Realtime EGSE for Testing Radar RF Subsystems

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ABSTRACT

Radar remote sensing from space offers a remarkable contribution to a set of scientific applications that are challenging to achieve from the ground, such as weather forecast. Radar RF testing systems are essential throughout Radars' development and testing life cycles. Such test systems are challenged with potential adaptations during the development phase and with achieving the target performance within a nominal budget. This paper briefly describes these challenges and focuses on a proposed solution and related experience, which are gained through the development of ESA's MetOp-SG Scatterometer RFSCOE testing system.

INTRODUCTION

The Electrical Ground Support Equipment (EGSE) is an integrated suite of electrical Satellite testing solutions to make sure that a Satellite under development works perfectly. The Radio Frequency Special Check-Out Equipment (RFSCOE) is the EGSE industrial-standard solution to test the radio frequency sub-systems of a Satellite with the highest degree of precision. An RFSCOE is an integrated hardware and software system with heterogeneous components from different COTS providers and suppliers, such as signal generators and spectrum analyzers. Each RFSCOE is specifically designed to allow fully automated execution of calibration and tests of the target Payload. RFSCOEs targeting Radar payload systems mainly contain: (1) a timing control module, which determines when and which Radar assembly begins with its work, and (2) an RF transponder module, which sends RF pulses according to a timing scheme and receives scattered RF signals.

The MetOp-SG-SCA (shortly SCA) payload is a real-aperture C-band (5355MHz ± 1MHz) pulsed imaging radar system, which provides mainly wind observation over oceans [1]. The SCA instrument is being developed by Airbus DS in Germany [2]. AtoS, Austria, is providing the mission's RFSCOE Back-end (RFSCOE-BE), which is used during the Assembly Integration and Test (AIT) program for the SCA instrument on MetOp-SG [3]. The RFSCOE-BE forms part of the SCA EGSE acting as the counterpart of an SCA part called RFSCOE Front-End (FE). The SCA RFSCOE-FE distributes the SCA high power Transmit (Tx) pulses via a high-power ferrite switch matrix to the individual antennas according to a timing scheme provided by the sequencer of the Digital Control Unit (DCU). During on-ground testing, Tx Pulses and DCU timing signals are made available to the RFSCOE-BE via coaxial cables and LVDS interfaces, respectively. The RFSCOE-BE allows for the characterization of the SCA Tx Pulses as well as injection of RF Stimulus signals into the SCA Received (Rx) chain.

PROBLEM DESCRIPTION

The current SCA RFSCOE-BE includes a set of COTS RF measurement devices and radio generators running under Linux or the Windows Operating System. All instruments are connected to a central Controller by means of standard peripherals, USB and LAN connections for control, data acquisition, and data analysis. Due to the timing constraints of Radar signals under test, the central controller must acquire radio measurement, process them, and perform actions on signal generators upon the reception of each timing pulse. The Pulse Repetition Interval (PRI), as illustrated in Fig. 1, has 32.25ms duration, hence 32 PRIs per second. Each PRI is divided into an RF transmitting window (Tx Pulse), an RF receiving window (Echo), a Calibration and a Noise window. The MetOp-SG-SCA instrument has two PRI configurations, one for mid beam and another for side beam antennas, as shown in Fig. 1. Both mid and side beam configurations differ in the starting time and duration of the Echo window. As shown in Fig. 1, the central controller should acquire Radar signals, e.g., Tx and Echo, process the raw data and reconfigure target instruments within 18.93ms (worst case scenario for side beam configuration). These tasks should be performed by the RFSCOE-BE controller 32 times per second.

