Galileo RF Constellation Simulator Design Verification and Testing

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Abstract — **The characterisation and certification of Galileo Ground Receiver Chain (GRC) elements for the Galileo satellite-based navigation system is a critical programme activity, particularly for the In-Orbit Verification phase (IOV).**

Spirent has been contracted by the European Space Agency (ESA) via Thales Alenia Space to provide reference test equipment in the form of RF Constellation Simulators (RFCS) to support certification of the GRC and Test User receiver elements. These RFCS are able to support all the Galileo frequencies and services, including Open Service, Commercial Service, Safety-of-Life Service and Public Regulated Service (PRS).

This paper begins by presenting a brief technical description of the RCFS design and architecture and proceeds to describe the scope of and approach to the formal verification process.

Where appropriate, further detail of some of the verification techniques used are presented including a statement of the requirement, the test equipment and procedures involved and a summary of the results obtained. Most specific PRS aspects are excluded from this paper due to their classified status.

Initial conclusions are drawn and future work is described.

I. INTRODUCTION

Galileo is the result of a European initiative to design, deploy and operate a constellation of satellites to provide a global positioning capability similar to GPS. As part of the system infrastructure, a network of ground stations is required to monitor the signals-in-space. This Ground Mission Segment (GMS) of Galileo requires development of the associated Ground Receiver Chain (GRC), which will receive and measure the satellite signals, well in advance of satellite deployment.

In order to develop and certify these GRC elements, an alternative source of signals-in-space is required. In the GPS domain, RF Constellation Simulators (RFCS) have become the de-facto test and development tool. Such simulators create accurate facsimiles of the signals as they would be received from an actual orbital constellation of satellites, but under full control of the operator, and allow extensive, repetitive and accurate test campaigns to be conducted without the need to compromise on signal availability or to adopt special test modes in the item under test.

Spirent has adapted and extended its proven and established top-of-the-range GSS7700 GPS Simulator platform to fulfil the RFCS requirement for Galileo. The resulting GSS7800 comprises a sophisticated RF signal generator unit and dedicated industry-standard personal computer (PC) running 'SimGEN for Windows' (SimGEN) under Microsoft's WindowsXP® operating system as shown in Figure 1. SimGEN employs a Graphical User Interface (GUI) of the point-and-click type and is supported by on-line, context-sensitive 'Help' facilities.

Figure 1 GSS7800 RFCS with SimGEN PC

The ability of the GSS7800 RFCS to accurately represent the signals-in-space is vested in the hardware and embedded software design of the signal generator elements and the implementation of numerous mathematical models within SimGEN itself.

The models within SimGEN address satellite motion propagation, atmospheric degradation of signals, multipath reflections antenna reception gain and phase patterns, as well as being able to define a global simulated position with realistic trajectory generation for land, air, sea and space vehicles, which is particularly relevant to the Test User Segment (TUS) requirement.

In addition, one of the core functions unique to RF simulation is the ability to introduce comprehensive errors, both systematic and environmental.

In order to certify the performance of a GRC receiver design prior to satellite deployment using an RFCS, the RFCS must itself be subjected to an exhaustive series of tests to determine that it meets the required specification.

This paper identifies the verification approach adopted for the non-PRS aspects of RFCS performance. The classified nature of Public Regulated Service (PRS) precludes publishing details of its verification results. The paper describes the broad scope of the testing undertaken, a significant percentage of which was witnessed and approved by representatives of the contracting authority. The limited scope of this paper enables only the more interesting and challenging tests performed to be described, the formal written report on which extends to more than 250 pages. It is intended that a future paper will describe more of the innovative verification test methods employed and results obtained in greater detail.

At the time this paper was written all of the non-PRS testing has been successfully completed, subject only to resolution of a small number of issues and clarifications arising from review of the test results by the customer and from the witnessed testing.

II. RFCS Signal Generator

The GSS7800 signal generator sub-system incorporates a digitally-intensive architecture heavily based on FPGA technology. The result is a highly accurate, highly stable generator capable of exceptionally high fidelity and resolution and with hugely flexible plug-in backplane configuration. Communication with the required computer sub-system is via the industry-standard IEEE-488 interface and is housed in a rack-mountable case. The generator's large built-in front panel LCD displays simulation data for each fitted hardware channel such as power level, modulation type, velocity and PRN as well Built-In Test Equipment (BITE) messages. The simplified block diagram of Spirent's GSS7800 RFCS is shown in Figure 2. All the generator configurations and carriers feature an embedded multipath fader, which provides multiple additional paths for each generator channel in the hardware itself, considerably reducing the need to use other channels to generate reflected signals.

