Embedded Recording in Flight Test Telemetry Receiver

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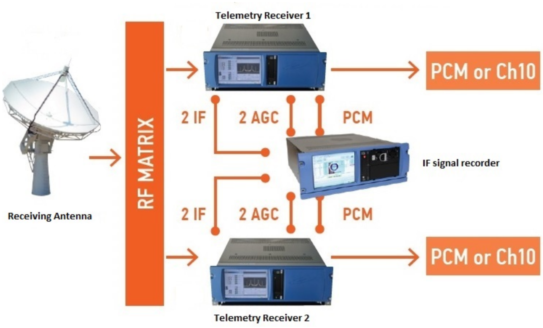
Abstract:

Telemetry hardware has continuously evolved over the decades pursuing the goal of evermore-integrated and easy-to-use systems. Digital signal processing techniques and FPGAs enabled manufacturers to develop Telemetry receivers with multiple channels in a single box. Yet, recording of ground station signals was left to separate units because of technical impossibilities. This paper presents an all-integrated Telemetry system embedding a best in class Telemetry Receiver and an IRIG-CH10 compliant Recorder. First, the system technical specifications are presented, with a focus on the type of signals to record and the required playback capabilities. Then, the technical approach that enables to run both the receiver and the recorder tasks on the same signal processing FPGA board is described. Finally, the performance of the system is assessed in terms of BER degradation of the playback signals.

Key words: Telemetry, Flight Test, Recorder & Reproducer, Multi-channel Recording, IRIG106.

Introduction

In this paper, we consider the following setup as the benchmark to evaluate the complexity of a ground station:



Two telemetry channels are transmitted at different RF frequencies. Each telemetry channel consists of two polarization signals (LHCP and RHCP) generated by the antenna, and demodulated by a dual-channel telemetry receiver. This reception configuration is named "polarization diversity": both polarization signals are demodulated independently, and a third demodulation channel is being created after combination of the two polarization signals (pre-detection combination), leading to an improvement of the budget link up to 3dB.

An additional 3dB improvement on the budget link and a better robustness to multi-paths are possible if the same data is being transmitted on the two telemetry channels : the outputs of the pre-detection combiner of each dual-channel telemetry receiver can be recombined, creating a four channel pre-detection combined signal. This mode is named "polarization and frequency diversity". It will not be studied in this article, and shall be considered as a possible improvement of the presented ground station setup.

There are four RF signals coming from the antenna via a RF matrix : two per dual-channel telemetry receiver. Each receiver is able to translate them to IF (70Mhz) for further recording by a four-channel IF recorder.

Each dual-channel telemetry receiver is able to output three PCM data : one for each received signal, plus one for the internally created combined channel. A PCM data consists of a pair of data and clock signals, which are sent to a decommutator and data processing unit.

Simultaneous processing by the decommutator and recording by the IF recorder is possible, at the cost of TTL splitters.

The presented ground station is then made of the following elements:

Tab. 1: Equipments

Item	Description	Nb
Receiver	Dual-channel telemetry receiver with embedded screen and keyboard for control and connectors in the backpanel 4U height	2
Recorder	Four-channel IF recorder with embedded screen and key board for control and connectors in the backpanel 4U height	1

Tab. 2: Interconnection

Item	Type	Nb
Antenna to RF splitters/matrix	N-type coax RF splitters (1 to 2)	2 2
RF splitters/matrix to receivers 1&2	N-type coax	4
Receivers 1&2 to IF recorder **(IF signals recording)**	BNC coax	4
Receivers 1&2 to IF recorder **(AGC signals recording)**	Custom cable RS422 D-sub44 to D-sub9	2
Receivers 1&2 to TTL splitters **(PCM outputs of each receiver)**	BNC coax TTL splitters (1 to 2)	12 12
TTL splitters to IF recorder **(PCM inputs of the IF recorder)**	BNC coax	12
TTL splitters to decommutator **(PCM inputs of the decommutator)**	BNC coax	12
Network to receivers 1&2 and IF recorder **(Monitoring&control)**	RJ45 cable	3
Receivers 1&2 to decommutator **(Telemetry data)**	RJ45 cable	2
Power supply to to receivers 1&2 and IF recorder	Power suppy cable	3

