Record and Playback System for GNSS: Real Performances for Real Applications

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BIOGRAPHY

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Jean-Serge Cardinal is an RF designer at Averna. His main fields of interest are RF circuit architecture and design, mixed signal design and DSP. His contribution in Averna is mainly with the RF player. Before Averna he was in the Telecom industry for 15 years working on transceiver front-ends and Physical-layer.

Peter Blood is the Director of R&D for hardware in the instrumentation division of Averna Technologies. His main fields of interest are RF signal generation and RF record / playback products for validation of automotive radio, navigation and video products. He has over 15 years of experience in the design and development of test & measurement products for wireless applications with Marconi Instruments and Aeroflex.

Peter France is involved with technology development in the Mapping and GIS division of Trimble, based in Christchurch, New Zealand. He is interested in improving positioning in difficult environments.

INTRODUCTION

Record and playback (RP) systems are increasingly popular in GNSS receivers' test and validation process. For testing, we need a better understanding of the RP contribution to the tested receiver (UUT) raw measurements. To understand the RP usage, let us imagine a setup where the RP is placed between the source of the signals (e.g. GNSS satellites + source of interferences) and the UUT. It is obvious that the ideal RP system should be transparent for capturing and reproducing these signals by the UUT. In real live, the impairments introduced by the RP system have to be negligible, at least for main parameters that affect signal distortion and noise. As the RP, by definition, is always between the signal source and the UUT, the criteria for RP system impairments are defined by the UUT itself. Let us see how the performances of the RP are related to the measurements quality of the tested receiver. The analysis is based on the state of the art RP from Averna technologies and high grade GNSS receivers.

1 RP CONTRIBUTION TO GNSS RAW DATA

The real RP cannot record and replay the live signals without some penalty. Instead, it can be expected that the RP can play back the live recorded signal with impairments that are not detectable (or at least acceptable) by the UUT. To achieve this, the RP has to be significantly *better* than the UUT. Let us see how *good* an RP can be for targeted UUT based on the receiver's raw data analysis.

1.1 GNSS RECEIVER AND RAW MEASUREMENTS

The accuracy and precision of the position, velocity and time (PVT) solution estimated by the GNSS receiver is determined by the quality of the raw range measurements and the satellites geometry. Recall here that the raw range estimates are extracted from the code and the carrier phase measurements and are respectively pseudorange

(PSR) and accumulated Doppler range (ADR). In the generalized form, the expression for PSR and ADR is given by the Eqn. (1).

$$
\begin{aligned}
P_{L1} &= r + C_S + C_R + I_{L1} + T + p_{L1} + n_{L1} \\
P_{L2} &= r + C_S + C_R + I_{L2} + T + p_{L2} + n_{L2} \\
\Phi_{L1} &= r + N_{L1} + \varphi_{L1} + C_S + C_R - I_{L1} + T + \varepsilon_{L1} \\
\Phi_{L2} &= r + N_{L2} + \varphi_{L2} + C_S + C_R - I_{L2} + T + \varepsilon_{L2}
\end{aligned}
\qquad (1)
$$

where,

$P_{L1,L2}$	PSR on L1 and L2 respectively
$\Phi_{L1,L2}$	ADR on L1 and L2 respectively
r	True geometrical distance between the satellite and the receiver
C_S	Satellite clock error
C_R	Receiver clock bias
$I_{L1,L2}$	Ionospheric delay on L1 and L2 respectively
T	Tropospheric delay (same for L1 and L2)
$p_{L1,L2}$	Delay due to system processing error or random delay (e.g. multipath)
$n_{L1,L2}$	Noises on the code measurements
$N_{L1,L2}$	Number of cycles (ambiguities) on phase measurements on L1 and L2 respectively
$\varphi_{L1,L2}$	Fractional part of cycle on phase measurements on L1 and L2 respectively
$\varepsilon_{L1,L2}$	Noises on the phase measurements

For more details concerning the PSR and ADR computation, we refer to [1] and [2].

1.2 KEY PARAMETERS OF THE RP

In this subsection we identify the main parameters of the RP system that may contribute to the raw data impairments. The following parameters are considered: NF, usable bandwidth, dynamic range, phase noise, inter-channel time offset, group delay, phase coherence, clock stability and inter-channel biases.

