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FREQUENCY STABILITY OF SOFTWARE-DEFINED RADIOS – PART I. MEASUREMENTS

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Abstract

The popularity and high efficiency of the software-defined radio (SDR) architecture led to its export to other areas of technology, *e.g.*, software-defined networks, vehicles, infrastructure, *etc.* These devices, as commercial off-the-shelf (COTS), are the basis for numerous implementations and prototyping of new solutions. SDR allows easy adoption of existing or development and testing of new communication standards, protocols, *etc.*, also thanks to the support of open and free applications. SDR frequency stability is important in numerous applications especially in techniques based on frequency measurement. This paper presents the methodology of frequency stability measurements for several popular COTS SDR platforms. Measurement was conducted in two variants, with and without an external rubidium frequency standard (RFS). We generally analyse two groups of frequency stability metrics, *i.e.*, the fundamental parameters and the Allan deviation that provide comparison of measurement and manufacturer datasheet. These parameters are analyzed as a function of time depending on the selected measurement intervals. We determine the distribution of the tested parameters, which is the basis for assessing and classifying SDRs. The results obtained can serve as a basis for modelling the SDR instability phenomenon in future simulation studies, including our own planned work as well as broader research conducted by the scientific community.

Keywords: software-defined radio (SDR), frequency stability, Allan deviation, measurement, modelling.

1. Introduction

Traditional radio communication systems are usually designed for a specific application, which can lead to limitations in flexibility and reconfigurability. The development of *software-defined radios* (SDR) introduces new possibilities for the design of communication systems, both in terms of flexibility and efficiency [1, 2]. It is crucial to continuously monitor technological progress to adapt to the dynamically changing communication environment. Software-defined radio is constantly evolving, driving innovation in wireless communications [3, 4].

SDR technology has been used for many years in the consumer, commercial, and military sectors. In addition to the previously mentioned reconfigurability, SDRs consume much less energy than traditional radios, which makes them much more efficient, thus enabling implementation in battery-powered devices, *e.g.* sensors and mobile phones. Thanks to the use of digital signal processing, SDR technology also enables the implementation of much more advanced signal processing functions, which mainly affect the quality of the received signals. Therefore, it can be said that SDR is the future of radio technology [4, 5]. Hence, it is impossible to list all its directions of SDR development. The first is the integration of *artificial intelligence* (AI) algorithms, especially *machine learning* (ML), [4, 6, 7]. Using AI algorithms, it is possible

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to automatically adapt both the modulation and the waveform used to the conditions that prevail in the communication channel [8, 9]. Integration with subsequent generations of mobile network standards, such as *Long Term Evolution* (LTE), *fifth generation New Radio* (5G NR), or *six generation* (6G), is also an important element of the development of SDR. This technology also plays a key role in ensuring reliable vehicle connectivity [10, 11].

SDR is also being developed in the military market [12]. Today, it is difficult to find new radios that are not based on this technology [13]. Thanks to a wide range of operating frequencies, spectrum monitoring and quick tuning, it allows to carry out electromagnetic attacks and to protect against them. Minimizing the size of the SDR means that it is increasingly used in implementations on *unmanned aerial vehicles* (UAVs) [14, 15]. This enables the development of new technologies related to identifying and locating enemy forces [16]. Additionally, in the case of Doppler effect-based localization methods [16, 17], frequency stability is crucial for localization accuracy in contrast to other methods, *e.g.* [18].

Frequency stability is a frequently discussed topic in metrology journals [19-21]. Many SDR-based sensor applications require high frequency stability. For this reason, the paper focuses on the methodology of measurement for selected *commercial off-the-shelf* (COTS) SDR platforms. The presented analysis is based on the results of frequency stability measurements of SDR platforms made without or using a *rubidium frequency standard* (RFS). The study was performed with an additional external frequency standard to assess how it will affect the frequency stability of the SDRs. The results obtained will facilitate decision making in future sensor implementations as to whether its use is necessary. In the SDR datasheets, the frequency accuracy is often omitted or given based only on the accuracy of the oscillator used in an SDR platform. The method and range of empirically determining the frequency accuracy and on this basis classification of SDR determine the originality and novelty of this paper.

This paper consists of two parts. The main contributions of the Part I are listed below.

- We describe SDR platforms with particular emphasis on frequency accuracy, weight, size, and power consumption.
- We present the methodology of frequency stability measurements for SDR platforms.
- Based on empirical studies, we classify SDR platforms in terms of frequency stability.
- We demonstrate the effectiveness of using RFS to minimize the frequency instability error of the SDR local generator.

The main aim of this paper is to develop and present a methodology for the empirical evaluation of frequency stability in selected commercial SDR platforms, with and without the use of an RFS.

Part II of this paper [22] focuses on the use of measurement results to model the SDR frequency instability phenomenon for simulation studies.

The remainder of the paper is organized as follows. Section 2 briefly discusses the SDR platforms. Section 3 shows the testbed and measurement methodology. Section 4 includes the results of measuring the frequency stability of SDR platforms. The synthesis of the results is also presented, which allowed us to compare the SDR platforms. Section 6 provides a summary.

2. SDR Platforms Comparison

For the research, it was decided to choose SDRs that are widely available on the market. Moreover, they are often used in various sensor implementations requiring high frequency stability. However, they come from different price ranges and, therefore, are characterized by different stability parameters.

The first of them, ADALM-PLUTO, is an educational platform that by default operates in the frequency range from 325 to 3800 MHz. It is possible to extend this range through a software modification, which allows the radio to operate from 70 to 6000 MHz [23]. The SDR

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has one transmitting and one receiving *SubMiniature version A* (SMA) output. The frequency accuracy declared by the manufacturer of ADALM-PLUTO is ±25 ppm [24].

An even smaller and lighter solution is the *Universal Software Radio Peripheral* (USRP) B200mini equipped with the highly integrated *radio frequency* (RF) Agile Transceiver AD9364 [25]. It enables transmitting and receiving in the range of 70-6000 MHz with a bandwidth of 56 MHz. The frequency accuracy specified in the device specifications is ±2 ppm.

Another compact and very interesting solution is the bladeRF 2.0 micro xA4 from Nuand [26]. The radio frequency range is 47-6000 MHz for receiving and 70-6000 MHz for transmitting with a maximum bandwidth of 56 MHz. Using a *global positioning system disciplined oscillator* (GPSDO) in laboratory tests, a 1 GHz carrier can be accurate to approximately 500 mHz (±0.5 ppb).

The USRP N210 from the networked series [27] is much more larger than its predecessors. The platform was tested with three different daughteboards: WBX, RFX1200 and XCVR2450. The operating frequency ranges are as follows: 50-2200 MHz for WBX, 1150-1450 MHz for RFX1200, 2400-2500 MHz and 4900-5900 MHz for XCVR2450 [28]. The frequency accuracy of the SDR is estimated to be ±2.5 ppm.

The USRP-2930 is another SDR included in our tests. The operating frequency range of the platform is 50-2200 MHz with a maximum instantaneous real-time bandwidth of 40 MHz. The frequency accuracy of the implemented *oven-controlled crystal oscillator* (OCXO) is equal to ±25 ppb if not locked to *global positioning system* (GPS) and ±10 ppb if locked to GPS [29].