AtoS Austria provides an integrated suite of electrical Satellite EGSE testing solutions based on proven generic and mission-independent components [3]. AtoS' EGSE solution (called GSE) allows for a fully automated execution of RF calibrations and tests and it easily integrates with heterogeneous components from different providers and suppliers. The GSE software part is defined in the open source language TCL, which makes it portable across a variety of different architectures and operating systems. However, the TCL-based GSE does not guarantee hard Realtime

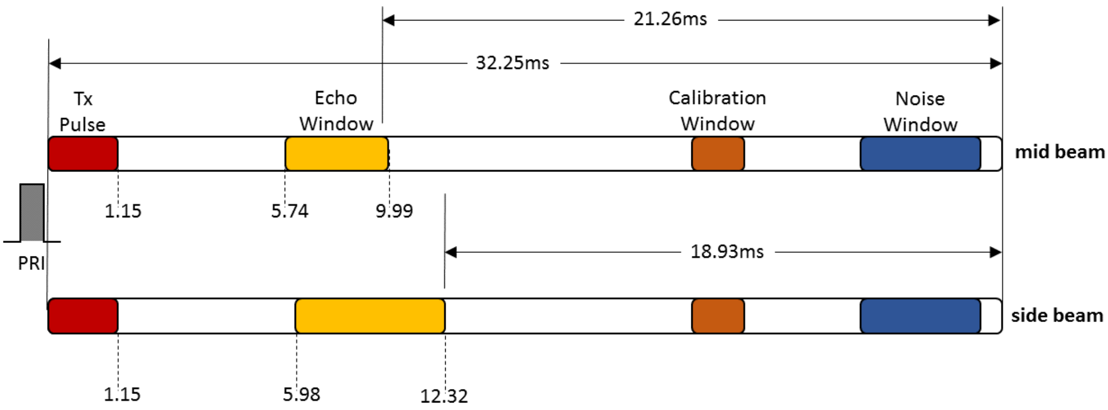

Fig. 1: SCA Instrument Timing within a Pulse Repetition Interval (PRI) for Side and Mid Antennas

operations for acquiring, processing, and archiving to HDD radio data within a PRI valid window (e.g., 18.93ms shown in Fig. 1). Furthermore, the current GSE platform does not support multithreading to simultaneously acquire and process information from multiple devices. A new GSE solution is under continuous development to overcome these issues.

HARDWARE SETUP

The SCA RFSCOE-BE shall allow measuring, and archiving Tx Pulses transmitted by the RFSCOE-FE during the Tx window and to inject RF Stimulus signals into the Rx Window and/or the noise acquisition window (See Fig. 1). To perform these tasks, the RFSCOE-BE needs to be synchronised to the SCA instrument operation. This is achieved via the SCA timing signals generated by the SCA DCU and made available for the RFSCOE-BE, as shown in Fig. 2, by means of LVDS connections. RF Tx Pulses and stimulated RF Echo signals are connected to the RFSCOE-FE by means of Coaxial cables. Both signals (Tx and Rx) are connected to a power detector within the RFSCOE-FE, which allows voltage measurements inside the RFSCOE-BE using a twisted pair cable connection.

As described in the SCA RFSCOE-BE requirement specification document by Airbus DS, Germany, the RFSCOE-BE shall comprise at least the following key building blocks (see Fig. 2): (1) two channels Peak power meter (PPM), (2) Digital Voltmeter (DVM), (3) Signal generator, (4) Realtime Spectrum Analyser (RSA), (5) RF Test-Transponder (TRP), (6) Timing Control Module (TCM), and (7) RFSCOE-BE controller. An RF matching and switching unit is bridging the connections between the Satellite's RF Subsystem and each measurement unit. A brief description of each RFSCOE-BE component is described in the following subsections.

RF Matching and Switching Unit

The matching and switching unit is an AtoS in-house product, which distributes, attenuates and switches incoming RF signals to measurement equipment and the Test-Transponder with proper power levels including the cable losses of the RF harness to/from the Satellite RF Subsystem. The matching unit also switches and attenuates the outgoing RF signals to the requested level, such that a damage RF level can never be reached at the RFSCOE-FE.