Noise figure

The NF has a direct impact on the PSR and ADR noise. First of all, the NF deteriorates the C/N_0 of the processed RP signal, that in turn increases the jitter in the receiver processing loops. It can be shown that the variations on the jitter are related to the variation on the C/N_0 as follow [3]:

$$\frac{\sigma_{RP}}{\sigma_{Rx}} = \sqrt{\frac{\frac{C}{N_{0_{Rx}}}}{\frac{C}{N_{0_{RP}}}}} \qquad (2)$$

In this equation, σ is the standard deviation and index *Rx* and *RP* designate receiver and RP system respectively. Suppose we have a difference in NF between the tested receiver and the RP of 0.5dB. In this case the noise on the PSR and ADR measurements in presence of the RP are roughly:

$$\sigma_{RP} = \sigma_{Rx}\sqrt{\frac{\frac{C}{N_{0_{Rx}}}}{\frac{C}{N_{0_{RP}}}}} \cong 1.06 \cdot \sigma_{Rx} \qquad (3)$$

This means that the degradation of the C/N_0 by 0.5dB, in presence of the RP, increases the noise in the receiver's code and carrier measurements (this noise is specified in the receiver performances datasheet) by 6%. If both the RP and the GNSS receiver are connected to the same active GNSS antenna, there is little or no degradation expected due to the NF.

Usable bandwidth

Mismatch in the usable bandwidth can lead to additional noise and signal distortion. As the rule of thumb, the bandwidth of the RP should be at least the bandwidth of the receiver under test. If this is not possible, the RP should cover at least the full bandwidth of the signal of interest (e.g., GPS L1 P(Y) code at 20.46 MHz), but in this case, some discrepancies in C/N_0 (live/playback) may occur. With partially covered signal spectrum, we have to account for degradation in C/N_0 ratio due to the correlation losses (i.e. additional noises in PSR and ADR). Normally, an RP for GNSS applications is able to cover a bandwidth of about 50 MHz that is suitable for a majority of GNSS signals. With a properly tuned RP system, no additional noise is expected. The only concerns are out-of-band (for UUT) interference. If the bandwidth is wider than the UUT requires, interference may infiltrate the recorder channel. Due to the finite dynamic range, this may increases the equivalent noise floor in the recorded signals degrading the C/N_0 in playback.

Dynamic range

There are two major parts in the RP system to contribute to the total DR: the RF chain (amplifiers and frequency converters) and the digitizers (i.e. ADC and DAC). Based on good practice, the total DR of the RP should exceed the DR of the tested unit [4]. With equal DR, the inter-modulation products in the tested receiver may be a little higher in the presence of the RP. As long as the DR of the

RP is higher than the DR of the tested receiver, there is no visible impact on the raw measurements.

Phase Noise

There are two main sources of the phase noise and phase jitter in the RP: 1) local oscillator (LO) and digitizers (i.e. ADC and DAC). Let us consider the effect of the LO, as this source is dominant. The phase noise of the oscillator (especially at low frequency offset) impacts the receiver's carrier and the code tracking loops. Mainly, the phase noise narrows the carrier loops effective bandwidth and increases the correlation losses in the code tracking loops. There are some publications specifying the bounds for oscillator phase noises as function of the GNSS receiver performances [5]. The typical phase noise value for high grade RP ([6] and [7]) is presented in Table 1.

Table 1 RP Typical Phase Noise

Frequency Offset	Phase Noise (dBc/Hz)
10 Hz	-60
100 Hz	-82
1 kHz	-100
10 kHz	-107
100 kHz	-120
1 MHz	-140

It can be shown that this phase noise translates into a phase jitter of about 0.43ps or 0.13mm (rms) [8] and the effect on the correlation peak (even with long integration times) is negligible [5]. Also, this phase noise will have little effect on the carrier tracking loop.

Inter-channel time offset

The inter-channels time offset is mainly due to the difference in electrical length of the hardware wiring and the clock/trigger distribution inside and between channels. External to the RP system wiring also contributes to the total time offset. The software/hardware time offset between any two channels in the system can vary from hundreds of picoseconds to several nanoseconds. This delay is directly translated into the channel-to-channel PSR measurements offset as follow:

$$\Delta p_t = [\![(\Delta t]\!]_r + \Delta t_p) \cdot c \tag{4}$$

Where, Δp_t is the pseudorange offset expressed in meters, $\Delta t_{r,p}$ are the time offset in the recorder and playback respectively in seconds and $c = 2.99792458 \cdot \mathbf{10^8}$ is the speed of the light in *m/s*. In the state of the art RP, this offset can be tuned to about 100ps level by the inter-channel synchronization control (e.g. in the Averna's RP based on equipment from National Instrument, this offset is controlled by T-clock functionality) [9]. Based on known RP systems, the time offset vary from 100ps to 3ns. With this consideration, let us bound Δp_t as follows:

$$0.0\mathbf{3}m < \Delta p_t < \mathbf{1}m \tag{5}$$

The time delay due to signal routing will depend on the cables and splitters quality. For better results, the matched set of cables should be used. The following equation shows the relation between the delay in the cable and the cable length:

$$\Delta p_c = \frac{l_c}{k} \tag{6}$$

Where, Δp_c is the delay created by cable in meters, *lc* is the cable length in meters and *k* is a factor that depends of cable characteristics (*k* < 1). For example, for k = 0.67, the difference in length between two cables of 10 cm is translated into the offset equal to 14.9 cm. Let us assume a calibrated set of cables. In this case, the inter-channel time offset will mainly depend on software/hardware time delay mentioned above.

Group delay

The group delay Δp_{gd} in the RP system is created essentially by the filtering. This group delay is translated into additional frequency dependent delay added to PSR. The filter group delay greatly varies with filters type and manufacturing. From experience, let us considered:

$$\Delta p_{gd} < 0.\mathbf{5}m \tag{7}$$

Phase coherence

Phase coherence between any two transmitted by GNSS satellite frequencies is maintained by the use of the shared high stability reference clock. For example for GPS, the L1 and L2 frequencies are formed by multiplying the reference frequency of 10.23MHz by 154 and by 120 to obtain L1 and L2 frequencies respectively. As long as both L1 and L2 signals are coherent, the range measurements in the multi-frequency receiver are the same (of course except the delay added by ionosphere). If the coherence is broken, a phase rotation between the L1 and L2 channel is observed. It can be shown that this phase rotation leads to an accumulated range measurements error Δp_{coh} that can be estimated using the following expression:

$$\Delta p_{coh} \cong \Delta f * t * \lambda \tag{8}$$

where,

Δf	Frequency error between any two frequency channels due the phase rotation
t	Period of time for which the range is calculated
λ	Wavelength of the carrier frequency to consider (e.g. L1 or L2)

This error accumulates with time and with ADR computation until the receiver loses the tracking of the signal in one of the frequency channels (e.g. for GPS on L2 channel). For this reason, the coherency between any two channels must be maintained inside the RP. This is easy to do for a particular set of frequencies but is more difficult task for any arbitrary set of frequencies. For state of the art multi-constellation RP system, the accumulated range error Δp_{coh} due to the coherency imperfection is measured as:

$$\Delta p_{coh} < \frac{0.002m}{hour} \tag{9}$$

Clock stability

Poor clock accuracy of the RP can interfere with the tested receiver's acquisition and tracking process at the point that the tracking is no longer possible. In the RP for GNSS applications, it is common to use the reference clock with performance comparable of the state of the art GNSS simulators. Let us consider a reference clock having an aging rate of $5 \cdot 10^{-10}$ per day and a temperature stability of $\pm 5 \cdot 10^{-9}$ over temperature range from 0° to +50°C. This clock error is equally distributed between RP channels and will count for common for all satellites time offset. There is no impact on the position estimate as this error is absorbed by the time offset of the tested receiver's clock [10].

Channel-to-channel isolation

With a poor isolation, signals from adjacent channels can act as interfering signals contributing to the noise level in the raw measurements. Nowadays it is common to have hardware channel isolation better than 80dB. This is confirmed by tests done with the state of the art multi-channel RP system. For this reason, the contribution from inter-channels biases to PSR and ADR range can be considered as negligible.

Based on our analysis done so far, we can expect that the RP will add impairments in the form of noise and delay to the receiver's raw range estimates. Let us summarize the sources of these errors.

Source of Delays

We can group the main sources of delay in the RP system into four categories: (1) system setup (e.g. cables, splitters and external to RP filters), (2) inter-channels time synchronization, (3) inter-channels group delays and (4) phase coherence between the local oscillators.

Setup delays are due to the nature of the setup itself (mainly connectivity between the RP and the unit under test). These kinds of delays are easily handled by calibration (e.g., calibration of the cables for a particular test setup). We can consider this relative delay to be under a couple of picoseconds.