The most expensive SDR we tested is the USRP-2950R. Its frequency accuracy is the same as USRP-2930, corresponding to ± 25 ppb. In case of locked to GPS, frequency accuracy can reach even ±5 ppb. The operating frequency range is also identical to its predecessor, however the USRP-2950R operating instantaneous real-time bandwidth is up to 120 MHz [30].

Comparison of the frequency parameters, power consumption, dimensions and weights of tested SDRs are included in Table 1.

Table 1. Selected technical parameters of the tested platforms

SDR platform	**Frequency range (MHz)**	**Max bandwidth (MHz)**	**Frequency accuracy (ppm)**	**Power consumption (W)**	**Dimensions (mm)****	**Weight (g)**
ADALM-PLUTO	70-6000	20	±25	2.5	78x117x23	116
B200mini	70-6000	56	±2	2.5	55x79x16	108
bladeRF 2.0 micro xA4	47(70)-6000*	56	±0.026	4.5	72x110x24	112
N210 + WBX	70-6000	40	±2.5	13.8	160x204x48	1160
N210 + XCVR2450	2400-2500 & 4900-5900	48	±0.025	12-15	160x204x48	1218
N210 + RFX1200	1150-1450	40	±0.025	12-15	160x204x48	1218
NI-2930	50-2200	40	±0.025	38-44	218x267x39	1787
NI-2950R	50-2200	120	±0.025	38-44	218x267x39	1787

* For bladeRF 2.0 micro xA4, the frequency ranges are 47-6000 MHz or 70-6000 MHz for Tx and Rx, respectively.

**width × depth × height.

3. Measurement Testbed and Methodology

3.1. Testbed

The block scheme of the testbed for measuring the frequency stability of SDR platforms is shown in Fig. 1. A photo of the actual testbed assembled in the laboratory is shown in Fig. 2.

The testbed consists of a transmitting part and a receiving part. The transmitting part includes a Keysight (Agilent) E4438C ESG Vector Signal Generator with an attached FS725 RFS. The receiving part includes a laptop for recording, analyzing, and processing signals, as well as the SDR platforms described in the previous chapter.

The study was carried out in two variants: the first variant assumed no stabilization of SDR platforms with a frequency standard, while in the second variant the platforms were stabilized. *The GNU Radio Companion* (GRC) environment, visible on the laptop screen in Fig. 2, was used to record the signal. The GRC environment was used to record the signal, which is visible in Fig. 2. The GRC environment allows for the simple connection of various SDRs and recording of signals without the need to write complex software, which is why it was decided to use it. Further analysis and signal processing were performed in the Matlab environment, which allows for a more advanced visualization of the research results. One SDR was tested at a time. It was decided to perform the test for two significantly different frequencies f = 1358 MHz and f = 5138 MHz.

All SDRs have been tested at frequency f = 1358 MHz: ADALM-PLUTO, USRP B200mini, bladeRF 2.0 micro xA4, USRP N210 with WBX or RFX1200 daughterboard, USRP-2930, USRP-2950R. At frequency f = 5138 MHz only three SDRs were tested: USRP B200mini, bladeRF 2.0 micro xA4, USRP N210 with XCVR2450 daughterboard.

During the measurements, a complex harmonic signal was generated from the Keysight (Agilent) E4438C ESG Vector Signal Generator shown in Fig. 1 and Fig. 2, at the carrier frequency $f_0 = f + 10$ kHz. This signal was received on SDRs using the GNU Radio Companion environment. The receiver frequency was equal to the test frequency f.

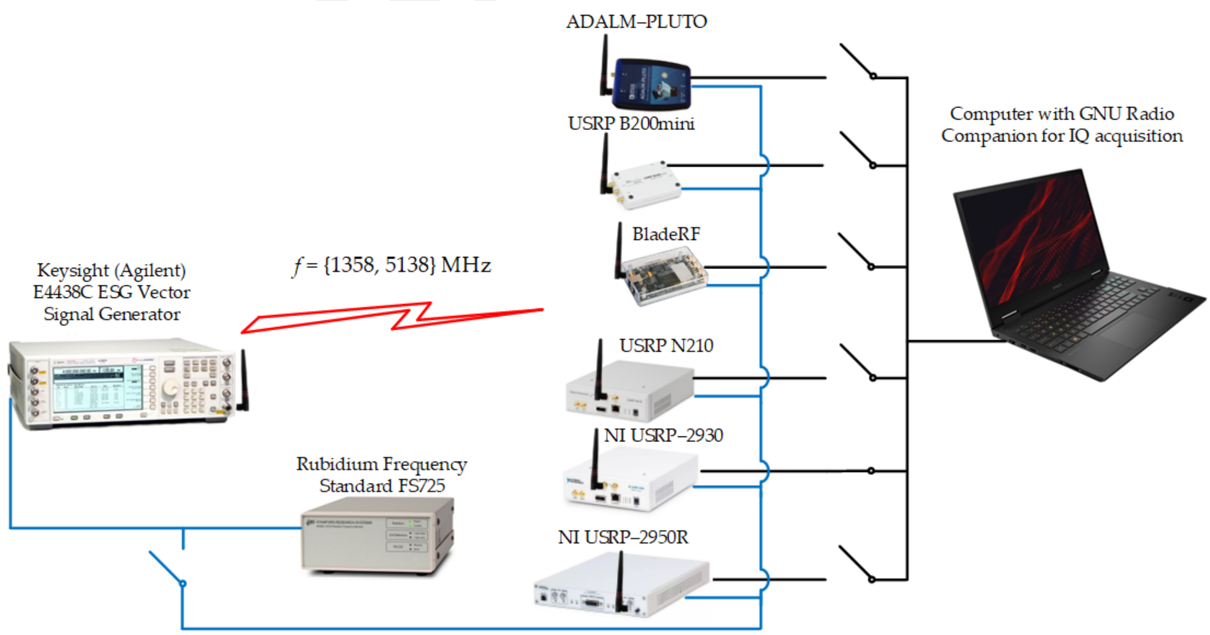

Fig. 1. Block scheme of testbed for frequency stability measurement.

