SIGNAL PHASE ESTIMATION USING HACKRF ONE SDR FOR RADIO DIRECTION-FINDING APPLICATIONS

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Abstract

This work presents a method for detecting and visualizing the phase of a received radio signal using the HackRF One SDR system. A software module was implemented in GNU Radio Companion v3 to perform filtering, normalization, and phase demodulation of the signal, followed by graphical representation. The obtained results demonstrate the feasibility of this approach for analyzing phase shifts in positioning and direction-finding tasks involving unmanned aerial vehicles.

To determine the spatial coordinates of unmanned aerial vehicles (UAVs) in radio direction-finding systems, it is essential to estimate the Angle of Arrival (AoA) of the signal emitted by the RF source (RS). AoA estimation is based on measuring the phase difference between several receiving channels with antennas of the radar platform, which makes it possible to determine the direction to the RS [1].

To obtain the AoA, it is possible to use multichannel digital receivers integrated on a single platform with coherent frequency and phase synchronization, such as the KrakenSDR or USRP B210. However, such expensive systems can be replaced with a more cost-effective alternative – several HackRF One SDR receivers, which offer adequate performance for AoA estimation.

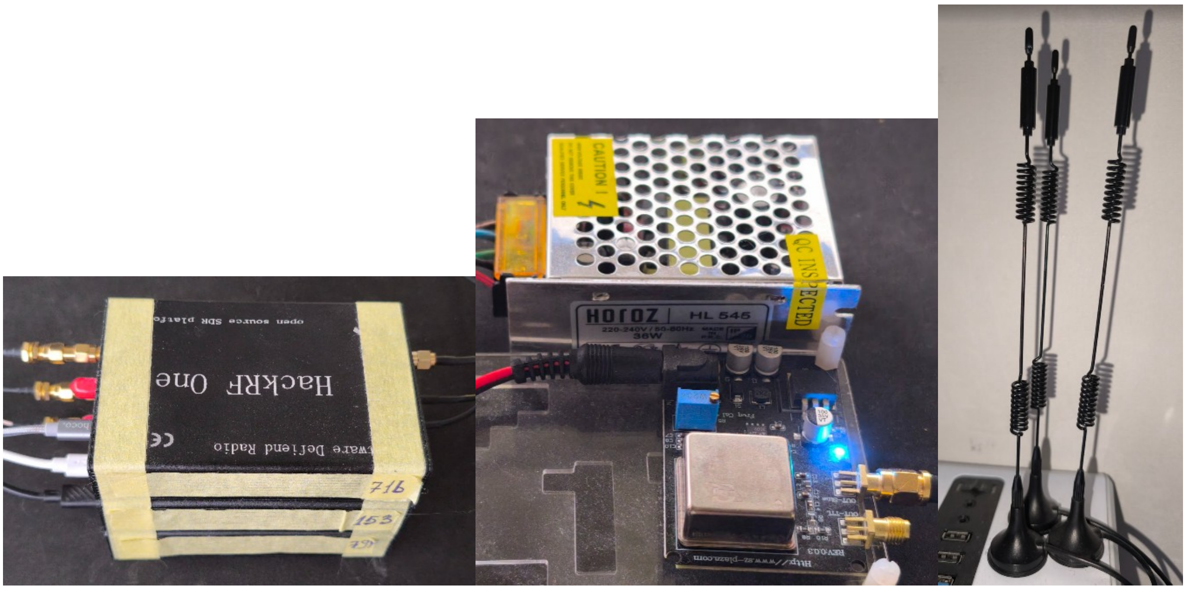
The HackRF One is not a coherent receiver and therefore requires an external 10 MHz reference clock to enable accurate phase measurements. Its internal oscillator suffers from frequency and phase instability, resulting in phase drift between multiple receivers. Providing a common 10 MHz reference signal synchronizes the local oscillators of all SDR modules, ensuring stable and repeatable phase values necessary for AoA algorithms and interferometric direction finding.