The total of each element sorted by category is depicted below:

Tab. 3: Cables by category

Item type	Nb
N-type coax	6
BNC coax	40
RJ45 cable	5
Power supply cable	3
AGC custom cable	2
TOTAL	***56***

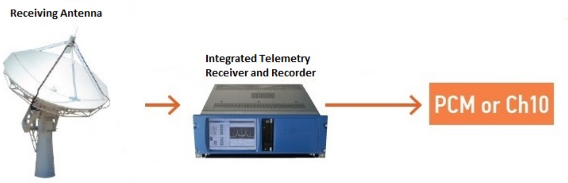
Tab. 4: Splitters by category

Item type	Nb
RF splitters (1 to 2)	6
TTL splitters (1 to 2)	12
TOTAL	***18***

More than 70 interconnection items of various types are needed, making harsh assembly, maintenance and flexibility of the ground station.

An all-integrated ground station

This article introduces an all-integrated ground stations, whose functionality and performances are strictly equivalent to those of the setup presented previously in this article. The new setup is then simplified as follows:



A single equipment performs the features of two dual-channel telemetry receivers and one IF signal recorder, reducing drastically the number of interconnection items needed. In addition, the new equipment embeds only two RF inputs (instead of four in the original setup): several telemetry channels (i.e. different carrier frequencies) can be processed on a single RF input, so that the equipment receives the two polarity signal (LHCP/RHCP) directly from the antenna. Splitters (or RF matrix) upfront the receiver are no longer required.

In the following, the all-integrated telemetry equipment is named receiver-recorder. As the IF and PCM recording is performed in the same box as the receiver, the cables required to perform IF, AGC and PCM recording are no longer required. Furthermore, three 4U equipments are now replaced by a single 4U equipment.

Below is the list of the required interconnection in a ground station using the new receiver-recorder:

Tab. 5: Interconnection (receiver-recorder)

Item	Type	Nb
Antenna to receiver-recorder	N-type coax	2
Receiver-recorder to decommutator **(PCM inputs of the decommutator)**	BNC coax	12
Network to receiver-recorder **(Monitoring&control)**	RJ45 cable	1
Receiver-recorder to decommutator **(Telemetry data)**	RJ45 cable	1
Power supply to to receiver-recorder	Power supply cable	1

The total of each element sorted by category is depicted below:

Tab. 6: Cables by category (receiver-recorder)

Item type	Nb new setup	Nb intial setup
N-type coax	2	6
BNC coax	12	40
RJ45 cable	2	5
Power supply cable	1	3
AGC custom cable	0	2
TOTAL	***17***	***56***

Tab. 7: Splitters by category (receiver-recorder)

Item type	Nb new setup	Nb initial setup
RF splitters (1 to 2)	0	6
TTL splitters (1 to 2)	0	12
TOTAL	***0***	***18***

The number of required cables is reduced drastically, and the need for splitters disappears.

Embedded recording specifications

By focusing on the use case presented earlier, we can easily write the specifications of the embedded recording. First, we can list the type of channels needed in the recording.

The quad channel receiver generates four down-concerted channels (IF1-4) centered at 70 MHz, with reduced level dynamics thanks to the AGC loops. Those AGC loops generate four signals (AGC1-4), each one holding the information of the gain that is applied to a particular channel. Recording of both those IF and AGC signals is of critical importance for two reasons. First, for post mission analysis. On a first order approximation, the profile of the AGC signal over time reflects the evolution of the link budget during the test scenario. Secondly, for playback. During playback, the receiver will require the AGC signals as inputs of its pre-detection algorithm, along with the IF signals. Without the AGC signals, the receiver will not be able to weight the IF contributors as expected in a MRC. The pre-detection combined signals that the receiver generates out of IF1-4 are considered as intermediate, redundant, signals that do not need to be recorded to save storage space, and system bandwidth.

