SDR BASED MULTIBAND PROCESSING FOR PICKUP SIGNALS IN SYNCHROTRONS

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Abstract

A proof of principle implementation in software-defined radio (SDR) for signal processing at multiple harmonics of the revolution frequency for intensity measurement applications is presented. Two off-the-shelf SDR frontends, USRP X310 and ADALM2000, are combined with the GNU Radio framework to provide real-time signal filtering. A maximum signal processing rate of 5 MSa/s is achieved, and the challenges of real-time processing in these devices are discussed. Beam measurements validating the implemented signal flowgraphs are shown.

INTRODUCTION

Software-defined radio (SDR) technology is recently being adopted for beam operations and diagnostics in accelerators. Applications such as beam excitation [1], signal digitization [2], and a spill optimization system [3] have been successfully commmissioned at the GSI SIS-18 synchrotron using the GNU Radio software. The goal of this work is to expand the application of SDRs to achieve further processing capabilities, namely for multi-band signal processing for synchrotrons.

Particles stored in a synchrotron perform multiple passes at a measurement pick-up location, producing multi-band signals at harmonics of revolution frequency; this is typically referred to as longitudinal Schottky signals. Each of these bands maintains the same integrated power while their heights and widths scale with the harmonics. The longitudinal Schottky signals can be used for non-destructive measurements of beam parameters, such as stored beam charge or current and momentum spread [4, 5]. Since each band encodes the same information distributed over a different number of frequency bins, acquiring many harmonic bands improves the signal-to-noise ratio (SNR) for the measurement. Processing Schottky signals requires the use of external low-noise-amplifiers (LNAs) to ensure that the low signal amplitudes can be detected by the acquisition system. At the same time, these low signals are susceptible to external interferences picked up or introduced by amplifiers and analog-to-digital converters (ADCs) in sampling hardware, which can significantly distort the measurement readings. Thus, Schottky band signals must be isolated from interference peaks using narrow-band filtering to ensure a correct beam measurement.

In this paper, we explore the application of SDR for processing and filtering Schottky bands to address these challenges with beam intensity measurements using the longitudinal Schottky signal.

SYSTEM DESIGN

The SDR processing schema presented in Fig. 1 is designed for live capture and processing of multiple signal bands at frequencies between 16 kHz and 2.5 MHz. Once the multi-band signals are picked-up by capacitive sensors and amplified with LNAs, they are sampled by the ADC in the SDR frontend. The samples are then streamed to the host PC and processed by GNU Radio. The user can set the revolution frequency, harmonic channels, filter bandwidth, and filter decimation in a custom GUI. The end result is an RMS measurement used to calculate the beam intensity.

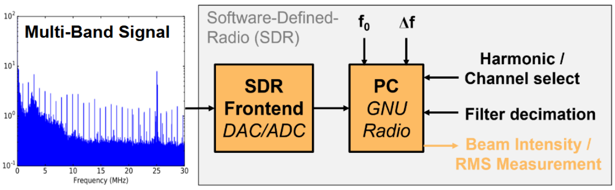

Figure 1: SDR multi-band signal acquisition and processing. Analog processing chain not depicted for brevity.

Frontend Hardware

Four frontend candidates were tested for signal acquisition: the USRP X310, ADALM2000, LimeSDR, and the Red Pitaya SDR-Lab. Based on their ADC rate and compatible frequency range (see Table 1), both the USRP X310 and ADALM2000 were selected for implementation as SDR frontends.

Table 1: SDR Frontend Candidates

Specifications	USRP X310	ADALM2000
ADC Rate	200 MSa/s	100 MSa/s
Streaming Rate	5 MSa/s	4.8 MSa/s
Frequency Range	0 to 30 MHz	0 to 2.5 MHz
Streaming Interface	1-10 GB Eth	USB2.0

Since the USRP is being used for other applications at GSI [1, 3], it was already optimized for data streaming in GNU Radio. Optimizing the ADALM in this processing schema proved challenging. The main parameters of the ADALM devices can be adjusted with the Analog Devices *gr-m2k* block library in GNU Radio. Unfortunately, the ADALM's internal hardware limits sampling rates to 1 , 10 , and 100 MSa/s. For capturing signal bands at higher harmonics and revolution frequencies, a minimum of 3 – 10 MSa/s is required. However, the ADALM could initially only reach 2.5 MSa/s due to the USB2.0 interface limiting