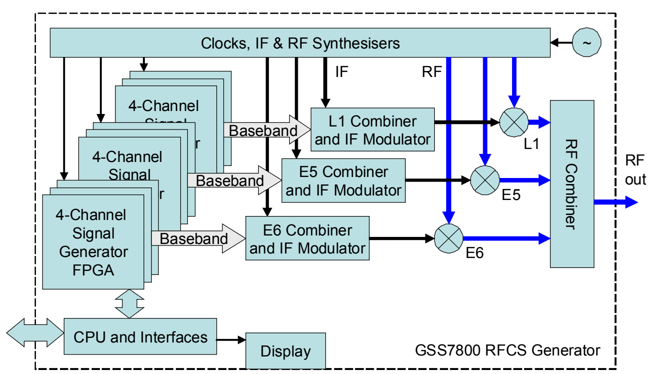

Figure 2 Simplified GSS7800 RFCS Block Diagram

To address the varied requirements of the GRC and TUS programmes, the generators have been supplied in one of three primary configurations, though others are readily possible.

1) PRS-GRC

L1-B/C BOC(1,1) and PRS at L1-A, plus E6-B/C PSK and PRS at E6-A. 12 satellite channels have been supplied for all signals, making a total of up to 24 primary satellite channels in a single chassis. The chassis can accommodate 4 more channels at each carrier.

2) Non PRS-GRC

L1-B/C BOC(1,1) and PRS-Noise[1] at L1-A, plus E6-B/C PSK and PRS-Noise at E6-A, plus E5ab ALTBOC 8-PSK. 12 satellite channels supplied at all three carriers, making a total of 36. Again this may be expanded, to a total of 48 channels.

3) Non PRS/PRS-GRC and TUS

This is essentially the same configuration as 2) above but with full PRS-capability reinstated at L1-A and E6-A.

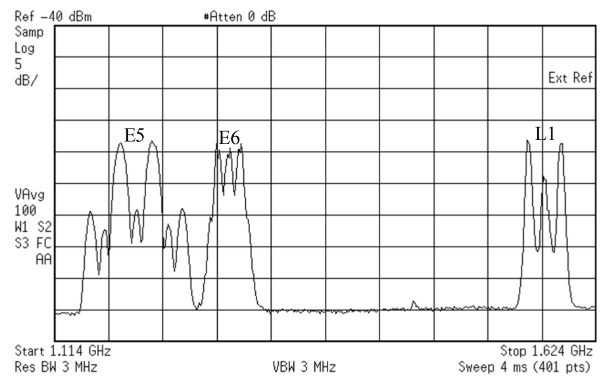

Figure 3 RFCS E1, E5 and E6 Signals

Figure 3 shows a spectrum analyser plot of the L1, E5 and E6 signals generated by the RFCS at their +20dB control level with respect to the nominal value of -152dBW. This is as viewed at the generator's RF monitor port, which is itself approximately 45dB above the level of the primary RF output.

III. RFCS Development Programme

Rapid availability of the RFCS was a cornerstone of the GRC and TUS programmes. Fully verified non-PRS capability was required no later than 14 months from Kick-off and PRS just 3 months later. Spirent's approach to RFCS fulfilment took full advantage of its proven GSS7700 GPS Simulator and SimGEN software to provide a carefully phased delivery schedule of capabilities that supported the parallel receiver development programmes. This allowed early delivery of advanced test equipment to customers capable of supporting multi-satellite, multi-carrier tracking with fully modelled satellite motion and navigation data extraction (using arbitrary content sourced from simple binary files) between three and six months after Kick-off. Increasingly more sophisticated capabilities, such as fully modelled

[1] PRS-Noise is a spectrally correct and coherent representation of the PRS Signal but does not utilise PRS structures.

navigation message structures, were added at mutually agreed milestones.