Inter-channel time synchronization defines the relative time offset between two signals in two separated channels in the RP unit itself. This time offset is due to hardware implementation specifics, clock distribution and digitizing (i.e. ADC and DAC in each of the record and playback channels). Using special techniques (e.g. T-clock functionality for NI equipment), this time offset can be tuned under 100ps.

Inter-channel group delays, as defined here, are the frequency dependent time offsets between signals in two different channels. A frequency dependent offset is caused by the filtering processing inside and outside the system (external to the RP filters may be used for specific tests). Normally, the frequency depended delays in the RP are measured and compensated using the same techniques as for inter-channels time synchronization and in consequences reduced to the inter-channel time offset level.

Lack of coherency between the local oscillators (one per channel) creates a phase rotation in baseband between two signals processed by two different channels. This phase rotation has a direct impact on the delays on ADR measurements. If not compensated, this delay may add an accumulated relative error between channels (e.g., ADR L1-ADR L2). With current techniques, this measurements error can be sustained under 2mm/hour.

Source of Noise

The main factors which add noise to raw measurements in presence of the RP are the system NF and phase noise. If the difference in NF of the RP is kept inside the 0.5dB, the noise in the code and carrier phase measurements (generated by the receiver itself) is increased by 6% at worst. This is not the total PSR and ADR measurements noise, but only the receiver's contribution.

1.3 RP AND RAW MEASUREMENTS

Now let us write the expression for the output raw data as seen by the receiver connected to the player's output (live signal was recorded and then played back).

$$\begin{aligned} P_{L1}^{RP} &= r - C_S + C_R + I_{L1} + T + p_{L1} + n_{L1} + p_{L1}^{RP} + n \\ P_{L2}^{RP} &= r - C_S + C_R + I_{L2} + T + p_{L2} + n_{L2} + p_{L2}^{RP} + n \end{aligned} \tag{10}$$

$$\Phi_{L1}^{RP} = r + N_{L1} + \varphi_{L1} - C_S + C_R - I_{L1} + T + \varepsilon_{L1} + +\varphi_{L1}^{RP} + \varepsilon_{L1}^{RP}$$

$$\Phi_{L2}^{RP} = r + N_{L2} + \varphi_{L2} - C_S + C_R - I_{L2} + T + \varepsilon_{L2} + +\varphi_{L2}^{RP} + \varepsilon_{L2}^{RP}$$

where,

$p_{L1,L2}^{RP}$	Delays introduced by the record and playback on the pseudorange on L1 and L2 respectively
$n_{L1,L2}^{RP}$	Noise added by the system on the pseudorange on L1 and L2 respectively
$\varphi_{L1,L2}^{RP}$	Delays added by the system to the ADR on L1 and L2 respectively
$\varepsilon_{L1,L2}^{RP}$	Noise added by the system to the ADR on L1 and L2 respectively

As we can see from the Eqn. (10), the main contributions from the RP system to the receiver's code and carrier measurements are delays and noise. The delays between L1/L2 measurements can be tuned under 1m for PSR and under 2mm/hour for ADR. Let us consider a typical high grade GPS/GLONASS L1/L2 GNSS receiver. The measurements noise and position accuracy for this kind of receivers is presented in the Table 2 and Table 3. The noise contribution (based on the section 1.2 and the typical GNSS receiver presented) is estimated as per Table 4. (We consider 6% contribution due the C/N_0 degradation of 0.5dB).

Table 2 Measurements Noise for Typical GNSS Receiver

	GPS	GLONASS
L1 C/A Code	5 cm	15cm
L1 Carrier Phase	0.5mm	1.5mm
L2 P(Y) Code	8cm	8cm
L2 Carrier Phase	1.0mm	1.5mm

Table 3 Horizontal Position Accuracy (RMS)

Mode	Precision
Single point L1	1.5m
Single point L1/L2	1.2m
SBAS	0.6m
DGPS	0.4m
RTK	1cm + 1ppm

Table 4 Estimated Noises Contribution of the RP

	GPS	GLONASS
L1 C/A Code	<0.3 cm	<0.9cm
L1 Carrier Phase	0.02mm	0.06mm
L2 P(Y) Code	<0.5cm	<0.5cm
L2 Carrier Phase	0.05mm	0.07mm

What can we conclude from all this? First of all, the RP system has no impact on the stand alone position estimate by a high grade GNSS receiver. Noise on the PSR measurements due to the RP are two orders of magnitude lower than errors on position estimates and can be considered negligible. Added by RP relative (between L1/L2 channels) delays are common for all satellites and will add a common offset on ionospheric estimate. This will not impact the final position estimate (offset on the pseudorange is compensated by the same amount of offset on the ionospheric delay). The only impact we can see so far is on the ionospheric delay estimate (but even this can be minimized by proper setup and tuning).