In this work, a three-channel experimental platform for phase difference estimation using HackRF One SDRs is proposed. The following equipment was used (Fig. 1):

- three HackRF One SDR receivers (Fig. 1a);
- a personal computer with a sufficient number of USB ports for powering the SDRs and processing the received data;
- a synchronizing generator – an OCXO 10 MHz frequency standard reference module with a power supply unit (Fig. 1b);
- a connecting cable for linking the generator output to the synchronization inputs (CLKIN) of the HackRF One modules;
- three identical wideband omnidirectional antennas (Fig. 1c).

An FM radio station operating at 103 MHz was selected as the radio emission source (RES), as it provided a high signal-to-noise ratio at the experiment location, ensuring stable signal reception and, consequently, accurate phase measurements.

To minimize phase shifts in the antennas, all coaxial cables must be of equal length, and the antennas should be placed at the same location, ensuring that practically identical signals are present at the inputs of each SDR receiver.



a) b) c)

Fig. 1. Equipment used in the experiment: (a) HackRF One SDRs, (b) synchronizing generator, (c) antennas

The experimental platform is designed to measure the phase difference between the channels of SDR receivers and to evaluate its impact on radio direction-finding tasks.

GNU Radio Companion v3 is used to process and display information about the phase difference. It is an open-source software tool for building and testing SDR systems. The platform operates on the principle of stream-based signal processing, where the user constructs a flowgraph from individual functional blocks (filtering, demodulation, analysis, visualization) connected in an appropriate manner. The system receives I/Q data from the SDR receiver, processes it in real time, and displays the results in the form of spectra, time-domain plots, phase characteristics, and more [2].

The algorithm for determining the current phase of the signal for a single SDR receiver in GNU Radio Companion consists of the following stages [3]:

1. Acquisition of I/Q data from the SDR. The receiver, configured with the required parameters (center frequency, gain, receive bandwidth), produces a sequence of complex samples, which can be expressed as:

$$s(t) = I(t) + jQ(t), \tag{1}$$

where $s(t)$ – is the complex signal received by the SDR; $I(t)$ – is the in-phase component (real part); $Q(t)$ is the quadrature component (imaginary part), shifted by 90°. These I/Q data fully describe the amplitude, frequency, and phase of the received signal. The block responsible for performing these operations is the Soapy HackRF Source block.

2. Spectrum translation to the zero-frequency region and preliminary filtering are carried out using the Frequency Xlating FIR Filter block. This block shifts the signal spectrum into the baseband region, extracts a narrow band around the carrier, and reduces noise and unwanted components. This step stabilizes the phase and prepares the signal for accurate phase analysis.

3. Additional filtering and suppression of high-frequency components are performed using a Low Pass Filter block. It suppresses high-frequency noise, smooths the signal shape, improves the signal-to-noise ratio, and ensures the stability of the phase characteristic by minimizing rapid phase fluctuations.

4. The phase of the complex signal is determined using the Complex to Arg block. It is computed from the I/Q data using the standard formula for the argument of a complex number:

$$\phi(t) = arg\left(I(t) + jQ(t)\right) = arctan\left(\frac{Q(t)}{I(t)}\right) \tag{2}$$

5. Phase visualization in the time domain is implemented using the QT GUI Time Sink [4], which displays real-time phase variations of the signal, including its drift, noise fluctuations, and local phase changes. This allows for analyzing the stability of the SDR operation and using phase information for further coherent direction-finding tasks such as AoA estimation.

The block diagram in GNU Radio Companion corresponding to the described algorithm is shown in Fig.2.

