEASUREMENT WITH SDR

Matej Bažec and Franc Dimc
Faculty of Maritime Studies and Transport, University of Ljubljana
Pot pomorščakov 4, 6320 Portorož, Slovenia
matej.bazec@fpp.uni-lj.si

Abstract

The measurements of the Doppler effect of a car in motion were performed with the analysis of the electromagnetic spectrum in the 433 MHz band using a continuous transmitter and a SDR receiver based on a RTL DVB-T receiver USB dongle. Despite the poor oscillator stability on both the receiver and the transmitter part on the one hand and the high frequency resolution requirements (in the order of few Hz) on the other, some of the measurements gave quite good results.

Keywords

Velocity measurement, Doppler effect, SDR

INTRODUCTION

Traffic situational awareness using electromagnetic waves concerns deeply nowadays all traffic modes. The earliest successful attempts in 1904, satisfying the ship collision avoidance refers to Christian Hülsmeyer, for his patented (DE 165546) instrument capable of detection of distant objects. Four decades later, the intensive use of the high-power pulse radar for airborne situation awareness has brought much to the decision on the winner of the war.

But the very implementation of Christian Doppler's invention on frequency variation use for determining the relative radial velocity of from the perspective of observer moving objects and also solving the clutter issues from relatively static objects, awaited for the progress of processing devices in the early 70's. In 1967, Joachim E. Wolf patented a Moving target indicator with automatic clutter residue control, capable of distinguishing the echoes from moving objects from static ones. Two years later, Harold Lee Massie and Bruce Elson Mount, secured their Doppler shift application by the US patent, known as Continuous wave (CW) doppler transceiver system [1].

An era of needs for a reliable and quick car awareness within neighboring area and for the law enforcement control brings the use of low power solid-state transmitters with ever progressing processing techniques. The sensitive but affordable parts with fast processing abilities of received and digitized CW signals open a wide range of the use of Doppler effect.

MOTIVATION

SDR has been already used for the measurement of the Doppler effect of the hydrogen line (1420.406 MHz) on astronomic objects [2], [3]. However, such objects are moving with a speed of several kilometers per second, while objects in the traffic usually move hundred times slower. In order to get a useful result a resolution of 1 m/s is needed. That means that the relative frequency resolution should be $0.3 \cdot 10^{-8}$ (or twice that value if the reflection is taken into account). For this reason commercially available devices work in the microwave region (around 30 GHz). That allows for a Doppler shift resolution of 100 Hz.

Our intention instead was to use some of the low budget radio emitting devices that work in the 433 MHz band in the combination with the low budget SDR based on the popular USB DVB-T dongle with RTL2832U chipset.

That would impose some restrictions. First, such a low emission frequency requires a resolution of 1.5 Hz on the receiver part. In order to achieve such a precision the measurement of the receiving signal should last at least for 0.7 s. However, in this time interval a vehicle can change its position substantially (order of 10 m). Second, in the measuring interval the oscillator frequency on both the transmitter and the receiver (probably tuner) side should be stable enough in order to not interfere with the measurement. And at last (but not least), the spectrum of the emitted signal should be sharp enough in order to make the shift observable. That means that also the amplitude and the phase should be stable, implying that the transmitter should radiate continuously.

PRELIMINARY MEASUREMENTS

In order to check for oscillator's stability and the spread of the emitting line a dry run was performed first. The transmitter was kept at rest approx. 8 m apart from the static receiver (see fig. 1).

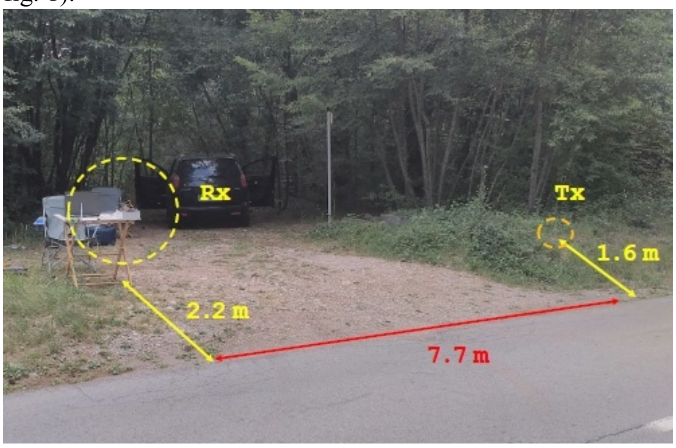

Figure 1: The actual test setup of 433MHz transmitter (Tx) and SDR (Rx) relative to the local road.

The sampling rate of the SDR receiver was set on its maximum (2 MHz). In order to get rid of DC offset, the intermediate frequency was set slightly below the transmitter's one at 433.5 MHz. The signal was then upconverted with software [4].

