Executive Summary
As GNSS receivers become more complex, it is imperative that real-world signals and conditions be employed for complete receiver testing and validation. For this reason, advanced record-and-playback systems are necessary for capturing real-world conditions, which can be used repeatedly in the lab. As well, given the complexity of the GNSS spectrum, recorders used in the field should handle wideband signals as well as multiple carriers. For example, the GNSS spectrum covers the frequency band from 1164 MHz to 1300 MHz in the lower L band and from 1559 MHz to 1610 MHz in the upper L band. Inside this frequency band, a multitude of signals belongs to different satellite constellations such as GPS, GLONASS, Galileo, and Compass. To address the many synchronization and coherency challenges of GNSS testing, Averna has developed a new software/hardware architecture that allows control and tight synchronization between multiple recording channels and multiple recording systems under the 1 nanosecond (ns) level.

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Introduction
In the first part of this paper, the **RP-5300 recorder** is presented as well as the **RF Studio software** that is used to control and synchronize the recording channels. In the second part of this paper, two real setups are described: 1) **wired** and 2) **wireless synchronization** of two RP-5300 recording units. The test results for each setup are presented and analyzed.

Two RP-5300 recorder systems are wired to form a four-channel, tightly synchronized recorder. For validation purposes, all channels are connected with the same GNSS antenna via an active high-isolation splitter. A high-grade GNSS receiver is connected with the same GNSS antenna and the raw data is collected for comparison between the live and played-back signals.

In the second use case, the same two RP-5300 two-channel recorder systems are wirelessly interconnected using the GPS time from two separate GPS timing receivers as reference. The coherency and synchronization between the two recorders is based on the GPS-disciplined 10-MHz referenced clock, PPS signals, and extracted UTC time. Two systems are connected with the same signal source. The shared signal is recorded on each recorder and binary baseband data is analyzed.

The Field Recorder
Averna’s RP-5300 Compact RF Recorder is specifically adapted to GNSS signal recording for mobile applications. The unit is powered by 12V DC (e.g., from the car battery) and has an incorporated touchscreen display. Detailed specifications of the RP-5300 can be found in [1]. The unit has two 50-MHz wide channels that can be tuned on any frequencies in the range from 330 MHz to 2500 MHz. Channels are tightly synchronized in time and frequency.
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This allows the recording of the signals on different frequencies coming from the same coherent sources (e.g., GPS L1 and GPS L2). The RP-5300 is portable (Figure 1) and easily installed inside the car (e.g., for drive testing).

The RP-5300 has several interesting features to assist the user in error-free recording. Let us describe two of them: an RF Chain Configuration window and a Noise Figure (NF) graph. The RF Chain Configuration window displays the recording setup as a multi-stage RF chain. The first two elements are external to the recorder and represent the active GNSS antenna and the antenna-recorder connector (Figure 2). The configuration starts by specifying the antenna NF, antenna gain and the cable losses. There are two filters (i.e., outside the recorder box) required for normal operation: a wideband GNSS filter (that cuts the frequencies at the edges of the GNSS spectrum) and image rejection filters, selected as a function of the recorded signal. For example, the L1 filter for the upper GNSS band (1159–1610) MHz and the L2 filter for the lower GNSS band (1164–1300) MHz. The filter's losses should also be specified (by the user) in the configuration window. The user has the choice of bit-resolution for data recording.

For example, if the recorded GNSS signal is subject to interference or jammers, the maximal 16-bit resolution is selected. If the recording is done in the 50-MHz bandwidth, this requires a data transfer speed of 250MB/s. For most GNSS applications, 4-bit resolution may be adequate. In this case, the required space for data storage is four times less compared to 16-bit recording. For mass-market-grade applications, the bit-rate may be set to 2-bit or even 1-bit.

The next feature is the NF graph (Figure 3), which assists users with system-gain selection. This is a very important parameter as the NF of the entire setup depends on it. The NF curve is calculated based on the configuration of the RF Chain Configuration window. In order to select the optimal system gain, the user just has to put the white dot (actual gain) in the green section of optimal gain. Skipping technical details, consider the optimal gain as an optimal threshold between the best system sensitivity and maximal dynamic range.
The RF Software

One of the most powerful features of the RP-5300 RF Recorder is the RF Studio software suite that allows multiple recording modules to work in sync. Each module works as a plugin and can record anything from audio, video, NMEA data, RF, etc. The modules are linked together through the RF Studio process, which ensures proper synchronization (local or remote). Figure 4 illustrates the basic building blocks of an RF Studio solution. Each box represents a process.

Because each module (or plugin) runs in its own memory space (multi-process application), the overall solution is more reliable and resistant to failure. If one custom module stops working, the other process can continue without any risk of cascading effects. Inter-process communication is done through TCP/IP. Therefore, a module may run on a remote computer. Figure 5 illustrates how multiple computers can run as a single application.