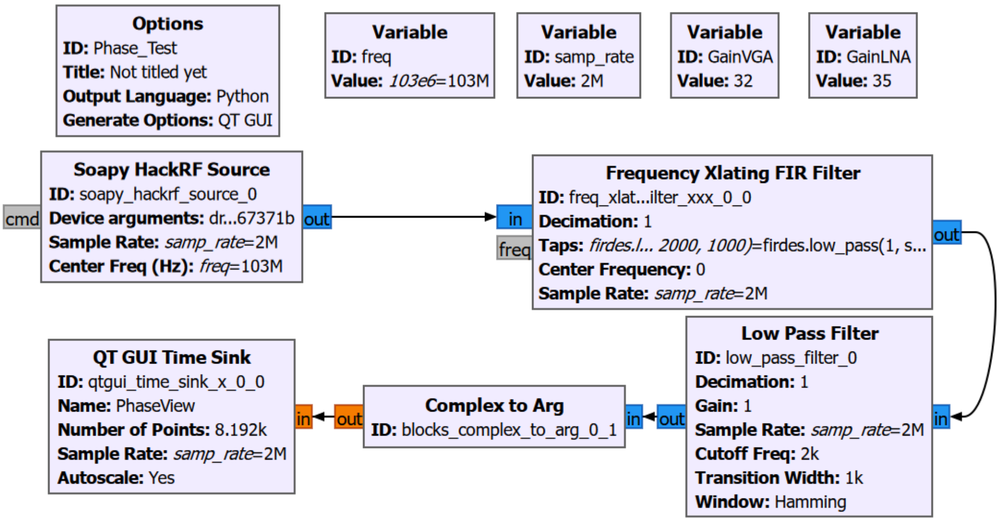


Fig. 2. GNU Radio Companion block diagram for signal reception, filtering, and instantaneous phase calculation

The output of the block diagram, showing the instantaneous phase of the received signal as displayed on the personal computer screen, is presented in Fig. 3.

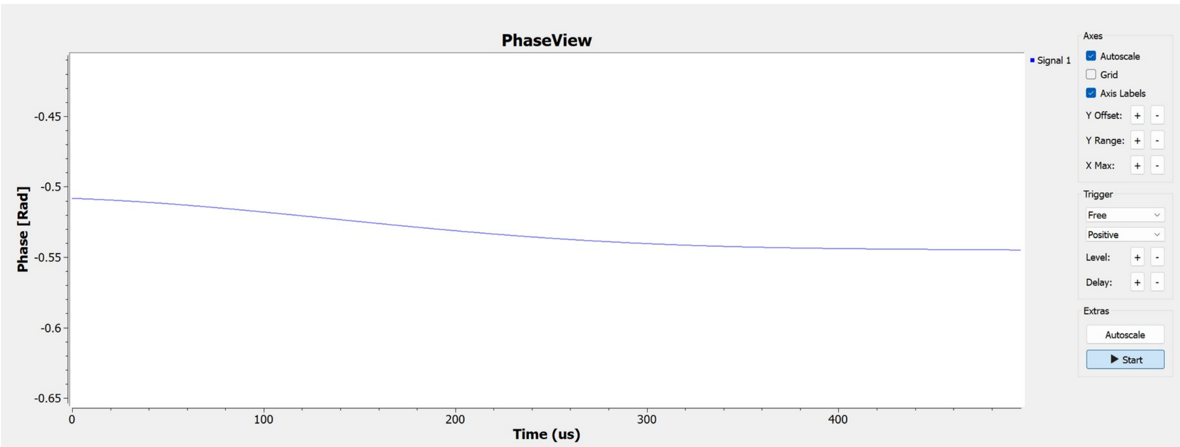


Fig. 3. Visualization of the instantaneous phase of the received signal obtained in GNU Radio

The graph shows that the phase variation over the entire observation interval is approximately 0.07 radians, or only about 4°, which indicates high signal stability and minimal phase fluctuations.

Next, we consider a three-channel direction-finding platform based on HackRF One SDR receivers operating in coherent mode, synchronized by a common external generator with a 10 MHz reference frequency (Fig. 4).