The samples were then merged in two chunks of 2^{18} one for the in-phase signal and the other for the quadrature. Such chunk size was chosen in order to get a satisfactory frequency resolution 7.6 Hz, yet to keep the time resolution (0.13 s) still within reasonable boundaries. Unfortunately, that meant a velocity resolution of 4 m/s (2 m/s for the reflected signal). However, that is the theoretical limit that can be achieved at 433.92 MHz.

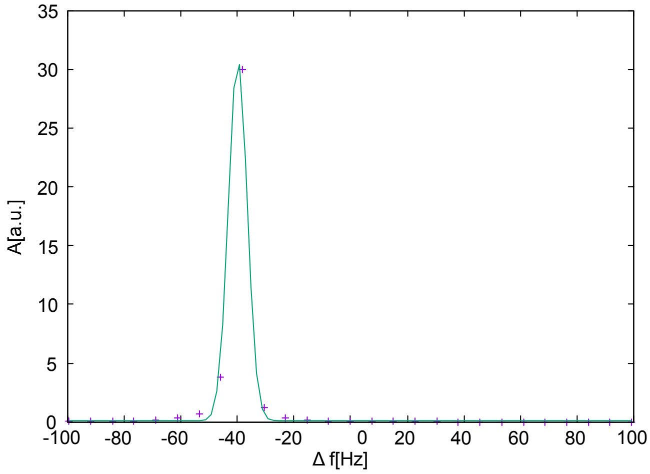

Figure 2: Power spectral distribution of the emitted signal near central frequency 433.92 MHz and its fit to the Gaussian distribution.

Both chunks were then combined in order to get the spectral power distribution. This was achieved by calculating the fast Fourier transform over the pair of chunks and then calculating the power according to this equation:

$$P=|A|^2=I_R^2+I_I^2+Q_R^2+Q_I^2-2I_RQ_I+2Q_RI_I,$$

where P is the power at the particular frequency, A is the complex amplitude, I and Q are the Fourier transforms of the in-phase and the quadratic signal respectively and the indexes R and I represent their real and imaginary component.

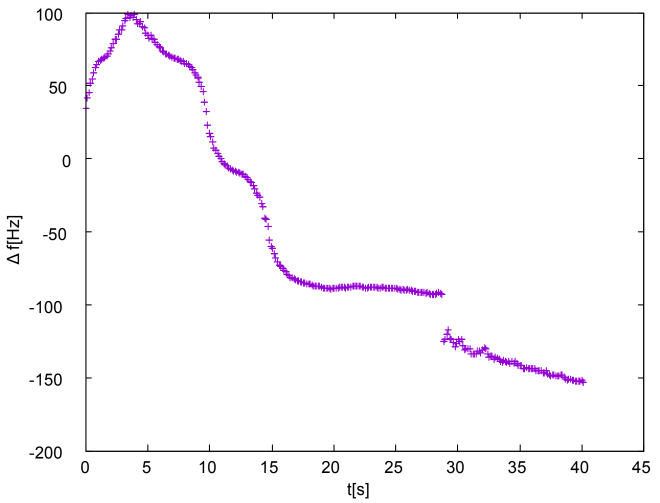

Figure 3: An observed frequency variation over an interval of 40 s. The central frequency is set to 433.92 MHz.

The acquired spectral power distribution was then fitted to a Gaussian distribution (fig. 2). From the fit, the following parameters were obtained: amplitude, central frequency and its standard deviation. The latter was in the range of 10-15 Hz. Although this is still enough to get a meaningful measurement it imposes further restrictions on overall accuracy.

The next obvious step was to monitor the time stability of the frequency. As it can be seen from figure 3 there are some epochs when the frequency variates considerably. On the other hand, during some epochs variations are flat enough that would make the measurements possible. It should be kept in mind that not all of the measurements are expected to give meaningful results.

RESULTS

Taking into account all the restrictions from the previous section, some real measurements were performed. The transmitter was put in a vehicle which was driven at different speeds. The receiver was positioned few meters from the road. Among all the measurements some will be presented that did not expose the issues mentioned above.

The waterfall representation of a single shot can be seen in figure 4. Note the substantial amplitude variation over time. This should be attributed to the SDR receiver error since the acquired amplitude of the background noise is highly correlated with the amplitude of the signal.