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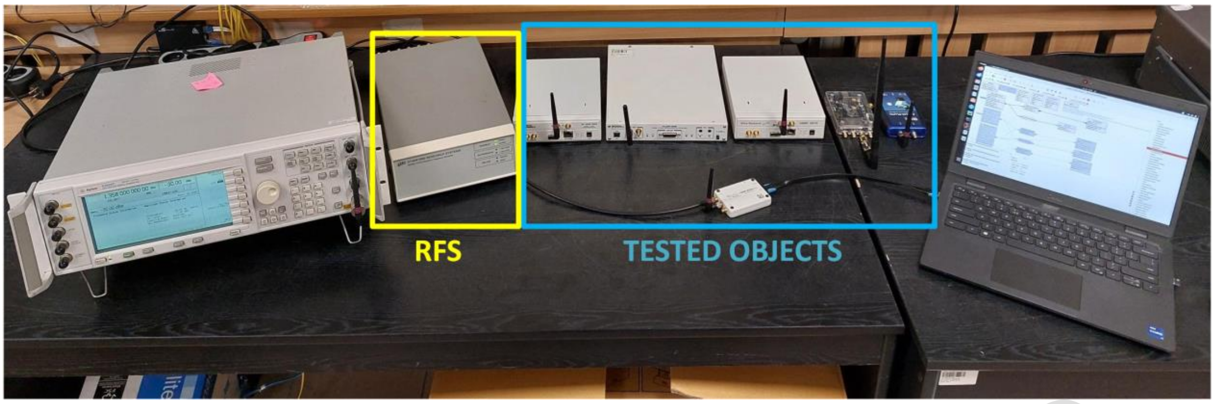

Fig. 2. The actual testbed for frequency stability measurement assembled in the laboratory.

3.2. Methodology

De-tuning between Rx and Tx is done to minimize the effect of DC component, which occurs when a quadrature signal is processed in the baseband. Ideally, after shifting the spectrum to the baseband and taking the 10 kHz offset between the receiver frequency f and the carrier frequency f_0 of the transmitted signal into account, the instantaneous frequency measured in the baseband f_p of the received signal should be 0 Hz. In fact, we are dealing with instability imposed by the internal SDR's oscillator or external RFS FS725, so the frequency value of the received signal changes as a function of time.

The sampling frequency f_s of the received signal was set to almost the lowest possible for the SDR tested. For this reason, for the bladeRF 2.0 micro xA4 it was f_s = 600 kHz, while for the other SDRs it was f_s = 200 kHz. The signal was recorded for 45 minutes.

In the MATLAB environment, the received signal $x(t)$ was further analyzed in the frequency domain, and therefore the received samples were transformed using *fast Fourier transform* (FFT) algorithms. The number of samples transformed in a single iteration was equal to $t_A \cdot f_s$ where t_A is the acquisition time and f_s is the previously mentioned sampling frequency, as shown in Fig. 3. The frequency resolution of the FFT was constant and equal to Δf = 0.01 Hz. Then, the maximum in the obtained spectrum was determined, and the corresponding frequency value f_p was assigned to the appropriate place on the time axis of the graph showing the changes in the instantaneous frequency measured in the baseband f_p of the signal as a function of time, which is visible at the bottom of Fig. 3. Subsequently, the analysis window of the mentioned size $t_A \cdot f_s$ was shifted in the time domain of the $x(t)$ signal by the value Δt_A, and subsequent samples were subjected to identical calculations to determine the next value of the instantaneous frequency of the signal measured in baseband f_p. The basis for further analysis of the recorded results is statistical analysis [31], also considering the Allan deviation [32].

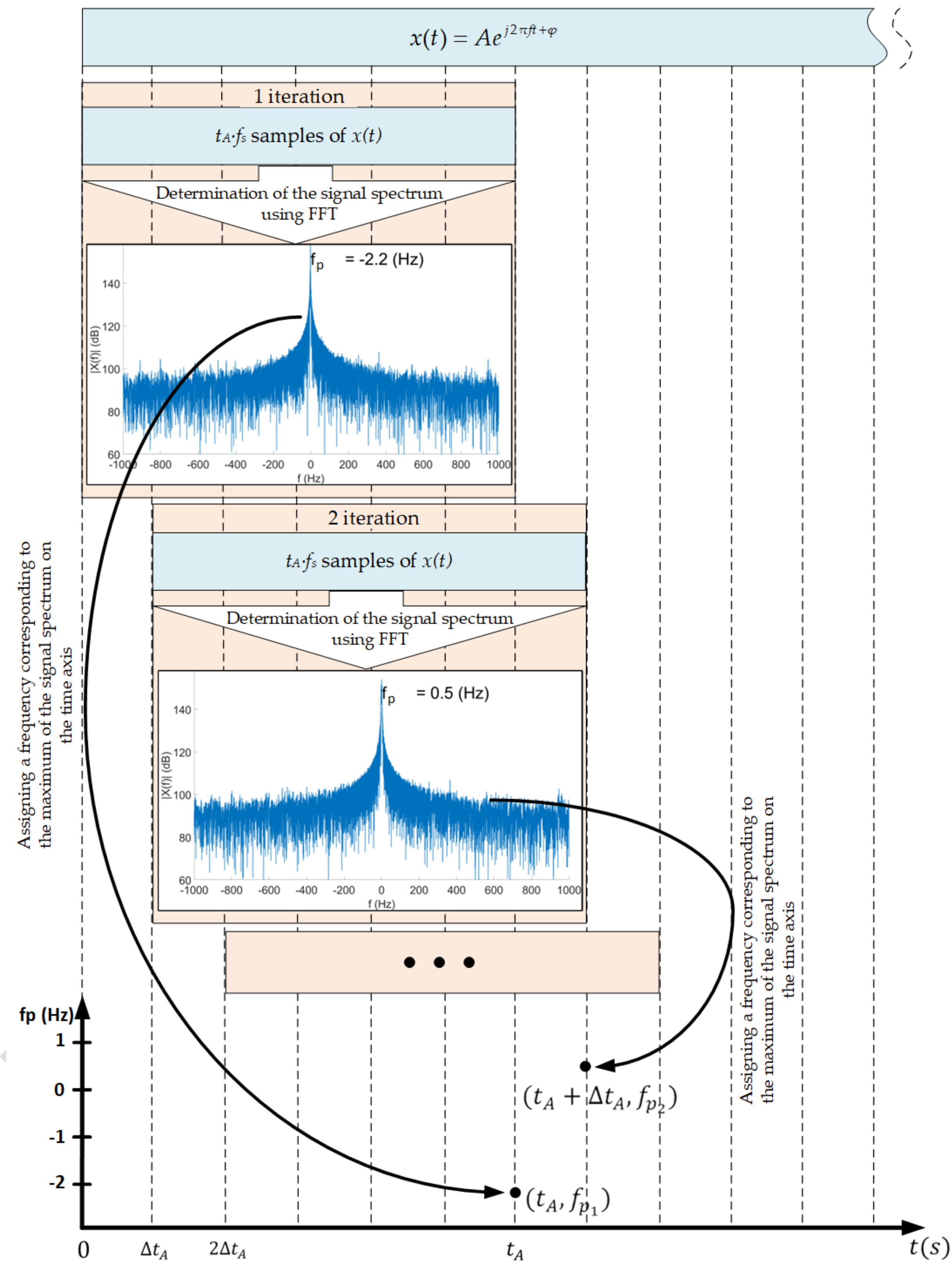

Fig. 3. Method for determining the plots of the instantaneous frequency measured in baseband f_p of the received signal as a function of time using overlapping.

Example of the instantaneous frequency measured in baseband f_p of the received signal as a function of time $f_p(t)$ is shown in Fig. 4.