The recording of IF and AGC signals might seems to be enough to keep track of the test scenario. Upon playback, a quad channel receiver with adequate AGC inputs would indeed be able to perform the MRC again, and provide the PCM outputs. This raises an important limitation of recording only IF and AGC channels: one depends on the receiver to be able to recover the PCM data again. However, PCM streams cost only a fraction (typ. 2%) of the bandwidth and storage space that are required for IF signals recording. It is evident that having the ability to access directly to PCM data without the need of the receiver is a must-have in a modern recorder. Most of the time, only the PCM data would be required for playback, possibly on remote CH10 compatible PCM recorders. A quad channel receiver as depicted earlier generates 6 PCM streams (4 individual channels, 2 combiners). It consequently seems a good option to record all six PCM channels (PCM1-6) along with IF (IF1-4), and AGC (AGC1-4) signals.

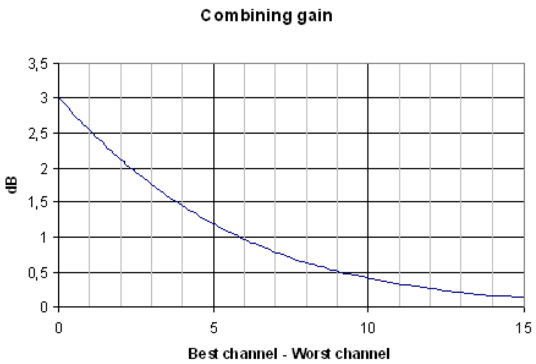
Now that the number and type of channels are clearly identified, we can elaborate on the required playback abilities. As explained in previous paragraph, the system shall be able to playback the PCM data on the usual connection with the decommutator. This means the data playback should be made available either through PCM electrical connection (TTL, RS-422) or through UDP streaming (RCC218-20, or CH10 UDP).

For IF replay, two principles can be investigated. First, it shall be possible to output the IF signals through the usual IF output of the receiver for external analysis or shortloop testing. In the same manner, the AGC signals shall be reproduced on the AGC outputs of the receiver. From an MRC point of view, in case of shortloop testing of the playback IF, it is important that either

- The receiver can process external AGC signals, along with IF signals whose level are set
- The IF level differences between the four IFs are reproduced.

For better interoperability of the system, we chose to implement the second solution. As the IF outputs of the receiver have a static and limited dynamic range (usually a digital scale, with Full-Scale at 10 dBm), it is not possible to cover the whole dynamic range of a low bitrate configuration (up to 100 dB) while keeping quantization error low. Yet, if we take a look at the combining gain, as a function of the level difference for a two channel MRC, for a same noise level under AGWN, it appears that the combining gain becomes hardly noticeable (0,1 dB) when the level difference reaches 15 dB.

This last value is compatible with a digital scale reproduction of the original dynamic range. Consequently, the playback shall reproduce the level *differences* among the sources, on a scale of at least 20 dB.



The second principle for playback of IF signal is to feed the IF signals directly in digital domain at the input of the receiver, to eliminate the need for external IF loopback. This, however, raises technical challenges that are not addressed in the present article.

Finally, other specification elements, such as time alignment, quantization scale, storage, can be extracted from the specification of a typical external flight test recorder, such as the Cortex RSR. The next table summarizes the technical specifications for the embedded recording.

Tab. 8: Embedded recording specification

	Item	No.	Details
0	File format	IRIG106 CH10	
1	IF channels	4	70 MHz, 8 bits/16 bits selectable
2	AGC channels	4	16 bits, > 300 kHz.
3	PCM channels	6	Bitrate bits per second. PCM throughput.
4	IRIG channels	2	Decoded time reference + 16b analog recording
5	Storage	Single cartridge, NVMe, 15 TB (> 4h at full speed)	
6	Aggregate bandwidth	8000 Mbps	
7	IF outputs	4	70 MHz, receiver outputs Ability to reproduce the level difference between IFs. 4 ns time alignment precision.
8	AGC outputs	4	Use of receiver ouputs
9	PCM outputs	6	Either PCM or UDP streaming.
10	IRIG output	1	Use of one high-BW video output of the receiver.
11	Recording and replay	Shall be operable independently from the receiver tasks. No impact of the recorder on the receiver operation of performance.	