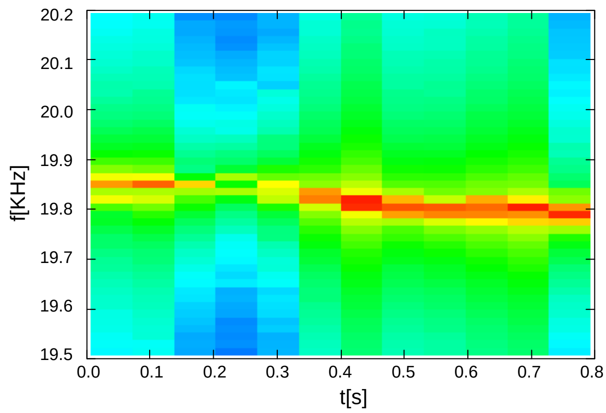

Figure 4: Waterfall of the acquired signal from a car driving at 60 km/h.

In order to test whether the frequency shift can be attributed to the Doppler effect, the correlation between the amplitude and the frequency shift was observed. The signal should be stronger when the shift occurs, since at that time the distance between the transmitter in the vehicle and the receiver in the SDR should be minimal.

The amplitude was calculated in three independent ways. One was the amplitude obtained from the fitting to the Gaussian curve, one was obtained by simply taking the maximal value of the power spectral density (PSD) and the last one was calculated by taking the sum of all the values of the PSD and by normalizing it with a proper value. The idea behind the latter method is to calculate the integral of the Gaussian function analytically and to compare it with the numerical integration of acquired signal.

$$\int_{-\infty}^{\infty} Ae^{-\frac{(f-f_0)^2}{2\sigma^2}} \mathrm{d}f = A\sqrt{2\pi}\sigma \doteq \Delta f \sum_i A_i$$

$$A \doteq \sum_i A_i \frac{\Delta f}{\sqrt{2\pi}\sigma}$$

The remainder of this section will be devoted to two specific measurements of the Doppler shift of the passing car. The signals were acquired while a car was driving at 60 km/h (figures 5 and 6) and 100 km/h (figures 7 and 8). The measurements at both speeds show a considerable correlation between the amplitude and the shift.

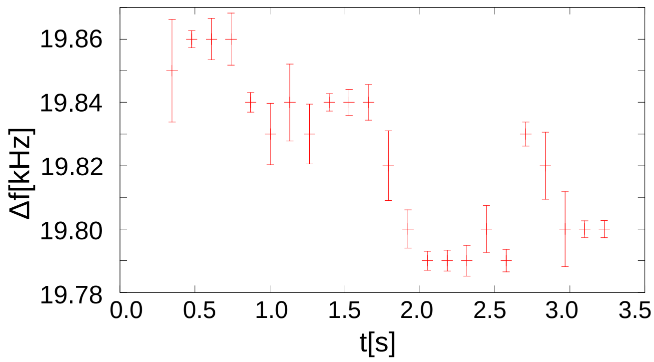

Figure 5: Doppler shift of the signal emitted from a car driving at 60 km/h.

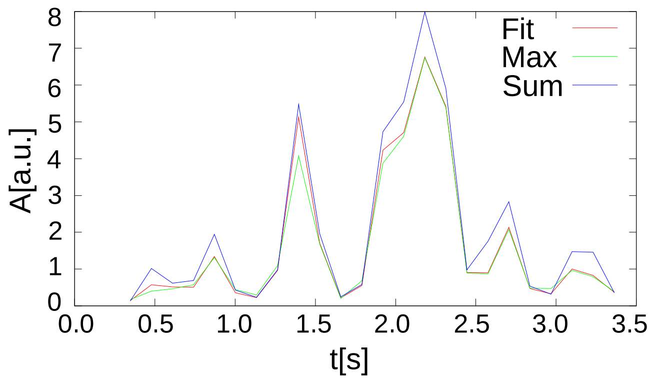

Figure 6: Amplitude of the signal emitted from a car driving at 60 km/h.

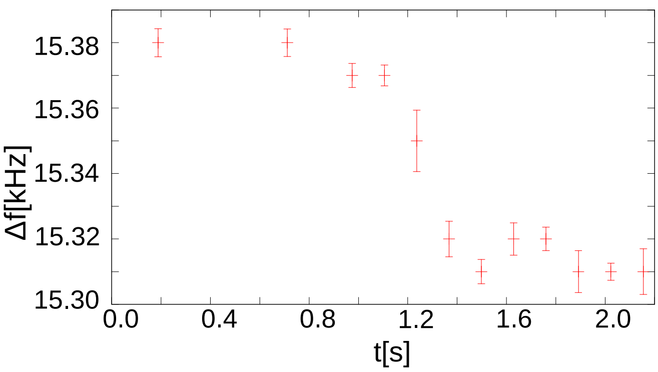

Figure 7: Doppler shift of the signal emitted from a car driving at 100 km/h.