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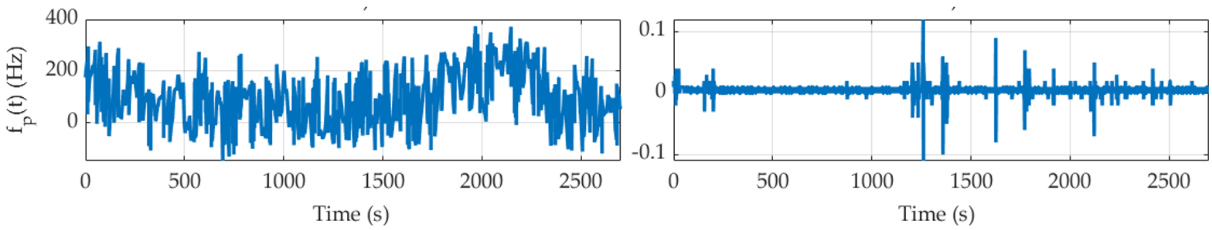

Fig. 4. Example of the instantaneous frequency measured in baseband f_p versus time (f = 1358 MHz, t_A = 1 s, Δt_A = 0.1 s) without RFS on the left and with RFS on the right for USRP-2930.

4. Measurement Results

4.1. Calculation of Fundamental Metrics

The following fundamental metrics and the equations that describe them were used to assess the frequency stability of the SDRs studied:

1) Mean value of the instantaneous frequency measured in baseband μ_f:

$$\mu_f = \frac{1}{K}\sum_{k=1}^{K} f_{p_k}, \tag{1}$$

where $k = 1,2,\ldots,K$ is the index of the selected measurement and K is the number of all measurement values.

2) Frequency oscillation range O_R:

$$O_R = f_{p_{max}} - f_{p_{min}}, \tag{2}$$

where $f_{p_{max}}$ and $f_{p_{min}}$ are the maximum and minimum of the instantaneous frequency measured in the baseband, respectively.

3) Standard deviation of the instantaneous frequency measured in the baseband σ_f:

$$\sigma_f = \sqrt{\frac{1}{K-1}\sum_{k=1}^{K}\left|f_{p_k} - \mu_f\right|^2}. \tag{3}$$

4) Frequency stability s_f [33-35]:

$$s_f = \frac{\sigma_f}{f_0}, \tag{4}$$

where f_0 means the carrier frequency of the signal generated.

In the next step of assessing the frequency stability of selected COTS SDRs, we analyse the values of these parameters. The calculated metrics for t_A = 1 s, Δt_A = 0.1 s, at the two tested carrier frequencies are presented in Table 2 for the first carrier frequency (f = 1358 MHz) and in Table 3 for the second carrier frequency (f = 5138 MHz).

The values of the measured parameters differ by up to several orders of magnitude. For example, for 1358 MHz, without clock synchronization signal, mean instantaneous frequency is from 10^1 Hz (for bladeRF 2.0) to 10^4 Hz (for ADALM-PLUTO), standard deviation of instantaneous frequency is from 10^0 Hz (for B200mini) to 10^2 Hz (for ADALM-PLUTO and N210 + WBX), frequency stability is in the order of 10^{-9} (for B200mini) to 10^{-7} (for ADALM-PLUTO and N210 + WBX), and oscillation range is in the order from 10^1 Hz (for B200mini) to 10^3 Hz (for ADALM-PLUTO and N210 + WBX). When using an external frequency standard for 1358 MHz, the mean instantaneous frequency is from 10^{-3} Hz (for N210 + WBX and NI-2930) to 10^1 Hz (for ADALM-PLUTO), the standard deviation of instantaneous frequency is from 10^{-3} Hz (for N210 + RFX1200) to 10^0 - 10^1 Hz (for ADALM-PLUTO), frequency stability ranges from 10^{-12} Hz (for N210 + RFX1200) to 10^{-9} Hz (for

ADALM-PLUTO), and oscillation range is from 10^{-1} Hz (for N210 + RFX1200) to 10^{1} Hz (for ADALM-PLUTO).

Table 2. Frequency stability results for various SDR platforms ($f = 1358$ MHz, $t_A = 1$ s, $\Delta t_A = 0.1$ s).

SDR platform	Without RFS				With RFS			
	μ_f(Hz)	σ_f (Hz)	s_f (–)	O_R (Hz)	μ_f (Hz)	σ_f (Hz)	s_f (–)	O_R (Hz)
ADALM-PLUTO	$1.67 \cdot 10^{4}$	$2.86 \cdot 10^{2}$	$2.11 \cdot 10^{-7}$	$1.19 \cdot 10^{3}$	$-5.50 \cdot 10^{1}$	$5.17 \cdot 10^{0}$	$3.81 \cdot 10^{-9}$	$3.89 \cdot 10^{1}$
B200mini	$1.44 \cdot 10^{3}$	$5.41 \cdot 10^{0}$	$3.98 \cdot 10^{-9}$	$3.72 \cdot 10^{1}$	$0.00 \cdot 10^{0}$	$1.30 \cdot 10^{0}$	$9.57 \cdot 10^{-10}$	$1.91 \cdot 10^{1}$
bladeRF	$-3.61 \cdot 10^{1}$	$3.52 \cdot 10^{1}$	$2.59 \cdot 10^{-8}$	$1.38 \cdot 10^{2}$	$-2.40 \cdot 10^{-1}$	$4.00 \cdot 10^{-3}$	$3.26 \cdot 10^{-12}$	$1.80 \cdot 10^{-1}$
N210 + WBX	$1.01 \cdot 10^{3}$	$1.85 \cdot 10^{2}$	$1.36 \cdot 10^{-7}$	$1.16 \cdot 10^{3}$	$4.00 \cdot 10^{-3}$	$1.40 \cdot 10^{-2}$	$1.05 \cdot 10^{-11}$	$8.00 \cdot 10^{-1}$
N210 + RFX1200	$1.18 \cdot 10^{3}$	$7.91 \cdot 10^{1}$	$5.82 \cdot 10^{-8}$	$4.17 \cdot 10^{2}$	$1.00 \cdot 10^{-2}$	$1.00 \cdot 10^{-3}$	$1.00 \cdot 10^{-12}$	$5.00 \cdot 10^{-2}$
NI-2930	$9.12 \cdot 10^{1}$	$9.76 \cdot 10^{1}$	$7.19 \cdot 10^{-8}$	$5.22 \cdot 10^{2}$	$4.00 \cdot 10^{-3}$	$7.00 \cdot 10^{-3}$	$5.04 \cdot 10^{-12}$	$2.30 \cdot 10^{-1}$
NI-2950R	$9.28 \cdot 10^{2}$	$1.41 \cdot 10^{1}$	$1.04 \cdot 10^{-8}$	$7.07 \cdot 10^{1}$	$-2.00 \cdot 10^{-2}$	$3.00 \cdot 10^{-3}$	$1.89 \cdot 10^{-12}$	$9.00 \cdot 10^{-2}$

Table 1. Frequency stability results for various SDR platforms ($f = 5138$ MHz, $t_A = 1$ s, $\Delta t_A = 0.1$ s).