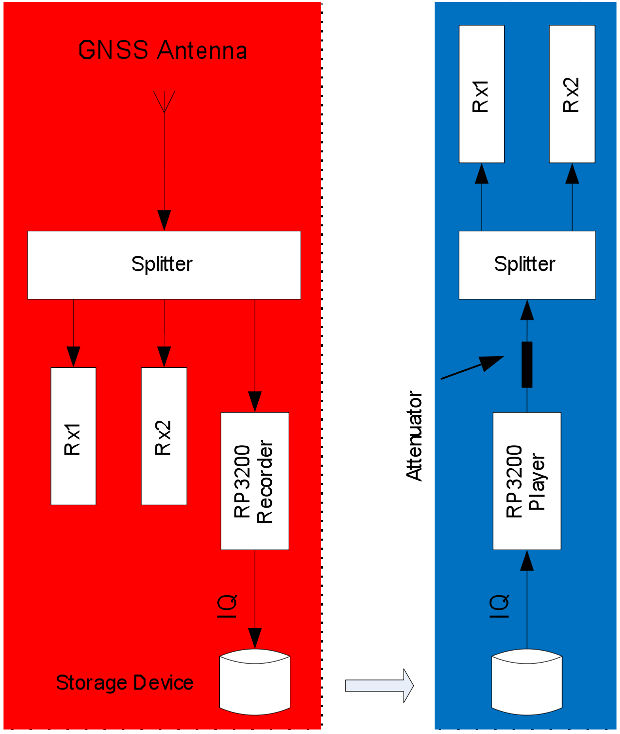
In differential mode, the inter-channel delays are eliminated in the single difference formation. The only thing that will count is the noise due to the RP. But even so, the extra-noise on the code is an order of magnitude lower than specified precision in differential mode. This is also true for Carrier Differential GNSS where the extra-noise added by the RP is an order of magnitude lower than specified receiver performances for Real Time Kinematic (RTK).

2 AVERNA RP FOR GNSS APPLICATIONS

Averna's wideband multi-frequency RP system is able to cover 3 x 50 MHz of the GNSS spectrum allowing simultaneous recording (and playback) of major GNSS signals. For the purpose of this paper, the system was tuned to cover GPS/GLONASS signals in both L1 and L2 bands.

2.1 TEST DESCRIPTION

The validation test setup is presented in the Figure 1. The active GNSS antenna is mounted on the roof of the Averna's 6-floor building in Montreal downtown. The signal from the antenna output is shared through the active splitter between the RP system and two high grade GNSS receivers (designated as Rx1 and Rx2). The usage of two GNSS receivers allows for single and double difference formations and also serves as an indicator on distribution of measurements error. During the recording, the raw measurements are logged by both GNSS receivers. The same receivers are used when the recorded data is played back. During the playback, the new set of measurements is logged each time the playback is repeated. Multiple playback serve for repeatability analysis. The raw measurements obtained live are compared against the measurements obtained in playback. The following primary parameters are considered: C/N_0, PSR and ADR. The primary parameters were used for Zero Difference (ZD), Time Difference (TD) and Double Difference formation as well as for coherency analysis.



a) b)

Figure 1 Test setup for a) Record and b) Playback

Zero Difference

ZD is formed as difference between code and phase measurements for the same frequency channel. More precisely, in our case, the ZD for L1 and L2 channels is defined as:

$$ZD = PSR - ADR \tag{11}$$

ZD is a good indicator of the multipath on the code phase measurements, as the common to PSR and ADR errors are eliminated (i.e. troposphere, satellite and receiver clock errors). For details about ZD formation, please refer to [11].

Time Difference

To obtain the TD, the ZD is differentiated between each consecutive sample. In TD, the first order multipath and ionospheric errors are further eliminated. What is obtained (i.e. second order tropospheric and ionospheric errors + code phase noises) can serve as an indicator of the contribution of the RP to the code phase noise.

