Time and sample rate synchronization of RTL-SDR using a GPS receiver

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***Abstract*—GPS receivers provide very precise Pulse Per Second (PPS) signal. A simple low cost method of time synchronization for RTL-SDR receivers using such GPS time signal is described. The PPS signal is injected into an IF stage of the RTL-SDR and detected by correlation of an expected signal shape and the measured data. The accuracy of such pulse detection algorithm is in the worst case 5 samples or up to 2.1 µs when using highest useful receiver sample rate of 2.4 MS/s. The algorithm can also be used to measure RTL-SDR oscillator offset with a very high precision for frequency corrections.**

The accuracy achieved is not enough for precise localization of ground targets, but it's sufficient enough to roughly estimate a location of an aircraft or a satellite.

***Index Terms*—RTL-SDR, time synchronization, GPS, TDOA**

I. Introduction

During a development of a method to localize an active satellite on a low Earth orbit I faced a problem how to precisely time synchronize multiple receivers in distant locations for multilateration purposes. The solution had to be cheap as multiple receivers are required and accurate enough to get the target position error within a few kilometers.

A common method to synchronize space separated receivers is to tune these receivers into a frequency of a known transmitter. By cross-correlating the received data the time difference between two receivers can be calculated and from the known receivers and transmitter location a precise time synchronization can be achieved [1].

Unfortunately such solution is not always possible. In many cases the receivers can be placed several hundreds kilometers away from each other with no common transmitter that would be in range of both receivers. In such situations a GPS time signal (a Pulse Per Second output is commonly available on GPS receivers) can be used to synchronize multiple receivers in time with nanoseconds accuracy [2].

A low cost RTL-SDR dongle has allowed many people to step into the world of software radios and digital signal processing. With a price of several dollars it is a great device for multiple receivers experiment. Unfortunately as it was originally designed as a consumer DVB-T receiver it doesn't contain any synchronization input and exact moment of the start of the sampling can not be precisely determined.

A cheap and reliable way to precisely synchronize records from multiple RTL-SDR receivers would allow creation of a collaborative distributed network of receivers for Time Difference of Arrival (TDOA) measurements for passive localization of various transmitters like airplanes, satellites, etc.

II. GPS time signal injection

The block layout of RTL-SDR dongle with GPS PPS signal inserted is shown on Fig. 1. The signal from antenna is amplified and converted into an intermediate frequency (IF) by the tuner, usually R820T2 in the latest revision. The IF is sampled by the RTL2832U and after further processing (filtering, etc.) sent to a computer over USB.

The R820T2 outputs a singe differential signal and the IQ demodulation is done inside the RTL2832U. Some other tuners, e. g. FC0012 contain the IQ demodulator inside and provide two separate differential signals (I and Q) to the RTL2832U.

There are two places where the PPS signal can be inserted. Either directly into the antenna input or between the tuner and the RTL2832U. The second option provides two advantages. The IF stage is isolated from the antenna by the tuner and the inserted signal is directly sampled by the RTL2832U without any further modifications. If a tuner with IQ demodulator included is used, the signal can be inserted in either of the I or Q inputs.

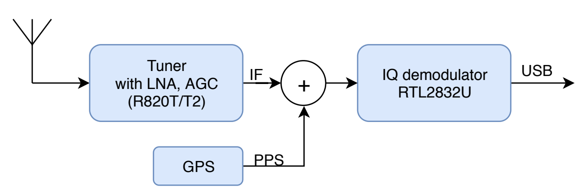

Fig. 1. Block layout of the RTL-SDR dongle with GPS PPS signal inserted

The signal from the tuner has to be modified by the PPS pulse in some way. An usual approach would be using PPS signal for gating output of an oscillator connected to the IF stage. This way most of the original signal would be preserved, only a narrow part of the signal spectrum would be modified. However such solution requires building an external circuit which increases the cost of the overall design.

After a few experiments it was verified, that the PPS signal can be directly coupled into the IF stage through a capacitor

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(to remove a DC component of the signal). This method was inspired by a direct sampling mode of the RTL-SDR dongle in which the antenna is connected directly to the signal input of the RTL2832U [3].

The input impedance of the demodulator is roughly 3300 Ω(according to experiments conducted in [4], RTL2832U documentation is not publicly available). The capacitor together with the input impedance forms a first order high pass filter. The PPS signal consists of square pulses, therefore only the edges will pass the filter as short peaks. These peaks are summed together with the signal from the tuner.

The capacitor value is not critical, lower value makes detecting the pulses harder as the edge can be lost in the noise or erased by much stronger signals from the tuner, higher values make pulse detection easier in stronger signals, but a longer part of the received signal is modified by the pulse.

For the experiments an RTL-SDR dongle with a FC0012 tuner was used together with a U-Blox NEO 6M GPS receiver. The PPS signal was injected to I channel of the RTL2832 tuner through a 100 nF ceramic capacitor. Lower values than approximately 1 nF rapidly decreased a successfulness of the pulse detection, higher values than 1 µF wiped unnecessary long part of the received signal, the experimental setup is shown on Fig. 2.