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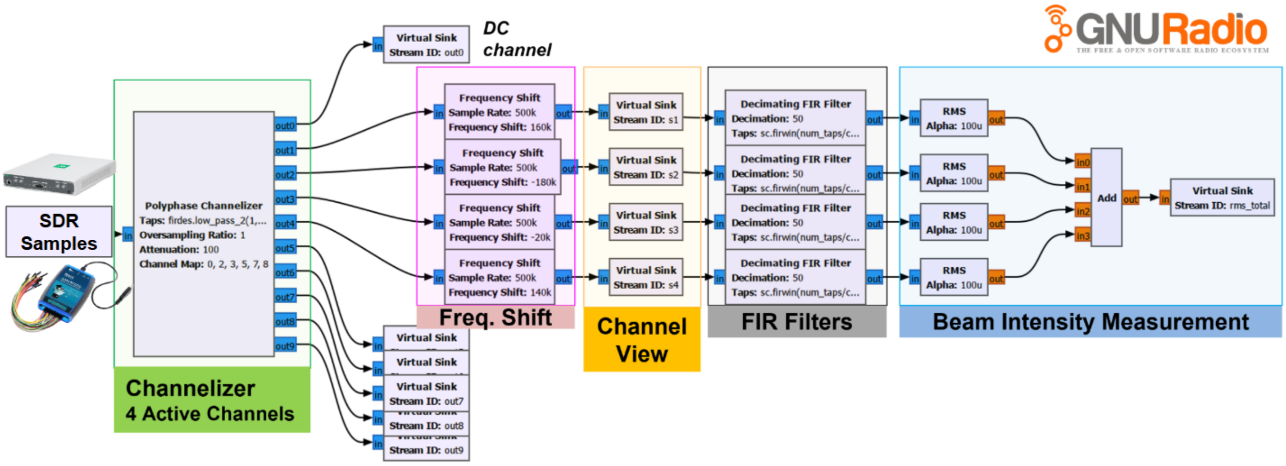


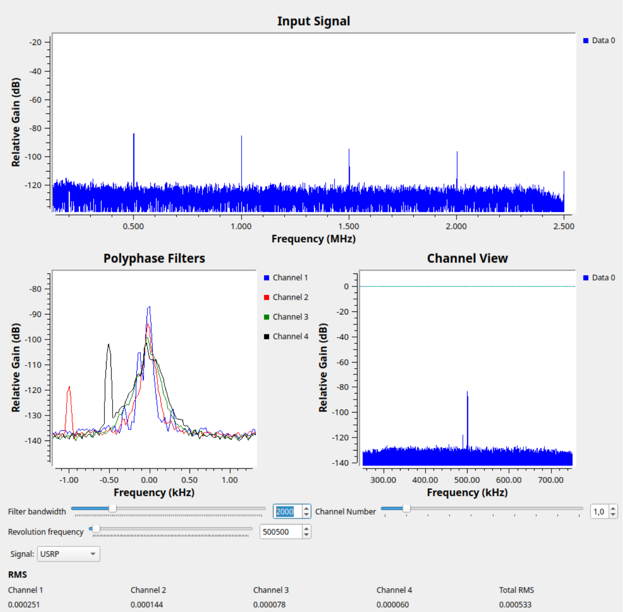
Figure 2: Simplified GNU Radio flowgraph for processing and filtering multiple signal bands for up to four active channels.

the data streaming rate, resulting in buffer underruns or non-continuous data transfer. After several iterations of sample rate testing using the *gr-m2k* library [6], an oversampling technique was used to address this data rate limitation. By applying an oversampling ratio, the ADALM device sets the ADC to sample at a lower rate that can be managed by the USB2.0 interface. A 10 MSa/s sample rate and an oversampling ratio of 2 were used to decimate the throughput rate to 5 MSa/s. After experimenting with optimial buffer sizes and kernel buffer settings, the ADALM could achieve 4.8 MSa/s of live data streaming to capture the higher revolution frequencies of interest. Higher data streaming rates could not be reached due to the USB2.0 interface.

Software - GNU Radio Processing Flowgraph

Processing the multi-band signals requires filters with a narrow bandwidth that scales with the harmonic number in order to eliminate interference peaks near the signal of interest. A challenge with processing multi-band signals is the significant digital processing lag that occurs from applying multiple narrow-band filters to a large sample stream. This issue is addressed in the GNU Radio signal processing schema by dividing it into three distinct stages (Fig. 2). First the entire input spectrum is split into equal channel bandwidths of 500 kHz using a polyphase channelizer [7, 8]. Doing this allows the application of filters with a lower number of taps to each channel, decreasing the overall computational load. Additionally, by using a channelizer, the intensity measurement of each band can be extracted separately from each other, so as to compare intensity values between channels.

After channelization, filters applied will be symmetrically oriented in the middle of the channel. If signal bands are off-center, then they must be shifted to the middle of the nearest channel. Thus, a frequency shifting Python script is used to automatically place and shift Schottky bands into the correct channel center and discard any empty channels by remapping the channelizer outputs. Finally, FIR filters are applied such that with each channel, the filter bandwidth scales harmonically. The functional range for filter widths in this acquisition system lies between 10 – 1000 Hz, as this ensures the entire bandwidth of the Schottky signal is captured while also removing nearby interference peaks [9]. Overall, this multi-stage channelizing and filtering process requires about 100 to 1000 filter taps. Compared to direct single-stage filtering for which 10 000 filter taps per band are needed, this approach reduces the computational load significantly. Taps are generated using the SciPy FIR windowing function (*scipy.signal.firwin*), and then passed to the GNU Radio decimating FIR block, where an additional decimation rate of 50 is set to reduce the processing demand even further. Finally, the filtered signals are each passed through an RMS blocks, where the average power is calculated. The α (R) gain value is used to adjust the averaging of the RMS and can be tuned in the flowgraph to reduce small fluctuations in the signal.