IV. RFCS Verification Principles

A traditional thorough verification approach was required, grouping tests into 4 method categories, A to D.

- Method A: Visual **Inspection** of various properties of the RFCS, such as physical attributes and availability of various interface ports.
- Method B: **Demonstration** of the ability of the RFCS to perform a range of user-controlled functions
- Method C: Deterministic **measurement** of parametric performance.
- Method D: Mathematical **analysis** and derivation of performance where deterministic measurement is not possible or inaccurate.

In principle, tests using Methods A through C would be subject to customer-witnessed verification, whilst Method D results would be submitted off-line for approval. A conservative analysis, however, of the timeframe required to conduct the witnessed tests yielded 3 months, rendering this impractical given the customer's diverse National representation from across Western Europe. As a result, Spirent agreed with its customer to move a number of Method C tests involving protracted duration into off-line analysis.

The use of a Galileo receiver to verify performance is generally precluded. Availability of a validated unit so early in this GNSS's programme is highly unlikely so more traditional methods are necessary. It was not considered necessary to re-verify Spirent's non-Galileo-specific capabilities that are an inherent and well proven part of its GPS Simulator range, such as accurate satellite motion propagation and calculation of range.

The performance of the generated signals must be characterised and verified both against the Galileo Signal-In-Space Interface Control Document (SISICD) [1] and the RFCS programme's Requirement Specification [2].

A. *SISICD Requirements*

The SISICD specifies primarily the structure of the signal at point of transmission whereas the RFCS has the role of representing the signals at point of reception. Nevertheless it is necessary to establish that the RFCS operates correctly in respect of the fundamentals.

It may be readily established, for example, that the generated signals have the correct carrier frequency by removing the modulation and simply using calibrated RF instruments on the resulting CW signals. Signal RF power levels may also be verified using standard instruments, but a combination of measurements is required since the received signals are below the thermal noise floor and cannot be measured directly. Measurements are first made at a monitoring point in the system where the RF levels are within the range of a calibrated RF power meter. In order to establish the difference between the monitor point and the final RF output, a much higher test signal is injected into the RF chain at the appropriate centre frequency such that it may be measured at both ports sequentially using a single instrument.

Establishing that the modulation envelopes and bandwidth has been correctly implemented is less straightforward. The lower trace of Figure 4 represents the theoretical modulation envelope for E5ab in the frequency domain as generated by Agilent's SystemVue™ from the SIS description and the upper trace captured from the RFCS RF port using a spectrum analyser with suitable filtering to remove noise; resolution is 5dB/div. A 5dB level bias has been applied to aid visibility. The high degree of correlation supports verification of several parameters in one test, particularly when supported by other tests such as correlation loss.

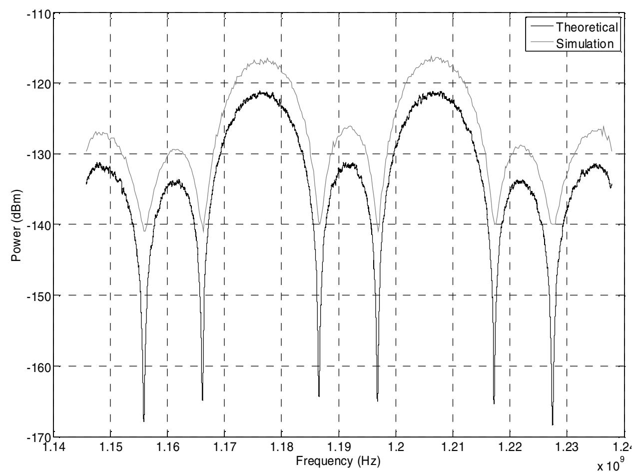

Figure 4 E5ab Frequency Spectrum - Measured vs Theoretical

Somewhat more complexity surrounds the supplementary modulation associated with Navigation Data messages, such as I/Nav and F/Nav. The fidelity of the underlying content may be examined by simply logging the calculated content to a disk file using a supplied utility. This is followed by off-line comparison with the expected content, derived independently from the constellation description and the specified date and time for the simulation, and structure against that defined by the SISICD. These principles may be readily extended to the application of Cyclic Redundancy Check (CRC) algorithms and Forward Error Correction (FEC).