Single and Double Difference

For the Zero Baseline (ZB) measurements (both GNSS receivers are connected to the same GNSS antenna) all common error in raw range measurements (for a given satellite) are eliminated [1]. What is left is the difference between the receivers' clock error. With Double Difference (DD), there are no common errors left except the receiver's noise. The DD is used to estimate the contribution of the RP on the code and carrier phase measurements noise [1].

Coherence validation

With range measurements (PSR and ADR) from the two different frequency channels, we can form inter-channels differences for coherency estimate. For the purpose of this paper, we use GPS L1/L2 PSR and ADR measurements. The following differences are formed:

$$\Delta PSR_{L1,L2} = PSR_{L1} - PSR_{L2} \tag{12}$$
$$\Delta ADR_{L1,L2} = ADR_{L1} - ADR_{L2}$$

In ideal case, we expect those differences to be the same in playback as in live recording.

2.2 TEST RESULTS

Figure 2 – 6 show the C/N_0, ZD, TD and DD for a given satellite in live and playback mode. The average value for those parameters is presented in Table 5 and Table 6. For the test done, a slight variation in the C/N_0 offset between L1 and L2 was seen. It was observed that this behavior is typical for the setup in which the recording/playback bandwidth (for given signals) does not match the receiver's bandwidth (for the same signal). In our test we configured the RP system for 50MHz of bandwidth centered at 1585MHz at L1 (1560MHz - 1610MHz) and 1235MHz at L2 (1210MHz - 1260MHz).
During the test we observed out-of-band (for GPS/GLONASS signals) interference (probably from the adjacent RF emitters on the roof) that were inside our 50MHz recording bandwidth. This may raise the equivalent noise floor by some value during the signal processing inside the RP. If it is assumed that this interference is outside the receiver's processing bandwidth, that explains the discrepancies we observed.

Analysis of the ZD shows that the RP system keeps the impairments of the live signal during the playback. More precisely, the multipaths in playback mode repeat the shape of live signals (see Figure 3). The difference between the ZD in live and playback is less than 2cm rms.

As we mentioned previously, the TD can be used to compare the code noise in live and playback following the variation in the measurements. For the test done, the increase in the code noise during the playback is less than

5% for the observed satellites. The same behavior is observed for DD formation. The DD noise in code and carrier measurements in playback is not worse than 5% compared to live mode.

Time offset between channels based on the code measurements is under 1.5ns (Figure 6). In this setup, we did not compensate for this offset in playback. As was mentioned in the section 1.2, this can be done by manual tuning (in software). The coherency between L1 and L2 channel, as based on the carrier phase measurements, is stabilized after a warm-up period and ADR drift between L1 and L2 channels is under 2mm/hour (Figure 6).

One of the most powerful features of the RP is the ability to replay the live recorded signal in a repeatable way. The raw measurements of the receiver under test (under the same configurations) are consistent from one playback to another (see Figure 7).

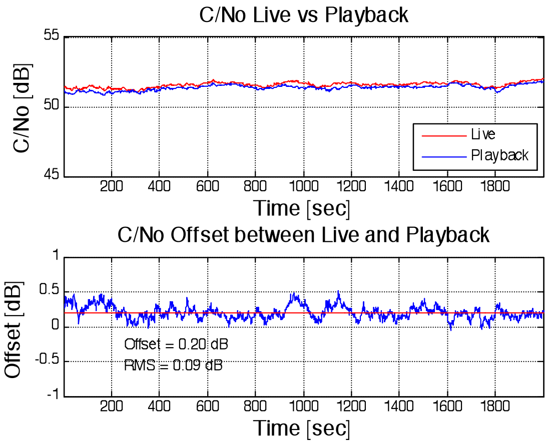


Figure 2 C/N_0 for PRN16 (Live/Playback)

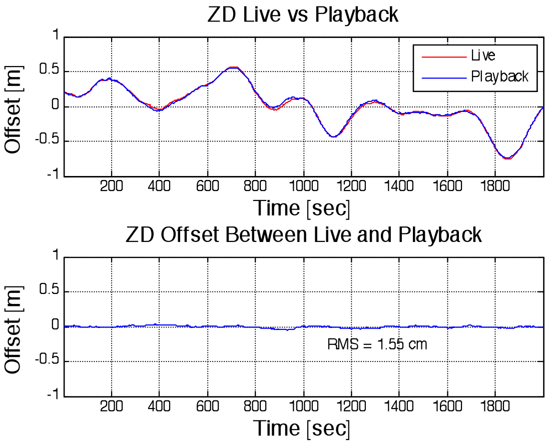


Figure 3 ZD for PRN16 (Live/Playback)