Embedded recording implementation

This paragraph depicts the challenges and the advantages of integrating the receiver and the recorder into a single box. The reduction of the number of cables required has been previously mentioned.

Software and Cybersecurity

The application software of the three equipment have been modified in order to be able to run on a single kernel and on the same operating system. The required effort to secure the ground station is then reduced accordingly.

Apart from this modification, the legacy of the software of each equipment is maintained, and the software interface remains the same as the one of the stand-alone equipment.

Implementation wise, the recorded and playback flow all pass through the PCIe interface between the high-level software and the low-level firmware. Even though both products are now inside a single platform, a particular attention has been given to the separation during the implementation in an effort to minimize any potential perturbation between the receiver and recorder operation. As an example of this effort, a second microcontroller is deployed onto the FPGA platform to process specific recorder functionalities and compartmentalize low-level application.

Filtering

One of the main advantage of this new compactness is that the recording can directly benefit from the several analog and digital filtering and decimation stages of the receiver. The IF signal recorded correspond exactly to what is seen by the demodulator inside the receptor. The recording configuration (acquisition bandwidth, input frequency, input selection) is automatically adjusted to correspond to the IF filter bandwidth.

Gain (AGC)

The recorder captures the sum of every variable gain inside the receiver downlink: analog AGC and digital gain. The gain of the IF signal is automatically recorded alongside the IF signal in the form of an additional CH10 flow. It creates analog packet with 16 bits samples that represent fixed-point (Q8.8) value of the gain in dB extracted at the defined rate of 390 kHz.

The TMATS contains for the CH10 packets of the IF signal information of the ADC full scale in Vpp and the input impedance. Combining those information with the recorded AGC gain allows the reconstitution of the signal input level in dBm.

It also enables a new functionality during the replay: the Dynamic Gain Replay. This allows to playback the variation of level between IF signals and therefore correctly use the pre-detection combiner. When the dynamic gain replay is disabled, the output IF signals during playback are at a constant level of -13 dBm. When the dynamic gain replay is enabled, the stronger of the two IF signals, based on AGC value, will playback at -13 dBm and the weakest signal will playback at -13 dBm less the difference of level between the two IF signals. Thus, only the difference of level is provided during the playback and not the absolute level.

PCM

The PCM streams are directly captured inside the digital domain the nearest possible of the demodulation output, before the physical output and the usual bitrate reconstruction algorithm. In the case where a FEC is present, the PCM streams are sampled after the decoding. This proximity has the advantage of always having a valid clock available for the recorder. Therefore, problematic case such as a discontinued clock does not have to be handled.

The PCM bitrate inside the recorder is automatically adapted to the receiver channel configuration.

Replay

A specific new filter for the up sampling process has been developed to adapt the sampling between what is inside the CH10 packet and what is needed for the DAC frequency. This filter is future proof in a way to adjust for the potential replay at RF Frequency (telemetry bands) and with others recorded sampling (i.e. from others vendors).

The same timing performance as expected of a recorder is kept. The RTC is at the center of the alignment process between the different types (IF and PCM) of signals. The RTC is also used to generate a coarse approximation of the frequency for the playback clock. The receiver outputs handle the fine final tuning.