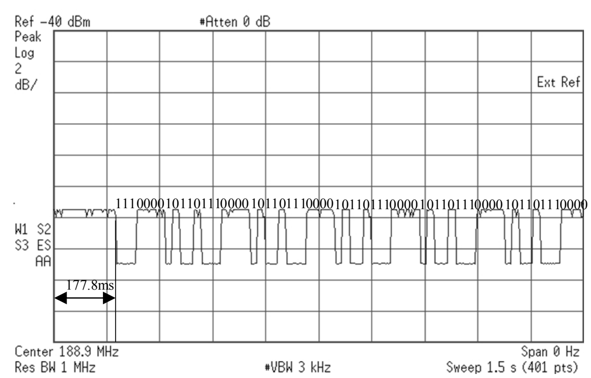

Figure 5 Demodulated Navigation Data Message

It is also necessary to establish that the data message is being modulated correctly onto the RF carrier. This requires demodulation and capture of the message from the signal. Spirent used a novel approach to demodulating content from RFCS signal channels. The signal of interest is generated with the required composition on an RFCS channel. A copy of the signal is coherently generated on a second channel but with the content of interest disabled. A spectrum analyser tuned to the carrier frequency and set to its “zero-span’ mode can act as a convenient Phase-to-Amplitude (PM-AM) demodulator since the amplitude of the resulting signal changes whenever the content of the two components is different. The sweep time can be set appropriately to the content of interest. Figure 5 shows an example of this technique used to extract the F/Nav message symbol stream from E5a.

The same technique can be used to extract the ranging code symbols as seen in Figure 6. The fact that Galileo uses Memory Codes provides a ready-made data reference source for comparison.

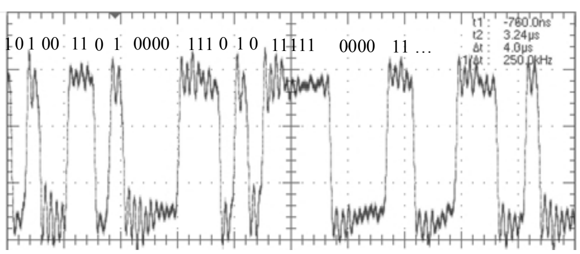

Figure 6 Demodulated Ranging Code

B. RFCS Specification Requirements

The RFCS has the task of faithfully representing the signals **as received**, not as transmitted. As such the SimGEN software must model the environment for the signals in space and configure the signal generator to deliver the signal with the appropriate delay and amplitude taking account of the simulated satellite motion, vehicle motion, ionosphere, troposphere etc.

The range of RFCS requirements is extensive and diverse, including transmit and receive antenna gain/phase pattern modelling, data display and storage, remote control, provision of interference signals, data message editors, vehicle motion models, deliberate error generation, complex multipath generation, plus numerous accuracy and stability demands.

It is necessary to validate that the RFCS performs all of these functions appropriately and with the specified precision. An example of this is where the RFCS has to ensure that multiple carriers are generated coherently with each other and that inter-carrier characteristics are representative of the simulated environment. The ionosphere introduces differential delay between carriers which must be modelled and applied accurately. Moreover, the RFCS has to implement modelled imperfections of satellites in controlling inter-carrier group delay.

Figure 7 shows the result of a test to verify the implementation of the Broadcast Group Delay (BGD) parameter applicable to a particular satellite, defined by the SimGEN user in this case to be 100ns. The digital oscilloscope traces were obtained using the discrete PM-AM demodulator shown in Figure 8 on the RF signal. The signal generator issues a start-of-run 1PPS pulse that is used to trigger the oscilloscope to capture the early ranging code chips. The upper trace shows the L1C result when the BGD is set to zero and the lower trace from a second run where the BGD is set to 100ns. The difference in the timing obtained is in full accordance with the requested value.