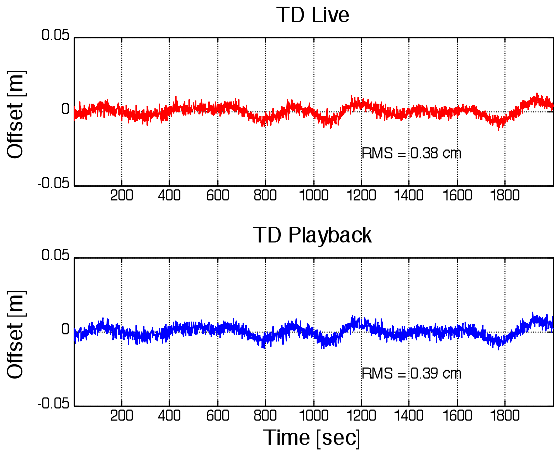


Figure 4 TD for PRN16 (Live/Playback)

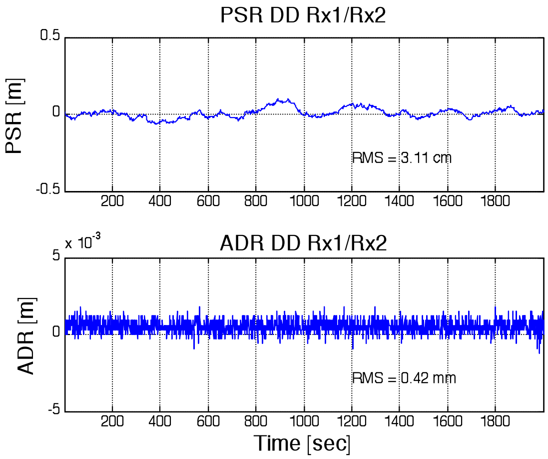


Figure 5 DD between Rx1 and Rx2 Measurements

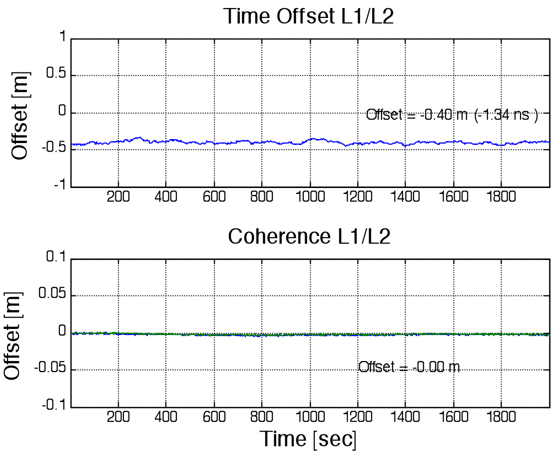


Figure 6 Coherence between L1/L2 channels

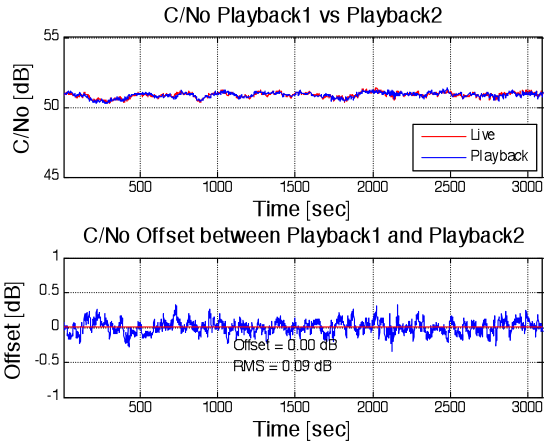


Figure 7 Repeatability between two Playbacks

Table 5 DD for Live and Playback

	Signal type		DD		
			Live	Playback	%
Rx1/ Rx2	L1	P	2.76cm	2.85cm	3.3
		C	0.42mm	0.43mm	2.4
	L2	P	3.31cm	3.48cm	5.1
		C	0.63mm	0.66mm	4.8

Table 6 C/N_0, ZD and TD for Live and Playback

	Signals	C/N_0 (live - playback)	ZD (live - playback)	TD (live/playback)		
		offset (dB)	offset (cm)	Live (cm)	Playback (cm)	%
Rx1	L1	0.26	1.52	0.54	0.55	1.8
	L2	0.44	1.75	0.57	0.59	3.5
Rx2	L1	0.24	1.43	0.62	0.63	1.6
	L2	0.47	1.74	0.82	0.85	3.7

3 REAL USE CASE

In this section, we present some examples of the RP usage by real GNSS receiver manufacture. Our customer, Trimble New Zealand kindly agreed to share with us some use cases for GNSS receiver testing.