SDR Platform	Without RFS				With RFS			
	μ_f(Hz)	σ_f (Hz)	s_f (–)	O_R (Hz)	μ_f (Hz)	σ_f (Hz)	s_f (–)	O_R (Hz)
B200mini	$5.52 \cdot 10^{3}$	$7.16 \cdot 10^{1}$	$1.39 \cdot 10^{-8}$	$2.82 \cdot 10^{2}$	$-2.00 \cdot 10^{-3}$	$5.22 \cdot 10^{0}$	$1.02 \cdot 10^{-9}$	$1.15 \cdot 10^{2}$
bladeRF	$5.52 \cdot 10^{2}$	$9.55 \cdot 10^{2}$	$1.86 \cdot 10^{-7}$	$2.45 \cdot 10^{3}$	$-1.67 \cdot 10^{0}$	$5.00 \cdot 10^{-3}$	$9.46 \cdot 10^{-13}$	$9.00 \cdot 10^{-2}$
N210 + XCVR2450	$4.73 \cdot 10^{3}$	$3.73 \cdot 10^{2}$	$7.26 \cdot 10^{-8}$	$2.09 \cdot 10^{3}$	$1.10 \cdot 10^{-2}$	$5.00 \cdot 10^{-3}$	$9.95 \cdot 10^{-13}$	$8.00 \cdot 10^{-2}$

Based on the results of the measurements, it can be seen that the use of an external clock generally improves the stabilization parameters of the COTS platforms by 2–4 orders of magnitude. Considering the obtained results, it can be concluded that ADALM-PLUTO is characterized by the worst clock stabilization parameters. The use of a frequency standard does not significantly improve the parameters of this platform. Therefore, we do not recommend using this SDR in applications where clock synchronization and stability play a crucial role. B200mini has the best parameters without an external clock, while connecting the frequency standard improves its metrics, but in this case this SDR is not classified at the top of the list. The best parameters using the frequency standard were obtained for the N210 + RFX1200, while the N210 + WBX platform without a clock had some of the worse parameters.

Operation in higher frequency ranges is only possible for three platforms, which are characterized by relatively good parameters with and without an external clock. Hence, considering all these aspects, we recommend the use of B200mini and bladeRF 2.0 as the best platforms operating in a wide frequency range with and without an external frequency reference, respectively. The small size and weight are their additional advantage, which allows implementing these COTS SDRs on UAVs.

4.2. Comparison of Manufacturers' and Measurement results

The frequency stability in a crystal oscillator is usually represented in relative units, the so-called ppm. The conversion of the ppm value to the equivalent frequency accuracy in Hz is realized as follows:

$$\delta_f(\mathrm{Hz}) = \Delta F(\mathrm{ppm}) \cdot f_0(\mathrm{MHz}) \qquad (5)$$

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where ΔF and f_0 means the frequency accuracy and carrier frequency of the generated signal, respectively.

The frequency stability results based on manufacturer data and measurements for analyzed COTS SDRs are presented in Table 4 and Table 5 for 1358 MHz and 5138 MHz, respectively.

Table 4. Comparison of tested SDR platforms based on manufacturer and measurement results for f = 1358 MHz.

SDR platform without external oscillator	**Manufacturers' data**		**Measurement data, $t_A = 1$ s, Δt_A=0.1 s**	
	ΔF(ppm)	δ_f(Hz)	μ_f (Hz)	σ_f (Hz)
ADALM-PLUTO	± 25	$3.39 \cdot 10^4$	$1.67 \cdot 10^4$	$2.86 \cdot 10^2$
N210 + WBX	± 2.5	$3.39 \cdot 10^3$	$1.01 \cdot 10^3$	$1.85 \cdot 10^2$
N210 + RFX1200	± 2.5	$3.39 \cdot 10^3$	$1.18 \cdot 10^3$	$7.91 \cdot 10^1$
B200mini	± 2	$2.72 \cdot 10^3$	$1.44 \cdot 10^3$	$5.41 \cdot 10^0$
bladeRF 2.0 micro xA4	± 0.026	$3.40 \cdot 10^1$	$-3.61 \cdot 10^1$	$3.52 \cdot 10^1$
NI–2950R	± 0.025	$3.39 \cdot 10^1$	$9.28 \cdot 10^2$	$1.41 \cdot 10^1$
NI–2930	± 0.025	$3.39 \cdot 10^1$	$9.12 \cdot 10^1$	$9.76 \cdot 10^1$
SDR platform with external oscillator	with GPSDO		with FS725 RFS	
ADALM-PLUTO	n/a	n/a	$-5.50 \cdot 10^1$	$5.17 \cdot 10^0$
N210 + WBX	± 0.01	$1.36 \cdot 10^1$	$4.00 \cdot 10^{-3}$	$1.40 \cdot 10^{-2}$
N210 + RFX1200	± 0.01	$1.36 \cdot 10^1$	$1.00 \cdot 10^{-2}$	$1.00 \cdot 10^{-3}$
B200mini	n/a	n/a	$0.00 \cdot 10^0$	$1.30 \cdot 10^0$
bladeRF 2.0 micro xA4	± 0.0005	$6.79 \cdot 10^{-1}$	$-2.40 \cdot 10^{-1}$	$4.00 \cdot 10^{-3}$
NI–2950R	± 0.005	$6.79 \cdot 10^0$	$-2.00 \cdot 10^{-2}$	$3.00 \cdot 10^{-3}$
NI–2930	± 0.01	$1.36 \cdot 10^1$	$4.00 \cdot 10^{-3}$	$7.00 \cdot 10^{-3}$

Table 5. Comparison of tested SDR platforms based on manufacturer and measurement results for f=5138 MHz.

SDR platform without external oscillator	**Manufacturers' data**		**Measurement data, $t_A = 1$ s, Δt_A=0.1 s**	
	ΔF(ppm)	δ_f(Hz)	μ_f (Hz)	σ_f (Hz)
N210 + XCVR2450	± 2.5	$1.28 \cdot 10^4$	$4.73 \cdot 10^3$	$3.73 \cdot 10^2$
B200mini	± 2	$1.03 \cdot 10^4$	$5.52 \cdot 10^3$	$7.16 \cdot 10^1$
bladeRF 2.0 micro xA4	± 0.026	$1.34 \cdot 10^2$	$5.52 \cdot 10^2$	$9.55 \cdot 10^2$
SDR platform with external oscillator	with GPSDO		with FS725 RFS	
N210 + XCVR2450	± 0.01	$5.14 \cdot 10^1$	$1.10 \cdot 10^{-2}$	$5.00 \cdot 10^{-3}$
B200mini	n/a	n/a	$-2.00 \cdot 10^{-3}$	$5.22 \cdot 10^0$
bladeRF 2.0 micro xA4	± 0.0005	$2.57 \cdot 10^0$	$-1.67 \cdot 10^0$	$5.00 \cdot 10^{-3}$

Comparing the frequency accuracy δ_f calculated according to formula (5) with the results of empirical studies for the case without RFS, we can see that the standard deviation σ_f calculated according to formula (3) is in most cases even several orders smaller than the frequency accuracy δ_f. To compare them, it is necessary to also include the mean value μ_f in the empirical results. The values obtained then are comparable. However, the results of studies with RFS are difficult to compare because the manufacturers provide data only for stabilization with GPSDO. Much better results were obtained in this case for empirical studies with RFS, for which σ_f could reach values on the order of a few millihertz (*i.e.*, 10^{-3} Hz), while the frequency accuracy δ_f was of the order of single hertz.