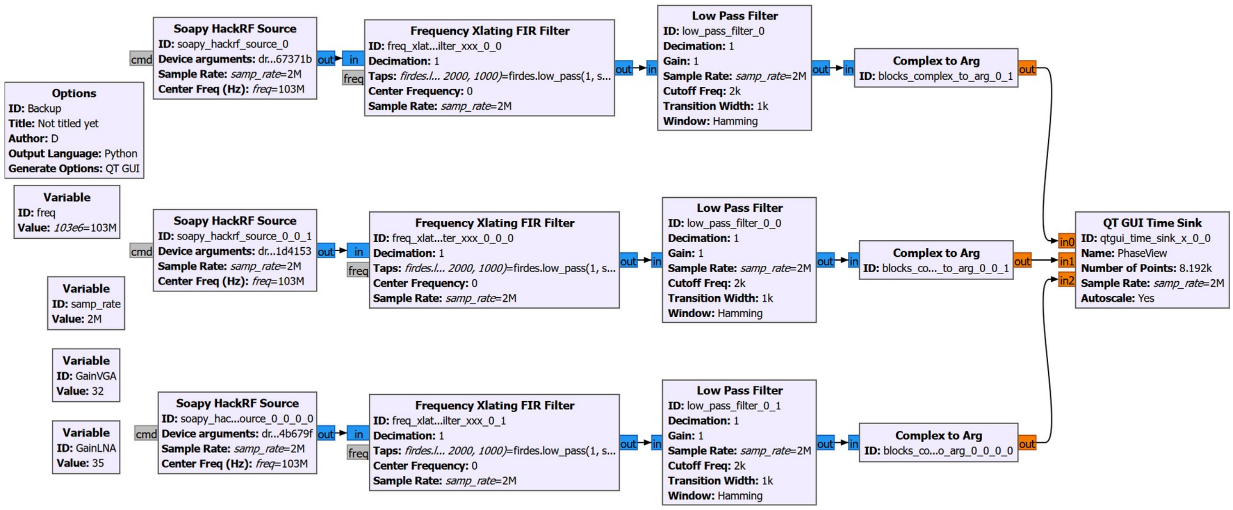
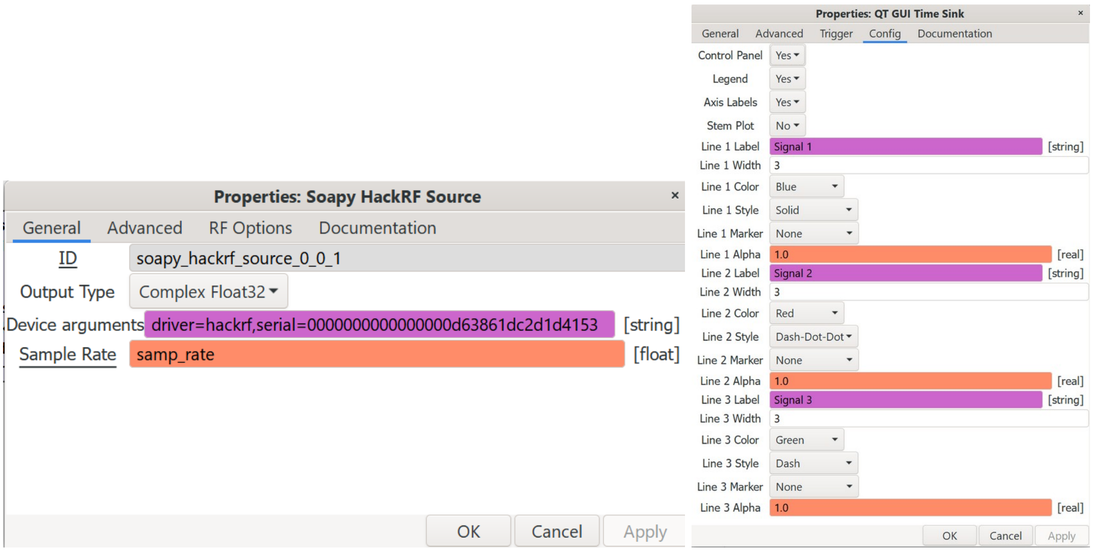


Fig. 4. Block diagram of signal phase visualization from three HackRF One receivers

In Fig. 4, the Variable blocks enable real-time adjustment of key parameters: the operating reception frequency, gain levels, and signal sampling rate. Each SDR has its own configuration block. The values of GainVGA and GainLNA should be selected based on reception conditions and the power of the analyzed signal. Excessive gain increase is undesirable, as it may lead to receiver chain overload, increased noise and phase fluctuations, which can significantly distort the measurement results.

All elements of the block diagram are configured identically, except for the Soapy HackRF Source block, where the Device arguments parameter must be specified by entering the serial number of the corresponding HackRF One receiver. This allows GNU Radio to uniquely identify each SDR in the three-receiver system (Fig. 5a). In the QT GUI Time Sink block, the display parameters are set: the number of points to ensure smooth curves, the color of each plot, line thickness, and line style [5]. An example of the interface configuration is shown in Fig. 5b.



a) b)

Fig. 5. Example of GNU Radio block configuration: a) the Device arguments parameter, which selects a specific HackRF One receiver by its serial number; b) signal display parameters in the QT GUI Time Sink block (color, line thickness, and line style).