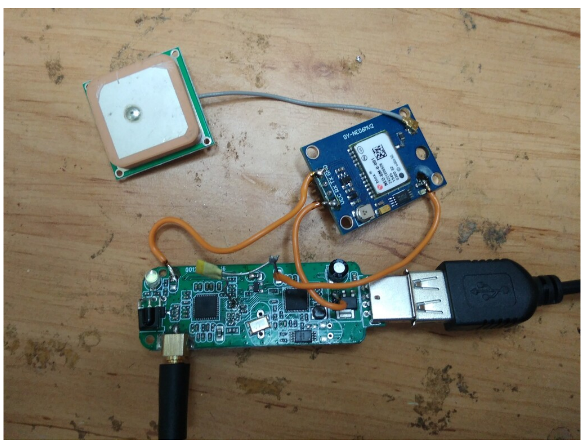

Fig. 2. Experimental setup.

III. A SIGNAL DETECTION ALGORITHM

The detection algorithm described here is designed to find an exact location of rising edges of the PPS signal. A sharp rising edge of the square signal passing through the high pass RC filter can be modeled as (1).

$$p(t) = e^{-\frac{t}{RC}} \tag{1}$$

The way this signal appears in the data send to the computer depends on the tuner used. If the FC0012 with integrated IQ demodulator is used, the signal will appear only in I or Q samples and the shape will match the theoretical one. However, if more common R820T2 is used, the IQ demodulation is done after the PPS signal injection and the pulse will appear in both channels and the shape will be different.

The described algorithm was designed for the first case. It can be still used even in the second case, but the accuracy of this method is affected. Further research will be needed in this area.

The RTL-SDR device provides IQ samples in 8 bit unsigned format. Each two bytes form one IQ sample (and can therefore be expressed as a single complex number). I or Q part of the signal (depends on the input to which the PPS signal was injected) forms a data stream which is cross-correlated [5] with an image of the expected PPS pulse shape.

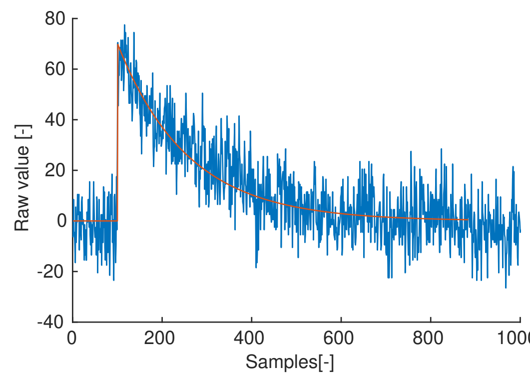

Fig. 3. Measured data (without antenna) and the simulated expected pulse shape.

As can be seen on the Fig. 3, the theoretical shape closely matches the measured pulse. As there are many uncertainties in the input chain (accuracy of the measured input impedance of the RTL2832U, tolerances of the coupling capacitor, etc.), the RC constant in the (1) must be fine tuned to match the real measured signal to achieve a high accuracy. After such fine tuning, the correlation peaks are sharp and clearly distinguishable (Fig. 4).

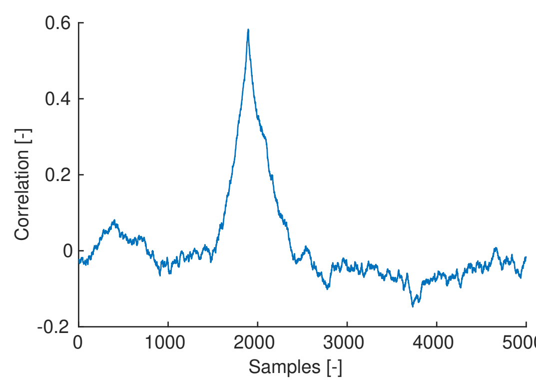

Fig. 4. Detailed real correlation result for a single pulse (antenna disconnected).

This simple approach is fast enough to run on a cheap computer like a Raspberry Pi in a real time even when written in python. It's robust enough to work in a presence of other stronger signals as can be seen in Fig. 5.

In the systems where the PPS pulse is injected before the IQ demodulation, it was found that this method still works

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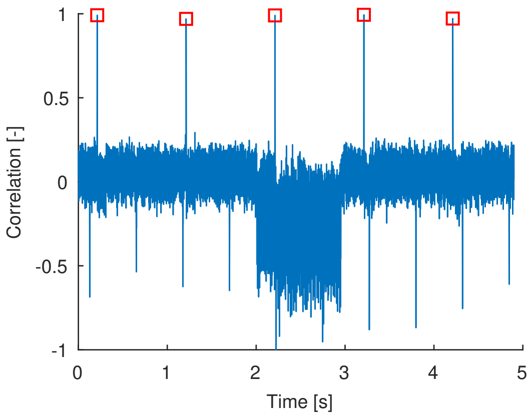

Fig. 5. Example of PPS pulses detection in presence of a stronger signal.

with a limited accuracy when applied on data stream formed from magnitudes of the IQ samples. Further research will be needed in this area to get better results.