4.3. Influence of data acquisition time on instantaneous frequency estimation

The example graph presented in Fig. 4 was obtained for an acquisition time equal to 1 s. The influence of changes in this parameter on the analyzed frequency stability phenomenon was shown using the example of the selected SDR. For this purpose, we have chosen the bladeRF 2.0 platform, which from the point of view of the application presented in [17, 35] provides sufficient stability with and without an external frequency standard in terms of the frequency oscillation range. For this SDR, we also show plots of instantaneous frequency versus time in Fig. 5 for 1358 MHz and different acquisition times, t_A = [0.1, 1, 10, 100] s.

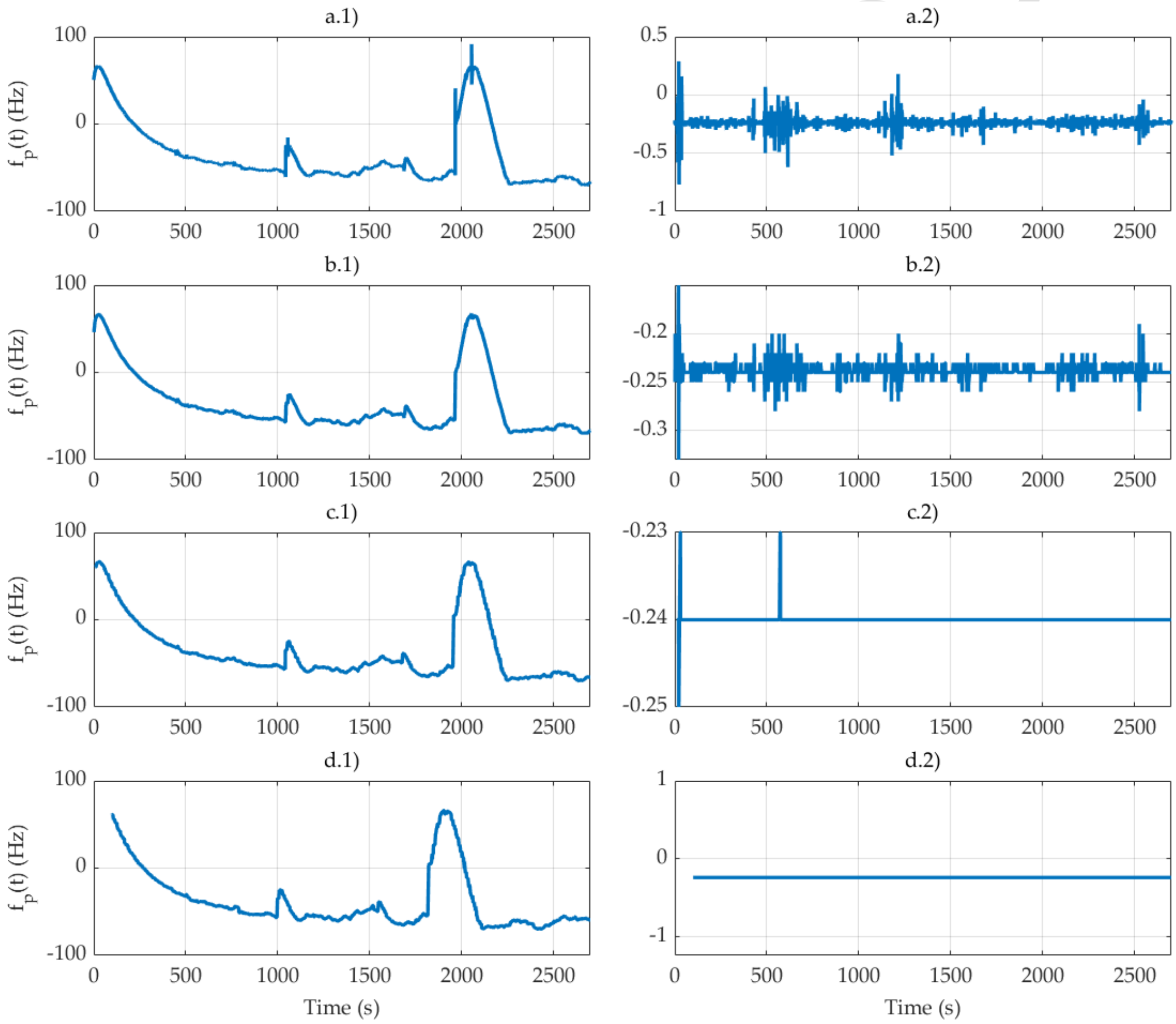

Fig. 3. Exemplary bladeRF's plots of instantaneous frequency measured in baseband f_p versus time without RFS on the left and with RFS on the right for f = 1358 MHz, Δt_A = 0.1 s, and different acquisition time: a) t_A = 0.1 s, b) t_A = 1 s, c) t_A = 10 s, d) t_A = 100 s.

Regardless of the adopted acquisition time, the nature of changes in the instantaneous frequency is generally the same. This is especially noticeable in cases without a frequency

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standard (see the graph on the left of Fig. 5). The use of a stable external clock allows one to eliminate the trend of changes in the average instantaneous frequency (see plot to the right of Fig. 5). In this case, increasing the acquisition time allows further reduction of frequency fluctuations of the obtained plots. For t_A = 100 s, the instantaneous frequency of the received signal is fully stabilized on the obtained plot and does not have any oscillations. In some graphs, we can see frequency jumps resulting from the operation of atomic clocks, which is also mentioned in [21].

5. Allan Deviation

The measure of frequency stability used to assess the stochastic stability of a clock as a function of the averaging time (measurement interval τ) is the Allan deviation σ_{A_f}, expressed by the following formula [32, 36]:

$$\sigma_{A_f}(\tau) = \sqrt{\frac{1}{2(K-1)}\sum_{k=1}^{K-1}\left(f_p^{k+1} - f_p^k\right)^2} \tag{6}$$

where f_p^k is the frequency difference between the measured frequency and the nominal frequency (in our case, this is the previously determined value of the instantaneous frequency measured in the baseband f_p) averaged over the measurement interval τ [37]:

$$f_p^k = \frac{1}{\tau}\int_{t_k}^{t_k+\tau} f_p(t)dt, \tag{7}$$

and K is the number of all averaged frequencies f_p^k.

We pay special attention to Allan deviation measurements, as a standardized frequency stability metric widely used by equipment manufacturers and research centers [38-40]. Exemplary Allan deviation plots versus averaging time obtained during measurements for tested SDRs are shown in Fig. 6 and Fig. 7 for 1358 MHz and 5138 MHz, respectively.