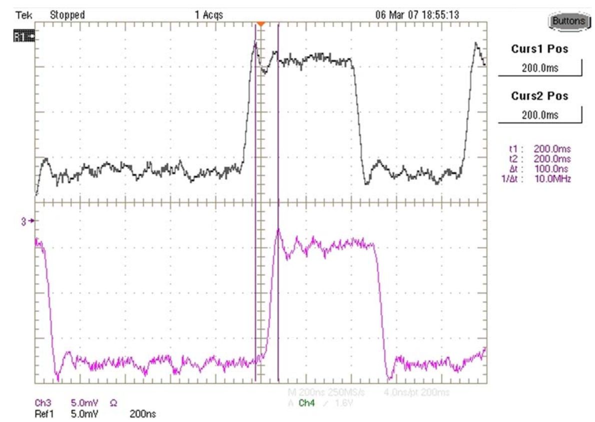

Figure 7 Broadcast Group Delay verification

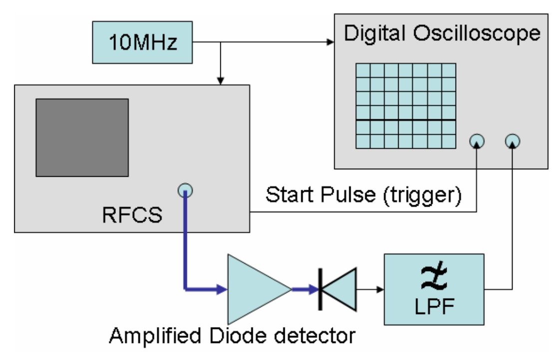

Figure 8 Discrete PM-AM Demodulator

Another multi-carrier aspect that requires high fidelity is the carrier phase dispersion with frequency due to ionosphere. In particular, it is especially applicable to the E5 signal, which is very broadband occupying 92MHz. The ALTBOC modulation scheme is an 8-PSK implementation of two signals with nominally different carrier frequencies separated by more than 30MHz. The SISICD describes a method for signal generation at the satellite using a single carrier halfway between the E5a and E5b carriers and based on a modulation state look-up table. However, if this were to be replicated exactly in the RFCS the resulting signal would not display the correct code phase dispersion.

The Spirent RFCS uses an innovative technique to generate the ALTBOC signal that correctly represents the carrier dispersion across the band and a particularly interesting technique was developed to demonstrate its fidelity.

A special test scenario was created to generate the received signals at E5 at a static equatorial location from two colocated satellites at zenith in geostationary orbit yielding constant range. In addition, the RFCS was configured to apply fixed ionospheric delay for the two satellites of 8m and 18m respectively that should introduce code and carrier divergence across the band. Using simulator tools, an additional pseudorange ramp was applied over a defined interval to reduce the code phase of the second satellite to that of the first, a change of 10m. This has the automatic effect of advancing its carrier phase by 10m, and results in a total carrier phase difference of 20m with no additional code/carrier divergence. Another RFCS function was then used to retard just the carrier phase alone by 20m and then by a further half cycle, theoretically placing the central carriers of the two satellites in anti-phase. The resultant of this exercise is displayed at IF in Figure 9 which shows the expected null at the band centre. The signal does not null fully across the band because of the wanted code phase dispersion across the signal bandwidth.