The instantaneous phase dependencies of the signal received by the three synchronized HackRF One SDR receivers are shown in Fig. 6.

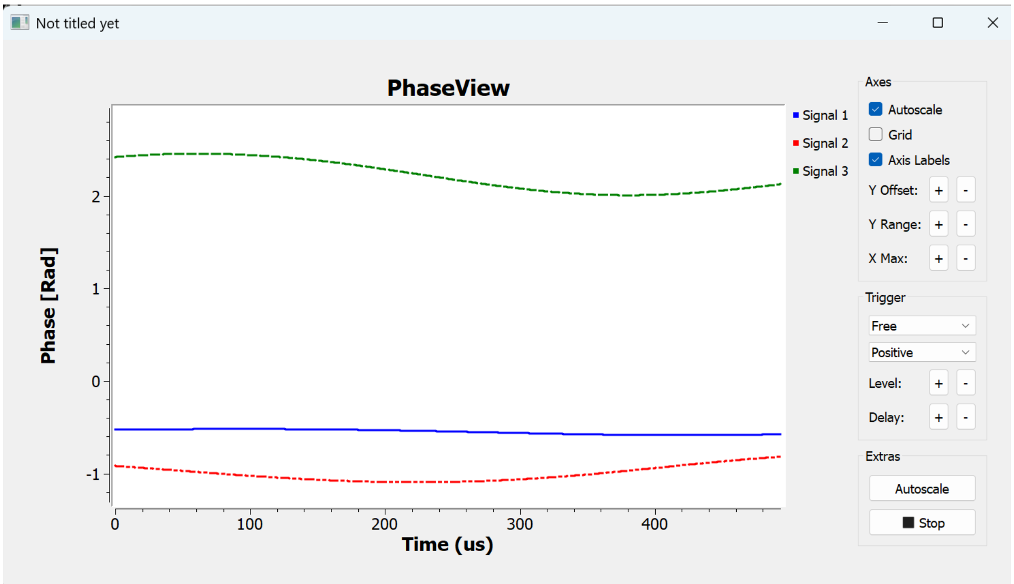


Fig. 6. Instantaneous phases of the received signal from the three SDRs obtained at the output of the GNU Radio block diagram.

As shown in Fig. 6, each channel exhibits its own constant phase offset, caused by differences in reception paths, antenna cable lengths, internal amplifiers, and the phase characteristics of the chips. At the same time, the phases of all three receivers demonstrate high stability: the phase deviation does not exceed approximately 4–11° (Signal 1 ≈ 4°, Signal 2 ≈ 5.7°, Signal 3 ≈ 11°). This confirms the effective synchronization provided by the external 10 MHz reference generator and the coherence of the HackRF One local oscillators. The slight smooth phase changes observed across all three plots follow the same pattern, indicating that all receivers are capturing the same radio signal and that the filters in the GNU Radio block diagram are functioning correctly. The absence of phase drift between the channels confirms that the system is capable of reliably measuring relative phase differences, which is a key requirement for implementing angle-of-arrival (AoA) estimation algorithms.

However, it can be observed that the absolute phase levels of the three receivers differ significantly – for example, the levels of Signal 1 and Signal 2 differ from that of Signal 3. This is likewise caused by the individual characteristics of each device's reception path, such as differences in internal delays, the phase response of the chips, amplifier conditions, cable lengths, and the non-identical behavior of analog components. What is more important is that these offsets are constant and do not change over time, as clearly seen in the graph. The stability of these differences indicates that they are systematic phase offsets that can be compensated for during calibration and subsequent AoA computation. In other words, the fact that the third receiver has a different initial phase value is not a problem – as long as this phase remains stable, the system remains fully functional for phase-based direction-finding tasks.

To eliminate the different phase levels between signals 1 and 2 and the significantly shifted level of signal 3, it is proposed to perform phase calibration prior to further experiments by subtracting the initial phase offsets of each channel.

These results demonstrate the operability of the multi-channel synchronized system and its readiness for further experiments involving phase-based direction finding.

References

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