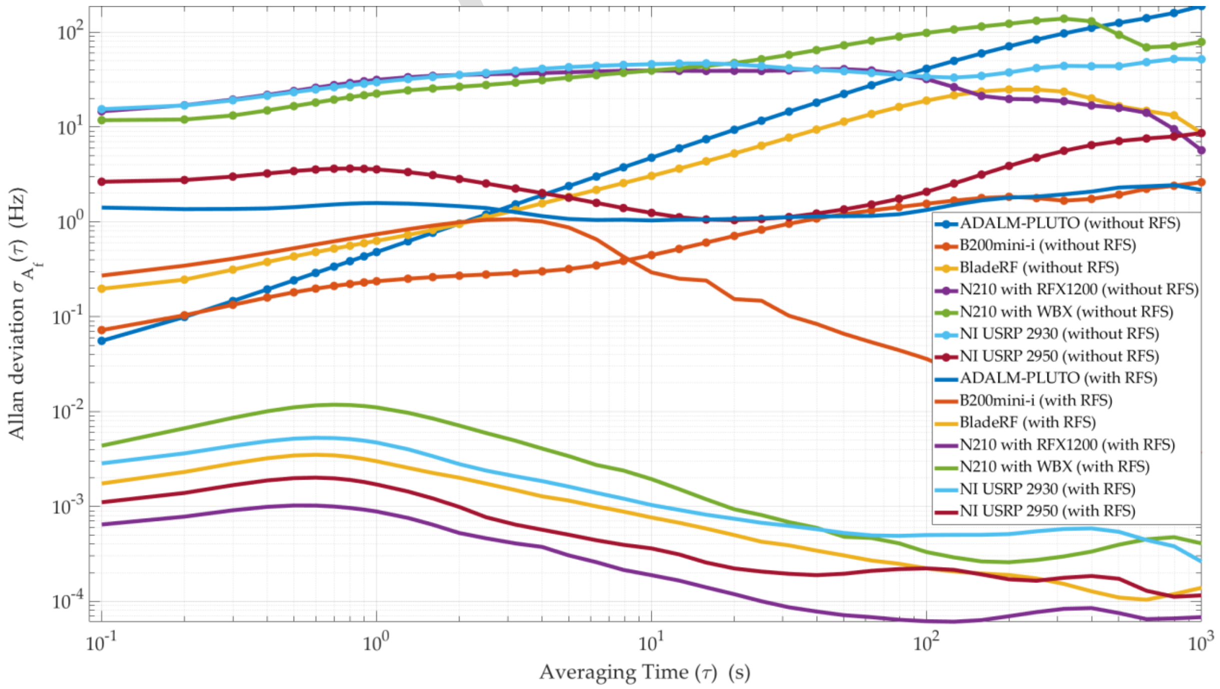

Fig. 6. Allan deviation versus averaging time for COTS SDRs and f = 1358 MHz.

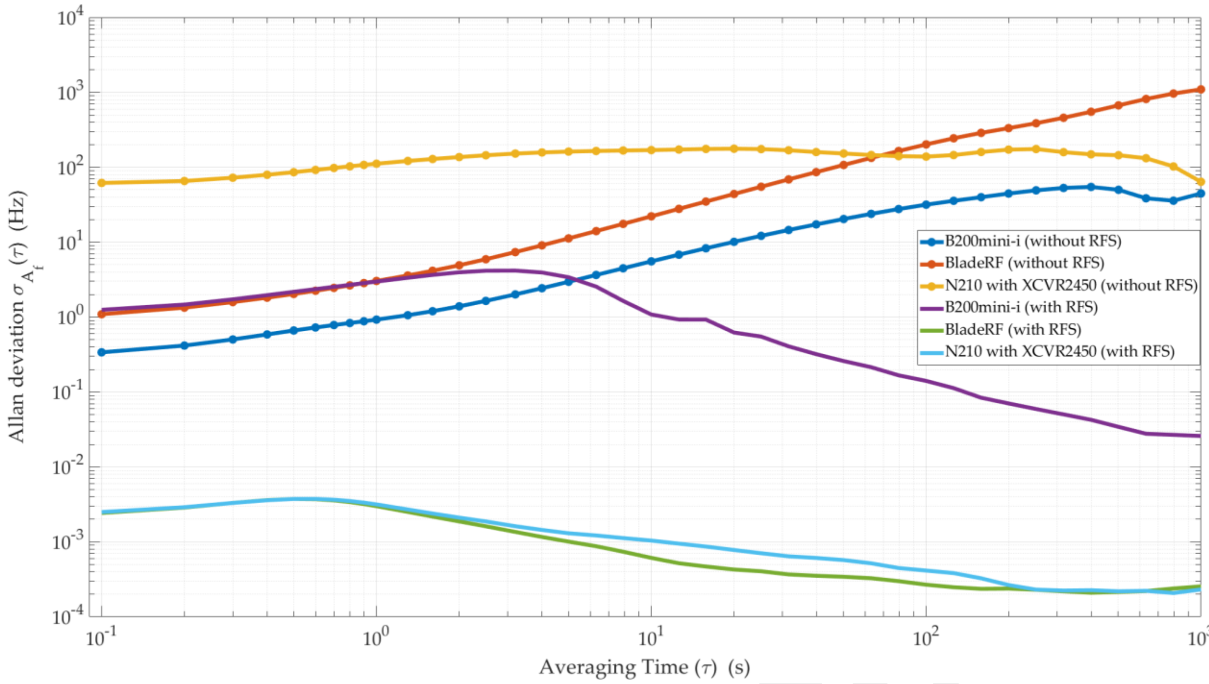

Fig. 7. Allan deviation versus averaging time for COTS SDRs and f = 5138 MHz.

The obtained results show that the conclusions from the Allan deviation analysis coincide in key issues obtained with the analysis of other parameters presented in Sections 4.1 and 4.2. The graphs clearly illustrate how an external frequency standard significantly improves the stability of the SDRs clock. The Allan deviation plots for the SDR study with the external clock attached are several orders of magnitude lower than those for the SDR without the external clock attached. In this case, the exceptions are ADALM-PLUTO (for 1358 MHz) and B200mini (for 1358 MHz and 5138 MHz), for which the Allan deviation measured with the external clock attached achieves values that are comparable to those obtained for the other SDRs tested without the external frequency clock attached. It is also interesting that for ADALM-PLUTO the Allan deviation measured without an external clock connected to the SDR is better (*i.e.* smaller) for the averaging time $\tau \leq 2$ s than for the test conducted with an external clock connected to the SDR. Similarly, for B200mini the Allan deviation measured without an external clock connected to the SDR is better for the averaging time $\tau \leq 8$ s (for 1358 MHz) and $\tau \leq 5$ s (for 5138 MHz) than for the test conducted with an external clock connected to the SDR.

The acquisition time t_A in the provided examples is 1 s with Δt_A step 0.1 s. A summary of the Allan deviation results for various acquisition times t_A and a single averaging time τ = 1 s are presented in Table 6 and Table 7 for f = 1358 MHz and f = 5138 MHz, respectively.