Filter bandwidth 2000 Channel Number 1,0
Revolution frequency 500500
Signal: USRP

RMS

Channel 1	Channel 2	Channel 3	Channel 4	Total RMS
0.000251	0.000144	0.000078	0.000060	0.000533

Figure 3: GUI of multi-band processing in GNU Radio. Pictured is the received signal for the USRP at 500 kHz revolution frequency in CRYRING under coasting beam conditions (top), the first channel centered (right), the four filtered bands (left) and the resulting RMS values (bottom).

The resulting user interface for the GNU Radio application (Fig. 3) shows the input signal, the channelizer view at each harmonic, and the signal filter view in up to four channels. Operators can adjust the filter bandwidth and revolution frequency parameters live within the GUI to best capture multi-band signals. The RMS measurement for each Schottky band is displayed at the bottom of the interface and can be used for subsequent intensity calculations.

APPLICATION AT GSI CRYRING

The SDR processing schema was put to testing at GSI CRYRING in March 2026. Data for 284 kHz, 500 kHz, and 1 MHz revolution frequencies was captured for bunched and coasting D^+ beams. For each revolution frequency, the bunched and coasting beam measurements were conducted under the same machine conditions, with only RF being switched off for the coasting case. Therefore, the calibrated Intergrating Current Transformer (ICT) measurements from bunched beam conditions were used for validation of the coasting beam SDR intensity measurements. An attenuator had to be connected at the USRP input due to signal overload in the bunched beam case. Power splitters upstream of the processing chain further reduced the signal power, and so the captured USRP signals were attenuated by at least 10 dB.

The signal shown in Fig. 3 corresponds to the 500 kHz coasting beam case. With the filter bandwidth set to 2 kHz, interference bands can be seen in several channels. These were suppressed using a harmonically scaled 40 Hz filter bandwidth (80 Hz for channel 2, 160 Hz for channel 4). Figure 4 compares the resulting RMS values for different beam intensities. The average power and its fluctuations in each channel for the measurement period of 3 s and an average of all channels is also shown. Depending on the harmonics utilized, the Schottky signals are either dominated by external additive noise, e.g amplifier and ADC, or by the inherent fluctuations inducing the Schottky signal itself, which manifests itself as a multiplicative noise. In the latter case, the ratio of mean intensity to std. deviation remains independent of the number of particles or beam current. Figure 4 suggests that for the lower harmonics processed in our scheme (pictured as channels 1 - 4), the noise is dominated by the Schottky signals itself, where the std. deviation increases with the signal mean. A linear slope can be fitted in the data and verifies that the SDR processing schema has a proportional output to the ICT measurements. Therefore, the SDR signal acquisition system can be normalized for estimating the absolute beam intensity for coasting beams. Measurements at 284 kHz with the ADALM and USRP further corroborate this data trend.

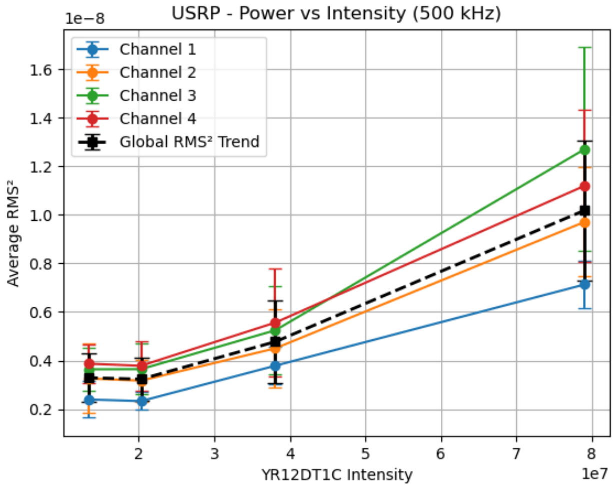


Figure 4: Schottky signal power estimates of the first four bands and their average (RMS values after SDR processing) from coasting beam measurement as a function of the ICT intensity from bunched beam measurement.

CONCLUSION

A proof of concept application of SDR processing of multi-band signals in GSI CRYRING was developed and tested, achieving normalizable results from real-time beam measurements. The system was fully realized using low-cost SDR frontends and GNU Radio, making the application accessible and easy to adapt for individual operator needs. Further information on this project can be found in the project repository [6].

While this processing schema has been used successfully for multi-band signal processing, there are many improvements to the design that must be made before further commissioning. As an immediate extension of this work, moving to few consecutive bands at higher harmonics around 20 – 30 MHz via heterodyne mixing would significantly improve the measurement resolution using the same flowgraph. A fitting routine in the GUI to extract momentum spread from various bands would also improve momentum spread estimates. Long term goals for this architecture may include further adaptation for analyzing transverse Schottky signals, which would provide operators with beam measurements of position, time, and chromaticity [10].

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