Time Control Module

The TCM module is used to perform time synchronization between RFSCOE-BE and DCU. To achieve this synchronization, the TCM module receives a set of clocks over LVDS interfaces from the DCU, such as SCA base clock (1.02762 MHz) and a PRI trigger (32Hz). The TCM main component is a COTS FPGA device with a USB interface for programming and loading to memory a timing configuration table [4]. The TCM timing table contains information about starting time, duration, and activation status for each instrument within the RFSCOE-BE on the PRI bases. Using TCM physical links, the following logical gate- and trigger signals are derived from the pre-defined SCA radar cycle:

- A Gate signal for the Test-Transponder for Tx RF Pulses acquisition
- A Trigger signal for Test-Transponder to stimulate the Echoed RF signal
- A Gate signal for the DVM for measuring the input and Echoed RF signal
- A Trigger signal for the PPM for measuring the Tx and Echoed RF signal.
- A Gate signal for the RSA to perform RF sampling and IQ recording (in the RSA internal memory) for the Tx and Echoed RF signal.
- A Gate signal for controlling the analogue signal generator

The SCA DCU LVDS interface and TCM digital output (gates and triggers) are passing through parallel ESD protection diodes. A (quasi)-Realtime tool with a GUI interface has been developed to program and visualize TCM timing signals at runtime.

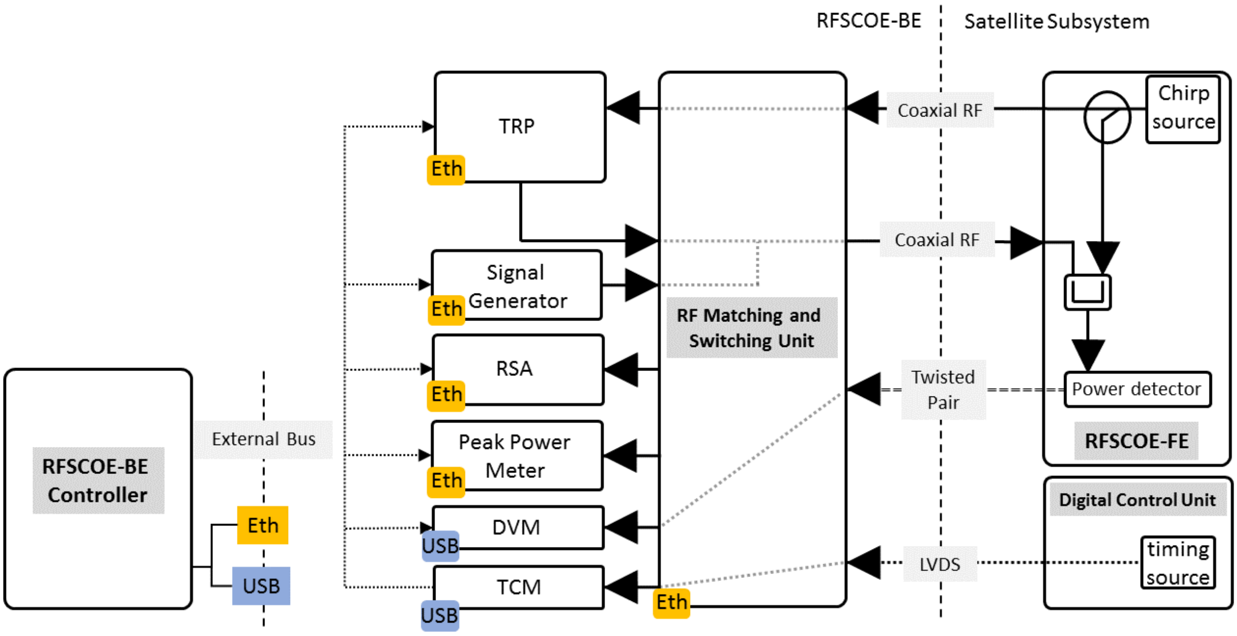

Fig. 2: MetOp-SG-SCA RFSCOE Hardware Setup

Signal Generator

A waveform signal generator with controllable center frequency and amplitude is used as a second RF Echo source [5]. The signal generator is supported with the Pulse-modulation option, which activates the RF interface only when an external input gate is logically high. The gate signal is provided by the TCM. The output RF amplitude and timing are updated by the RFSCOE-BE controller periodically on PRI bases.