Results

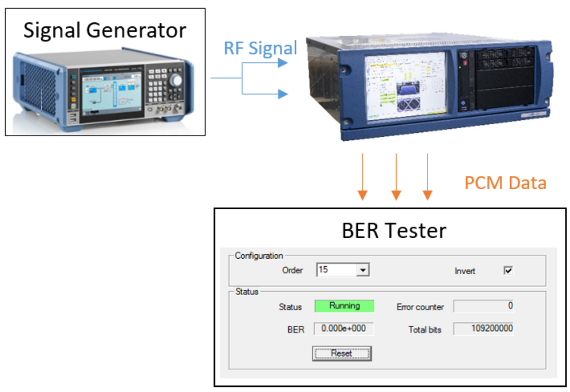
Setup presentation and expectations

The result part here will be focused on the capacity of this new equipment to both receive two IF signals with polarization diversity and record them. In the same time, the setup will show the capacity of the pre-detection combiner to create a third demodulation channel with a noticeable BER improvement.

After that, the setup is rearranged to focus on the playback mode (IF replay and PCM replay), showing the capacity of the embedded receiver to conserve the quality of the original IF signals and the PCM frames originally transmitted.

Note that the pre-detection combiner will be used again on the replayed IF signals to demonstrate that the performance gain during playback is the same as the original one.

Results will be demonstrated with the following setup:



This include a Signal Generator that simulates a signal we could receive through an antenna.

The RF signal is splitted on the two RF inputs, then converted to IF signals. Using the RF inputs gives the opportunity to use thermal noise by slowly decreasing the RF level on the generator. Due to the differences of the noise factor between the two RF channels, a slightly different BER on demodulation channel 1 and demodulation channel 2 maybe observed.

The pre-detection combiner is expected to demonstrate a significant performance improvement on demodulation channel 3.

The setup is limited to one dual-channel telemetry receiver-recorder that includes:

- a pre-detection combiner for the third PCM channel.
- The new recording part to capture both the two IF channels input and the three PCM channels. (2 from the direct inputs and one resulting of the pre-detection combiner).

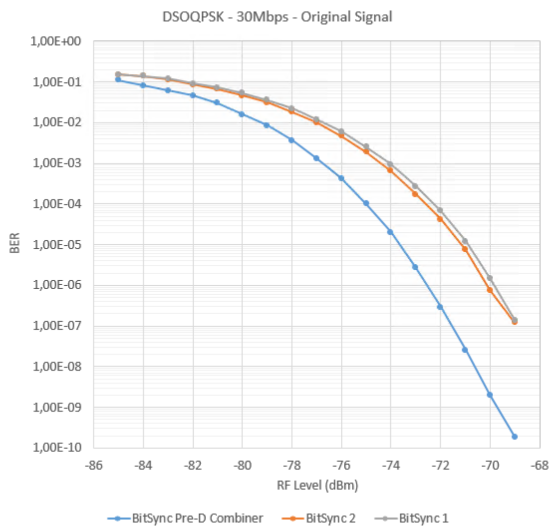
To ensure that the PCM outputs are correct, the BER is measured externally with an independent BER measurement system with three PCM inputs (data and clock signals).

Original signal measurement

The steps are the following:

1. Configure two IF signals on the two IF inputs of the receiver. (Generator IF output stays OFF)
2. Connect the three PCM outputs to the BER Tester Inputs.
3. Start Recording.
4. Switch ON the IF output on the generator.
5. Measure the BER and the number of frame received on the BER Tester.
6. Switch OFF the IF output on the generator.
7. Stop recording.

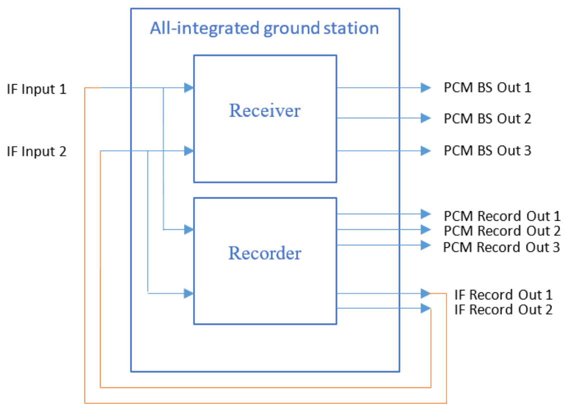
Those first steps allow us to get a first chart of three BER measurements for each demodulation output.