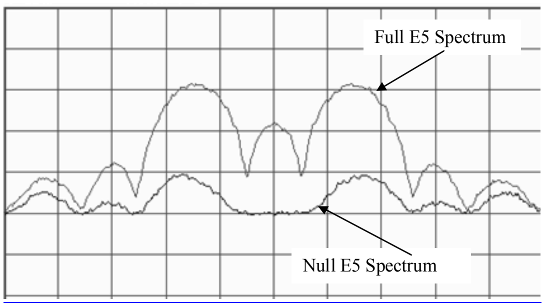

Figure 9 E5ab Dispersion Test – E5 Null

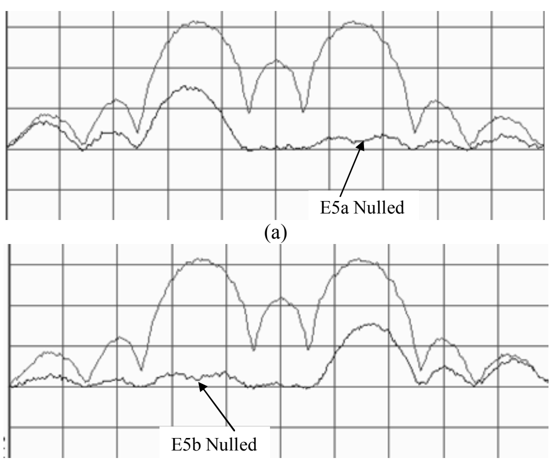

Figure 10 E5ab Dispersion Nulls at (a) E5a and (b) E5b

To check that this dispersion has the correct magnitude, the code phase of the second satellite was moved to create a best-possible null at E5a centre. This is shown in Figure 10(a). The code phase was then moved in the opposite direction to attain a null at the E5b carrier frequency (Figure 10(b)) and the value of the commanded change noted. This value was then compared to the expected value representing the theoretical dispersion and the capability verified. Note that this display is of an IF signal and that after up-conversion to RF the relative frequencies of E5a and E5b take on their appropriate frequency relationship.

A similar setup was used to verify the application of Ne-Quick [3], Galileo's reference Ionospheric model. From [1]:

$$\text{Ionospheric Delay}_{\text{Carrier}} = \frac{40.3 * 10^{16} * TEC}{10^{16} * (\text{Carrier Frequency})^2} \text{ (m)}$$

where TEC is Total Electron Count. The test applied a value of 185.1 for the ai_0 coefficient of the model, which yields a TEC of 1073.31×10^{15} electrons/m^2. The pseudorange delay at E6 equates to 26.38m or 88ns. Figure 11 shows the test result as seen on the digital oscilloscope, with the upper trace representing the reference case with TEC set to zero and the lower trace representing the test case. As can be seen from the zoomed area, the measured value of delay taken between unambiguously equivalent points on the traces provides exactly the required result.

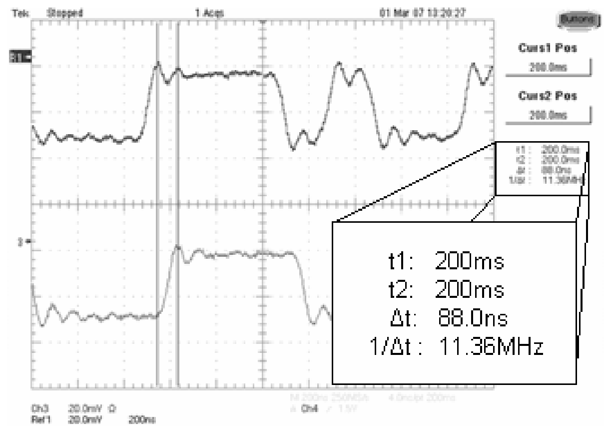

Figure 11 Ionospheric Delay at E6

An important RFCS requirement for the customer is that the bias between the RFCS's 1PPS reference hardware signal and the equivalent epoch at RF must be less than 500ps. Using a high speed digital oscilloscope with persistence ON it is possible to view the L-band signal directly along with the 1PPS. As can be seen from Figure 12 the challenge is to determine exactly where the true chip transition occurs in order to accurately measure the bias and to apply appropriate compensation. The uncertainty of the actual cross-over point is bounded by the markers and is approximately 1ns. The mid point should yield the 500ps required. In order to guarantee accuracy, however, it was necessary to perform a more in-depth mathematical analysis than to rely on a subjective estimate based on the raw visual data.

This involved capturing the digital samples squaring the L-band data then performing a 40^{th} order polynomial fit. This replaces an ambiguous cross-over point with a display that exhibits a distinct minimum value, as shown in Figure 13. Forty data sets were obtained in this way and the mean value determined. The mean was corrected for known fixed biases associated with the cables used between the test ports and the oscilloscope and the resulting correction value was applied to the generator's compensation element. The whole process was then repeated with the correction in place and a sub-500ps bias was affirmed. This result validates the use of the simpler oscilloscope approach for routine system alignment.