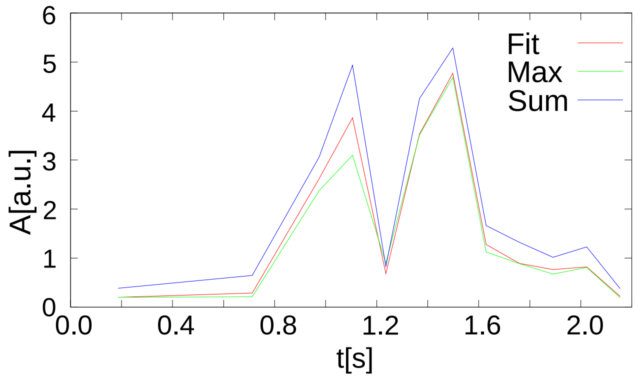

Figure 8: Amplitude of the signal emitted from a car driving at 100 km/h.

The velocity estimation can then be calculated by the following procedure. First the frequency shift calculations are split in three regions: the approaching region, the transition region and the distancing region. The data from the transition region is then discarded and a weighted average (weights are selected according to the standard deviation) is calculated for the remaining regions. The difference of the averages represents twice the Doppler shift frequency.

The measured frequency difference was 45 Hz and 65 Hz for the car driving at 60 km/h and 100 km/h respectively. This results in a speed measurement of 55 km/h and 81 km/h with an error margin of 10 km/h.

CONCLUSION

It has been shown that even with a very low budget equipment a Doppler shift based velocity measurement can be performed. Unfortunately, the results of such measurements are too much unreliable to be used in practical applications.

Figure 9: Stability checks of transmitter and SDR receiver (LSO).

However, there are some improvements that have already been done. The SDR receiver was connected to a high precision function generator and it showed a much more stable frequency acquisition (see fig. 10). It is therefore plausible to believe that the high frequency oscillations were inhibited by the transmitter. The next step is therefore towards an improvement of CW transmitter. In our opinion such a simple modification could make the measurements much more reliable.

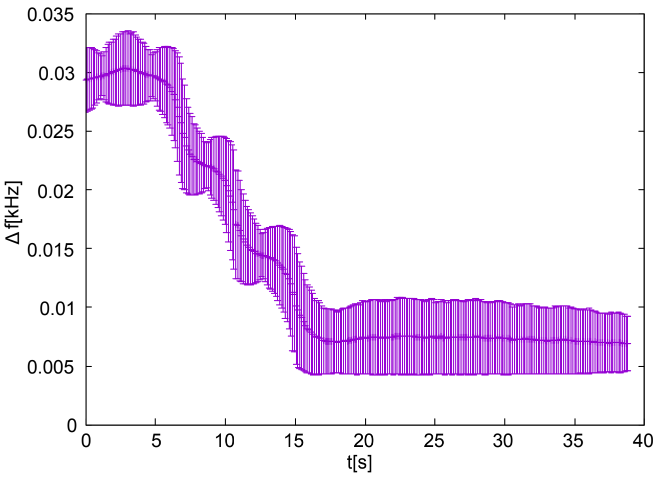

Figure 10: SDR acqusition of a signal from a stable source. Errorbar represents the standard deviation.

Next step in the speed measurement would be to move the transmitter from the car in motion to a fixed place. In this case the SDR receiver would acquire both the emitting and the reflected signal simultaneously. The frequency shift could be then determined from the spectrum of the received signal. This has many benefits. Beside that there is no need to put the receiver in the car, there is also no need to wait for a vehicle to traverse the antenna in order to measure the frequency shift. Beside this, the transmitter does not need to work in CW mode (although the emission should be long enough to get the desired frequency resolution).

ACKNOWLEDGMENTS

The authors would like to thank the staff from the Laboratory for Radiation and Optics (LSO) from the Faculty of Electrical Engineering, University of Ljubljana for their constructive attitude in lending us all the required equipment.

REFERENCES

1. Massie, H. L. and Mount, B. E., "CW Doppler Transceiver System", US Patent grant No. US3617993A, on February 23, 2018 at: https://patents.google.com/patent/US3617993.
2. RTLSDR.com RTL-SDR for Budget Radio Astronomy, available on February 23, 2018 at: https://www.rtl-sdr.com/rtl-sdr-for-budget-radio-astronomy/ .
3. Saje, T. and Vidmar, M., "A Compact Radio Telescope for the 21cm Neutral-Hydrogen Line", *Inf. MIDEM*, Vol. 47, No. 2 (2017), pp. 113-128.
4. RTL2832U, DVB-T COFDM Demodulator + USB 2.0, available on February 23, 2018 at: http://www.realtek.com.tw/products .
5. Wyglinsky, A. M. et al, Cognitive Radio Communications and Networks, Principles and Practice, Elsevier (2010), p. 150,177.