Previous test procedures

Trimble New Zealand develops and tests a variety of products including GNSS receivers and software with accuracy from metre-level down to centimetres. The company has developed test procedures that emulate their customers' working conditions. The test team has optically surveyed dozens of control points under tree canopy and near buildings, as well as in more open conditions. Testers manually collect GNSS measurement data at each point and the accuracy is automatically analyzed. This is a repetitive and time consuming process. In one year the testing group performed 680 GPS-related field tests; one engineer alone collected 900 files. Also, there is significant variability from test to test. Each individual test includes many variables such as the satellite constellation, and the user's field technique, even including where the operator stands at each control point, and hence which satellites are blocked. Tests must be repeated to ensure the validity of results. Even static tests cannot be performed inside using signal from a rooftop antenna, as the rooftop multipath and amplifier noise introduce undesirable artifacts. Most tests must be performed outside, which adds to the setup time. To reduce repetitive field testing, the company purchased an Averna RP system. This gave more repeatable results by eliminating environmental variables. The two 50MHz channels of the system allow for GPS and GLONASS testing on both L1 and L2 frequencies.

Regression testing

The company uses playback as a key time-saver for regression testing, particularly when receiver firmware or data collection software has changed. Trimble New

Zealand has developed tools that analyse the accuracy in several categories, from open-sky to very difficult environments. In open sky the positions are highly repeatable from replay to replay. This is especially true for carrier solutions; there is more variation in code solutions as they approach the limits of their precision. The team has found that in very difficult conditions with canopy and multipath, repeated replay runs still show significant variability in the positions. It has been concluded that this is caused by variations in receiver state, for example how long a new satellite is tracked before being deemed usable. The receivers perform a number of tasks in parallel, in a non-deterministic way, and so very small timing differences can determine whether a multipath-laden signal is used in a given epoch or not. However the company can still use this procedure to check for larger variances in difficult conditions that could be introduced by bugs or regressions. This occurred recently when an unmarked cycle slip resulted in positional errors under canopy. Replay testing confirmed that the fix worked correctly. Previously in a busy week the company's testing team was able to collect and analyse around 50 GNSS data files representing typical end-user workflows in various combinations of software and hardware. With the purchased playback system it is possible now replay and analyse over 500 files in a week and the data collection part is reduced to a few person-hours.

Self-jam testing

As more electronics, including cellular and Bluetooth transmitters, are added to devices that also include a GNSS receiver and antenna, and multiple GNSS bands and wider bandwidths are tracked, self-jamming has become a very difficult problem to overcome. It is possible to use live-sky signals to test self-jamming performance, but the results vary because of the changing environment, making it difficult to positively identify improvements. Playback eliminates those variables, and helps to reduce the amount of testing required to determine the effectiveness of each design change. For this kind of testing, the recorded signals are replayed into a shielded RF chamber, where the signal is radiated from an antenna towards the device under test. This process adds more noise than a live sky signal. This is because the recording antenna includes a preamp, and the device under test has its own antenna and preamp. The problem is that self-jamming noise gets drowned if there is too much noise in the replay. So for this type of testing, the recording is done with a high gain directional antenna in order to maximise the recorded signal to noise ratio. This means the original signal is higher relative to the noise, so the replayed result is closer to live-sky conditions. The test team could arguably have produced the same results with a simulator, but it would need to provide L2 and GLONASS signals to ensure that the whole bandwidth is free from self-jamming.

SBAS

The team used replay for testing WAAS and EGNOS operation in new revisions of firmware and software. Previously the company had to ship receivers around the world, where no debugging tools were available.

CONCLUSION

The RP can replay the previously recorded signal in the way that for most of the GNSS receivers/applications the impairments are undetectable or at least acceptable. This statement is confirmed by the tests results presented in this paper as well as by real usage case in the field. Also, the RP significantly reduce time/resources when the GNSS receivers have to be stressed in presence of live signals.

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