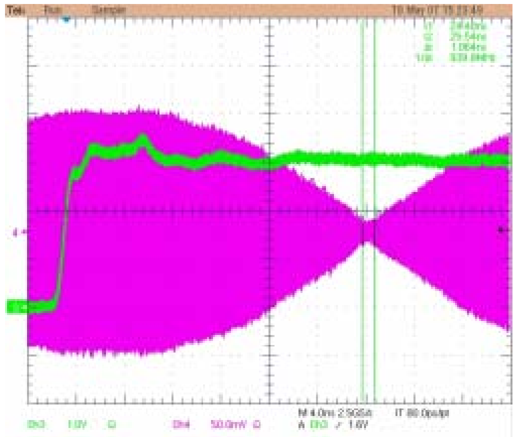

Figure 12   Cross-over Ambiguity for 1PPS RF Epoch

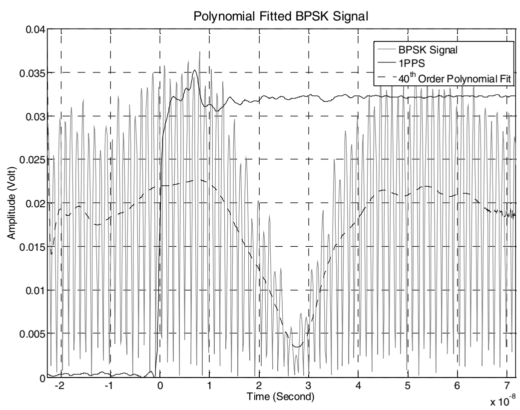

Figure 13   Polynomial fit to Squared Sample Data

A range of RFCS requirements revolved around the subject of signal stability between generator channels over extended periods. In an ideal scenario, this test would involve tracking a signal with a receiver and logging the variation with the elements such as ionospheric effects disabled. However, it has already been established that verified Galileo receivers are not available during the RFCS verification timeframe.

An alternate approach was adopted. Two identical signals were generated on separate channels at each carrier in turn. By adjusting the code phase of the signal from one signal channel and inverting its carrier phase, it is possible to obtain a signal power null on the spectrum analyser.

The resulting trace can then be stored and acts as a reference trace. The 'Max Hold' function of the analyser can then be invoked over the relevant extended period specified. Any systemic long-term code or carrier instability of the generated signals from either channel will cause degradation of the null and this will be captured in the 'Max Hold' trace, as shown in Figure 14 for E6. At the end of the period, the test operator observes the live trace of the signal null and deliberately degrades the null by making and recording small code-phase adjustments of one of the signals until the live trace approaches the limit of the 'Max Hold' trace. The amount of adjustment required is equivalent to the peak instability encountered over the period. A similar result can be obtained via carrier phase adjustments and compliancy can be established by comparison with required limits.

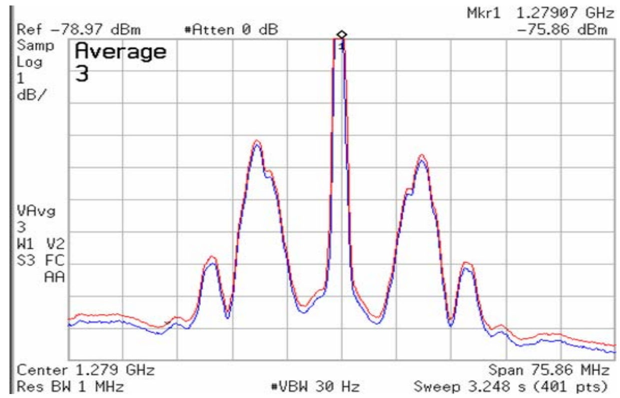

Figure 14   Max Hold Function Used To Capture Signal Instability

V. Summary and Future Work

This paper has described the methodology and a small selection of the exhaustive verification testing performed on a complex Galileo RF Constellation Simulator operating at all three carrier frequencies with all services enabled. The testing has established the overall suitability for its intended role in the certification of Galileo receivers to be used during IOV.

Spirent's will extend this verification work to the integration of the RFCS with its GPS simulators. A particular area of interest will be ensuring the inter-system coherency of the ionospheric delays provided by the two different models employed.

Acknowledgement

The authors wish to recognise the contribution of the Spirent RFCS design team in producing a product that fully meets the customer's extensive and challenging requirements.

References

[1] Galileo Development and In-Orbit Validation (IOV) Phase C/D/E1 Signal In Space Interface Control Document, Issue 12. 0, 24th October 2006

[2] Galileo GMS RFCS Specification, Alcatel Space GAL-REQ-ASP-RFCS-A/10536 Issue 2A, 27th July 2005

[3] Galileo Ionospheric Model for Single Frequency Receivers, ESA-APPNG-SPEC/00344-BAR Issue 4.1, 6th July 2004