Realtime Spectrum Analyzer

For manual signal analysis and debugging, an RSA with 40MHz instantaneous bandwidth is used [6]. The RSA is commanded and controlled using SCPI commands over a GbE connection. Furthermore, the RSA is equipped with 200Msample internal memory for IQ data recording. Each IQ sample is representative by a 16bit integer. In the RFSCOE-BE project, the RSA is used to record IQ data at *8MS/s rate*. The RFSCOE-BE controller streams these sample in a (quasi)-Realtime way for further processing.

Peak Power Meter

A PPM suited for radar applications is used to measure the RF power of Tx Pulses and Echoed RF signals using two power sensors [7]. Upon the reception of a trigger from the TCM module, the PPM samples a separate trace for each power sensor at a 3MHz frequency for 2ms. The sampled trace together with a set of statistics (e.g., Peak, Average, Min) are made available for acquisition over a GbE connection till the next coming trigger. The PPM receives two triggers per PRI (for a Tx pulse and RF Echo). The RFSCOE-BE Controller has two fetch the PPM in the period between two consecutive triggers.

Digital Voltmeter

A multifunction data acquisition device is used as a digital voltmeter, which samples *continuously* multiple differential-input analogue channels (up to 8) with a maximum overall sampling rate of 250KS/s at 16bit resolution [8]. The acquired input voltages during Tx Pulses and Echoed RF signals are used with a calibration table mapping between input power level and the output voltage of the power-detector depicted in Fig. 2. Calibrated voltage readings are processed by the RFSCOE-BE Controller to adjust the amplitude of Echoed RF signal to a specific target level. Depending on the actual measurement tasks, the target level may be set by Open-loop or Closed-loop algorithms.

In Open-loop operation, there is no direct relationship between the power level of the Tx Pulse and the injected RF Echoed signal. Instead, a predefined power level should be reached at the RFSCOE-FE Power Detector input port. In closed loop operation, the injected Echoed RF signal should have an equal power level to the Tx Pulse at the power-detector input port. Due to the timing criticality of this task and the variable data transfer latencies of voltage samples from the DVM hardware till the user-space of the Linux machine, a TCM gate with the 1µs resolution is continuously sampled in parallel with the voltage input channel (i.e., the DVM samples two channels in parallel each with 125KS/s). In this case, both input channels (TCM gate and voltage reading) experience the same latency over the USB interface and inside the Linux Kernel. This approach allows the RFSCOE-BE Controller to identify DVM samples corresponding to Tx Pulses and Echoed RF signals with 8µs (=1/250K) accuracy.

Test-Transponder

A base-band digital transceiver together with an IQ modulator are used as an RF Test-Transponder [9-11]. Signal flow inside the Test-Transponder is shown in Fig. 3:

- Acquisition of the SCA Tx RF pulses from RFSCOE-FE
- Digitization of SCA Tx RF pulses