With this scalable approach, we can combine as many channels as we want to form a multi-channel/ultra-wideband virtual recorder. The plugin architecture permits custom module development, which makes RF Studio a flexible solution for situations where RF and other types of input need to be recorded.
Wired Synchronization

The validation setup for wired synchronization is presented in Figure 6. Two recorders are connected to the active GNSS antenna through the active high-isolation splitter. The splitter ensures the same signal power for any of the splitter’s output. For validation purposes, a GNSS receiver shares the same signal as recorders through the common splitter. Each of the RP-5300 units has a synchronization card. There are three types of signal used for synchronization: 1) CLK, 2) SYNC and 3) TRIG. Those signals are generated by the unit 1 and are used as input signals for synchronization of unit 2, as well as unit 1 itself (except the TRIG signal, which is not shared).

Each recorder is configured to capture the GNSS signals in the frequency range (1559–1610) MHz for channel 1 and (1212–1262) MHz for channel 2. For referenced live raw data, a high-grade GNSS receiver is used. The synchronization is done based on the GPS as described earlier. Once synchronized, the two units form a virtual four-channel recorder. Data is recorded for about one hour. In playback, channels are recombined to mix the GNSS L1 band from one unit with GNSS L2 band from another one (L1 unit 1 + L2 unit 2 and L1 unit 2 + L2 unit 1). The time offset and coherency between the GPS L1 and GPS L2 signal is used for validation. A description of the validation methodology is found on [2].

Wireless Synchronization

The validation setup is shown in Figure 7. Multiple RP-5300 units use the GPS (or potentially other GNSS constellations) to extract the common reference clock. There are two types of signals used for wireless multi-unit synchronization: 1) the 10-MHz clock and 2) the 1PPS (TRIG) signal. The 10-MHz and 1PPS are directly extracted from the GPS-disciplined modules used on each of the RP-5300 units. UTC time is also supplied by the GPS receiver. The synchronization routine works as follows: prior to recording, each of the RP-5300 units is connected to GPS via an active GPS antenna (the antenna has to be under the open sky with no obstruction, severe multipath or interference). Normally, shortly after the GPS-disciplined modules lock onto the GPS signals, the modules supply the 1PPS and UTC time. Once those signals are available, each of the recorder units transits into READY mode. Now, the user specifies a start time (UTC time) that is sent via Internet to each of the RP-5300s.

With start time defined, the modules transit to ARMED mode. Exactly at the start time (as defined by the user), the triggering routine uses the 1PPS signal (that corresponds to the start time) as TRIG pulse.
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Test Results

Time offset and coherency between two recorder units are based on the receiver’s raw measurements. For coherency validation, the accumulated Doppler range (ADR) during the live data collection is compared with ADR collected during the playback. The following differences are considered:

\[
\Delta \text{ADR}_{\text{live}} = \text{ADR}_{L1\text{live}} - \text{ADR}_{L2\text{live}}
\]

\[
\Delta \text{ADR}_{\text{playback}} = \text{ADR}_{L1\text{playback}} - \text{ADR}_{L2\text{playback}}
\]

Time offset is based on the pseudorange (PSR) measurements. As for coherency validation, the PSR differences between L1 and L2 measurements are considered:

\[
\Delta \text{PSR}_{\text{live}} = \text{PSR}_{L1\text{live}} - \text{PSR}_{L2\text{live}}
\]

\[
\Delta \text{PSR}_{\text{playback}} = \text{PSR}_{L1\text{playback}} - \text{PSR}_{L2\text{playback}}
\]

The ADR difference for live versus playback mode is shown in Figure 8. The small offset in phase difference is mainly due to phase measurement routing in the receiver (e.g., cycle slipping) and it does not diverge over time. The PSR L1/L2 difference (Figure 9) is shaped by the multipath difference between L1 and L2. It can be observed that the shape of the line in playback follows the shape of the line for live signal acquisition. The observed offset is a combination of time offset and group delay between channels. Once group delay is compensated, the calculated time offset is \( \sim 1\text{ns} \).

In wireless synchronization, analysis was done based on the binary date recorded. For an input signal, a known signal pattern generated by a signal generator was used. The signal was split between the two recorders. The synchronization was done by GPS timing receiver using a 10-MHz clock and 1PPS pulse. The time offset between units (Figure 10) is in range of the 1PPS pulse precision (\( \sim 25\text{ns} \)). Future work will be done to further improve these results.
Conclusion

This paper has shown that multiple recorders can be tightly synchronized in order to expand the recording bandwidth. In the example, two RP-5300 recorders (2x50 MHz channels each) were synchronously inter-connected to form a virtual recorder with total bandwidth of 200 MHz. This allowed for full and simultaneous GNSS spectrum coverage. RF signals from all GNSS orbiting satellites can be recorded, stored and played back later in the lab to reproduce real-life RF signals. It was also shown that multiple RP-5300 recorders can be synchronized wirelessly using the GPS timing receiver (one per recording unit) that supplies the 10-MHz GPS referenced clock and 1PPS pulse. In this case, the time offset between any two synchronized units is in the range of 1PPS pulse precision. This resulted in a time offset of around 25ns. This level of synchronization allows for usage of multiple recorder units in differential GNSS where the distance between the recorders may reach tens or even hundreds of kilometers. In fact, due to global GPS referenced time, this level of synchronization will be kept regardless of the distance between units.

References