The performance improvement on the pre-detection combined channel is observed as expected.

IF Replay

Now that IF signals have been recorded, we can play them back on the embedded receiver with the following setup:



As mentioned earlier, the receiver and the recorder are two independent part.

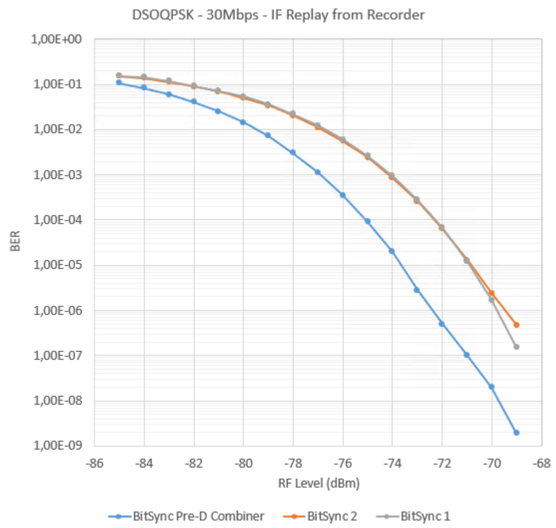
The recording starts with the signal OFF, then switched ON for a certain duration and finally switched back OFF before stopping the recording. This procedure ensure that the presence of the useful signal is fully recorded.

The steps are:

1. Connect the three PCM outputs to the BER Tester Inputs.
2. Start playing the record.
3. Measure the BER and the number of frames received on the BER Tester during the presence of the useful signal.

4. Wait for the end of the record.

By recording several files with a different RF level each time, we are now able to get the following charts:



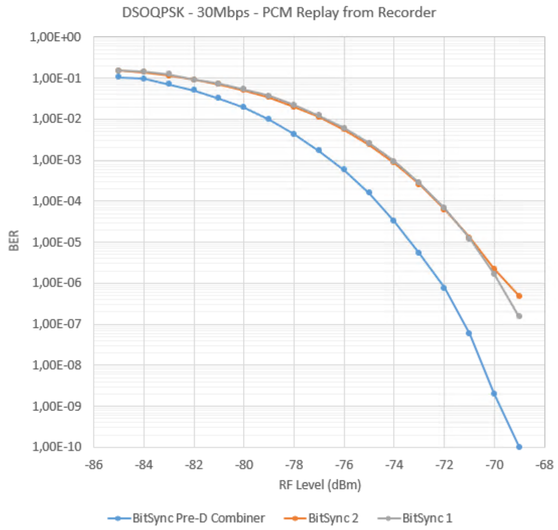
This replay shows the capacity of the recorder to ensure that the original IF signals are recorded without loosing any data.

Moreover, the pre-detection combiner is able to improve the BER on the 2 IF replay signals, showing that the IF signals are recorded without any timing difference.

PCM Replay

Now that the IF replay confirmed the good recording of both IF signals, we need to check that the PCM recorded after the demodulation units are consistant and give the same results.

To prove these, we don't need the receiver part anymore, we just have to replay the file and monitor the PCM Recorded Outputs (instead of the PCM Demodulated Outputs) with the external BER Tester.



Conclusion

This article presented the advantages of merging the telemetry receiver and IF signal recorder into a single box. The architecture choices were explained, and the record and playback capability without any performance loss was demonstrated.

The increasing integration presented in this article will continue to bring opportunities for new features in the near future, the first challenge being the implementation of a four channel pre-detection and post-detection combination.

Glossary

RHCP: right-hand circular polarization

LHCP: left-hand circular polarization

BSS: best source selector

RF: radio-frequency

IF: intermediate frequency

TMoIP: telemetry over IP

SNR: signal-to-noise ratio

PCM: pulse coded modulation

MRC: maximum ratio combining

ADC: analog to digital converter

DAC: digital to analog converter