IV. Measuring oscillator error

A 28.8 MHz oscillator used in consumer grade RTL-SDR dongles as a timing base for the tuner and the sampling circuit of the RTL2832U has a frequency offset in range of dozens of ppm. A precise frequency calibration of this oscillator is required to tune to the exact frequency and sample rate. As the sampling frequency is derived from the oscillator, it's possible to measure a real sample rate from the distance between the PPS pulses.

The expected oscillator frequency f_0 is divided by N to get a required sample rate f_{Sreq}. The real sample rate f_{Smeas} can be obtained simply by measuring an amount of samples between two detected PPS pulses as these are exactly one second away from each other.

The crystal offset can be compensated by RTL-SDR hardware itself. The PC driver allows user to set a crystal compensation register of the RTL2832U to a specific amount of crystal frequency error in ppm. The exact value can be calculated from the measured sample rate as (2).

$$E_{ppm} = \left(\frac{N f_{Smeas}}{f_0} - 1\right) 10^6 = \left(\frac{f_{Smeas}}{f_{Sreq}} - 1\right) 10^6 \quad (2)$$

The resolution of this method is given by the amount of samples used. It can be significantly increased by taking a distance between two PPS pulses separated by several seconds instead. With 2.4 MS/s sample rate, 0.42 ppm resolution can be achieved for 1 second interval between pulses. By doubling the amount of samples used for error correction the resolution is doubled. For 10 seconds interval, the resolution increases to 0.042 ppm.

The accuracy of the error correction is given by the accuracy of the PPS pulse detection. By increasing the amount of samples used for error calculation, the effects of the PPS pulse detection errors can be significantly reduced.

V. Timing accuracy

The RTL-SDR can run up to about 2.4 MS/s without loosing any samples. That gives a resolution up to 0.42 µs per sample. As the PPS signal period accuracy is in a range of nanoseconds [6], it could be considered zero for the further analysis.

To minimize the effect of RTL-SDR oscillator temperature drift, first 60 minutes of samples received after powering on were thrown away. First the oscillator error is compensated using the method described above to get exactly 2.4 MS/s. Then several minutes of data are recorded and processed by the pulse detection algorithm.

If there was no error in the pulse detection, the distances between the subsequent pulses should be exactly 2.4 million pulses (assuming the oscillator won't drift during recording). Differences in distances between pulses from the expected value from 200 measured pulses are shown on Fig. 6.

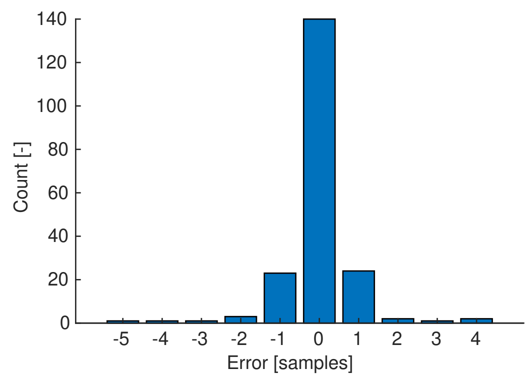

Fig. 6. Difference between consecutive detected pulses.

As show in the histogram, most of the pulses differ up to 1 sample from the expected value, the worst pulse detection error is -5 samples, significantly reducing a timing accuracy to 2.1 µs.

As differences bigger than 1 samples are quite rare, it's possible to filter these out simply by ignoring the pulse that differs from a previous one by more that 1 sample and calculating the correct position simply by adding an expected amount of pulses to the previous one.

VI. Conclusion

The method described allows to synchronize multiple RTL-SDR receivers with accuracy up to 2.1 µs, or 5 samples. A simple algorithm based on replacing pulses that are too far from the expected value by median of the distance between pulses can improve a short term accuracy approximately to 1 pulse, or 0.42 µs.

When used for multilateration purposes (therefore synchronizing two distant receivers) the errors are summed together. The worst case scenario gives error of 4.2 µs which is equal to 1260 m of the position uncertainty per a pair of signal receivers. This error is big enough to render this method unusable for target localization on ground, but it's still sufficient for a rough estimation of aircraft or satellite positions.

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The modification to the hardware required is trivial and cheap off the shelf components can be used. A low price of this solution allows building of the TDOA systems in prices of several dozens dollars per receiver with enough accuracy to track airplane or satellite signals.

Aside of the time synchronization, this method can be also used to measure the RTL-SDR oscillator error with high accuracy for precision calibration of the receiver.

The results described in this article will be further used in development of an experimental satellite localization system.

ACKNOWLEDGMENT

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