Based on Fig. 6 and Fig. 7, the Allan deviation takes values from 10^{-4} to 10^{2}, which gives 6 orders of magnitude. The range of Allan deviation changes is even greater based on calculations for different acquisition times. Analyzing Table 6 and Table 7, we can see that the Allan deviation changes range from about 10^{-10} to 10^{4}, which gives 14 orders of magnitude. Based on the plots presented in Fig. 6 and Fig. 7, the devices were classified according to the value of this parameter. Hence, we propose to set two blur limits at the levels 10^{-2} and 10^{0} Hz, which allow the tested SDRs to be divided into three classes in terms of clock stability. It was assumed that the first class of low-stability devices have Alan deviation values above 10^{0} Hz. The second class of medium-stability devices has values ranging from 10^{0} to 10^{-2} Hz. Devices for which the Allan deviation values are lower than 10^{-2} Hz were classified as third class devices with high-stability.

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Table 6. Allan deviations for all tested SDRs, 1358 MHz and different acquisition time t_A.

t_A (s) / **SDR Platform**	0.1	1	10	100	0.1	1	10	100
	Without RFS				**With RFS**			
	Allan deviation (Hz)							
ADALM-PLUTO	$2.30 \cdot 10^{-1}$	$2.30 \cdot 10^{-1}$	$2.79 \cdot 10^{0}$	$2.47 \cdot 10^{0}$	$4.60 \cdot 10^{0}$	$2.49 \cdot 10^{0}$	$6.35 \cdot 10^{-1}$	$6.25 \cdot 10^{-1}$
B200mini	$6.90 \cdot 10^{-2}$	$5.60 \cdot 10^{-2}$	$1.80 \cdot 10^{-2}$	$1.80 \cdot 10^{-2}$	$5.53 \cdot 10^{-1}$	$5.49 \cdot 10^{-1}$	$1.79 \cdot 10^{-1}$	$1.80 \cdot 10^{-1}$
bladeRF 2.0 micro xA4	$4.69 \cdot 10^{-1}$	$3.97 \cdot 10^{-1}$	$7.01 \cdot 10^{-1}$	$7.30 \cdot 10^{-1}$	$2.42 \cdot 10^{-5}$	$8.96 \cdot 10^{-6}$	$7.31 \cdot 10^{-8}$	$< 10^{-10}$
N210 + RFX1200	$1.03 \cdot 10^{3}$	$9.84 \cdot 10^{2}$	$3.59 \cdot 10^{2}$	$3.64 \cdot 10^{2}$	$5.12 \cdot 10^{-5}$	$7.81 \cdot 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$
N210 + WBX	$5.08 \cdot 10^{2}$	$5.04 \cdot 10^{2}$	$4.52 \cdot 10^{2}$	$4.45 \cdot 10^{2}$	$2.51 \cdot 10^{-4}$	$1.22 \cdot 10^{-4}$	$2.04 \cdot 10^{-6}$	$1.60 \cdot 10^{-7}$
NI–2930	$9.02 \cdot 10^{3}$	$8.76 \cdot 10^{2}$	$4.72 \cdot 10^{2}$	$4.82 \cdot 10^{2}$	$3.58 \cdot 10^{-5}$	$2.22 \cdot 10^{-5}$	$1.93 \cdot 10^{-6}$	$9.03 \cdot 10^{-8}$
NI–2950R	$1.40 \cdot 10^{1}$	$1.27 \cdot 10^{1}$	$2.53 \cdot 10^{0}$	$2.58 \cdot 10^{0}$	$1.83 \cdot 10^{-5}$	$2.90 \cdot 10^{-6}$	$< 10^{-10}$	$< 10^{-10}$

Table 7. Allan deviations for all tested SDRs, 5138 MHz and different acquisition time t_A.

t_A (s) / **SDR Platform**	0.1	1	10	100	0.1	1	10	100
	Without RFS				**With RFS**			
	Allan deviation (Hz)							
B200mini	$9.78 \cdot 10^{-1}$	$8.57 \cdot 10^{-1}$	$1.41 \cdot 10^{0}$	$1.41 \cdot 10^{0}$	$8.79 \cdot 10^{0}$	$8.88 \cdot 10^{0}$	$2.87 \cdot 10^{0}$	$2.81 \cdot 10^{0}$
bladeRF 2.0 micro xA4	$9.18 \cdot 10^{0}$	$9.21 \cdot 10^{0}$	$2.28 \cdot 10^{1}$	$1.59 \cdot 10^{2}$	$5.12 \cdot 10^{-5}$	$8.98 \cdot 10^{-6}$	$2.49 \cdot 10^{-8}$	$< 10^{-10}$
N210 + XCVR2450	$1.30 \cdot 10^{4}$	$1.24 \cdot 10^{4}$	$6.12 \cdot 10^{3}$	$6.14 \cdot 10^{3}$	$7.56 \cdot 10^{-5}$	$9.98 \cdot 10^{-6}$	$3.74 \cdot 10^{-8}$	$< 10^{-10}$

Based on this classification proposal and considering the Allan deviation for $f = 1358$ MHz and $\tau = 1$ s, N210 + RFX1200, N210 + WBX, NI–2930, and NI-2950R without RFS and ADALM-PLUTO with RFS are classified as low-stability class devices, ADALM-PLUTO, B200mini, and bladeRF 2.0 micro xA4 without RFS, and B200mini with RFS can be classified to medium-stability class devices, and bladeRF 2.0 micro xA4, N210 + RFX1200, N210 + WBX, NI-2930, and NI–2950R with RFS can be classified as high-stability class devices. Analogously, considering the Allan deviation for $f = 5138$ MHz and $\tau = 1$ s, N210 + XCVR2450 and bladeRF 2.0 micro xA4 without RFS and B200mini with RFS are classified as low-stability class devices, B200mini without RFS is classified as a medium-stability class device, and N210 + XCVR2450 and bladeRF 2.0 micro xA4 with RFS are classified as high-stability class devices.

6. Conclusions

This paper focuses on the measurement methodology, obtained result analysis, comparison of COTS SDR platforms regarding frequency stability. In our tests, we included six SDRs from three manufacturers, that is, ADALM-PLUTO, bladeRF 2.0 micro xA4, and four USRP models: B200mini, NI-2950R, NI-2930, and N210 with three daughterboards, WBX, RFX1200, and XCVR2450. Measurements were carried out for the 1358 and 5138 MHz frequencies and two variants, *i.e.*, without and with an external RFS. In the analysis, we used several metrics that allow for evaluating the tested devices in terms of frequency stability. Based on the Allan deviation, we proposed dividing SDRs into three classes: low-, medium- and high-stability devices. We also compared the measurement results obtained with the data presented by the device manufacturers.

The frequency stability of transmitting and receiving devices (including radio devices) plays a crucial role in all telecommunications and navigation systems, particularly in synchronization processes and many applications, for example [38, 41]. From the point of view of using COTS SDR in potential UAV-based mobile applications, weight, size, and power consumption issues play a crucial role in addition to frequency stability.

The presented analysis and comparison provide essential information for potential SDR users or system designers about a critical feature of the devices for specific applications. The obtained results are the basis for modelling the effects of frequency instability in the design of devices that use SDR. These issues are presented in the second part of this paper [22].

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