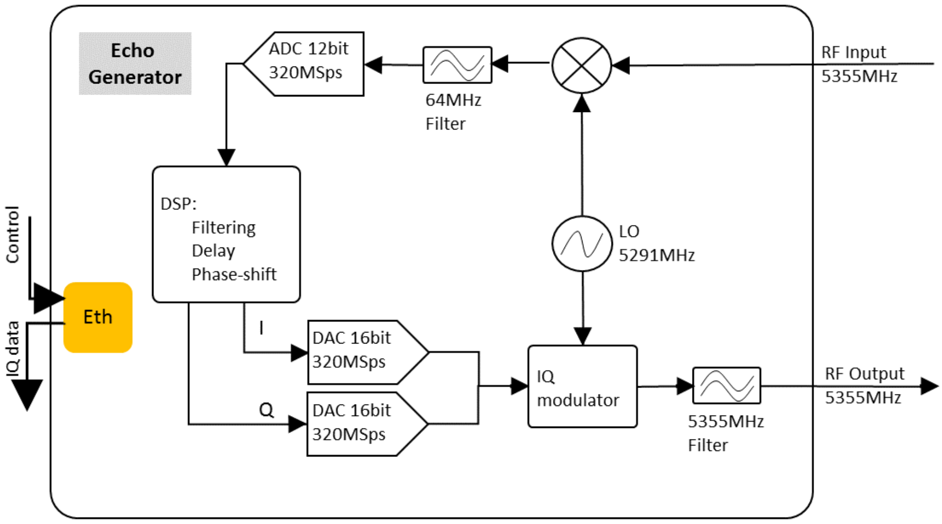

Fig. 3: RF Test-Transponder Setup

- Generation and injection of synthesized Rx Echoed RF signal with adjustable delay, attenuation, and Doppler shift
- Transfer of digitized Tx Pulse RF signal (IQ data) on PRI based to the main RFSCOE-BE Controller through GbE connection

To fulfil the Open-loop and Closed-loop operations (see Digital Voltmeter), the Echoed RF amplitude and delay should be updated periodically on PRI bases.

As shown in Fig. 3, the Test-Transponder includes (1) a downlink path containing a downconverter operating at 5291MHz, a 64MHz bandpass analogue filters, a 12-bit resolution Analogue-to-Digital-Converter (ADC) operating at 320MSps, and (2) an uplink path containing 16-bit resolution 2 DAC slices operating at 320MSps each, an IQ modulator, and a 5355MHz bandpass analogue filters. For fast signal processing, an FPGA with 2GS memory is used to bridge the communication between the ADC and DAC.

RFSCOE-BE Controller

The RFSCOE-BE Controller is a COTS rack server with a standard GbE, USB interfaces and equipped with quad-core (CPU Intel Xeon E3-1270v6 4C/8T 3.80 GHz) [12]. The RFSCOE-BE Controller is in charge of command and control of the RFSCOE-BE equipment. It provides the following functions:

- Control of all RFSCOE-BE equipment in stand-alone configuration via local commands or remote-controlled configuration via commands as received from the Instrument Central Check-Out System (I-CCS).
- Configuration and programming of the TCM and control its operating mode (i.e. position, length and activation of timing signals for each PRI)
- Signal conditioning of the RF stimulus signals (generated by RF Test-Transponder or Signal Generator) in Closed-loop or Open-loop operational modes
- Implementation of internal control loops for the RF stimulus signals used for high precision power gain stability measurements in Open-loop or Closed-loop operations
- Generation of RFSCOE-BE measurement reports
- Archiving of recorded RF measurement data for further evaluation

PROPOSED SOLUTION

As shown in Fig. 1, acquiring, processing, and archiving RF measurements from the different COTS components should be performed periodically and with a time-constraint (hard deadline) between every two consecutive triggers or gates. In the case of the Linux Operating System (OS), the standard Kernel does not provide Realtime capabilities. To achieving reliable and uninterrupted data acquisition and processing, a Realtime Preemptive Linux kernel is used in the RFSCOE-BE Controller. A Preemptive Linux Kernel allows program developers to create high priority tasks (processes) that cannot be interrupted (preempted) by any other task (process) with a lower priority. For the MetOp-SG-SCA RFSCOE-BE project, the Realtime Preemptive Linux Kernel published by CERN LHC is used [13]. Due to the far launch year of the SCA Satellite around 2030, the CentOS OS was selected over other Linux-based distributions (e.g., Ubuntu) due to its Long-Term-Support (LTS) period.

The current GSE solution from AtoS Austria based on TCL scripting language does not allow for task (process) allocation with Realtime priorities. Hence, a new GSE Orchestrator is under continuous development together with new C/C++ multithreading testing sequences (replacing TCL). This allows acquiring and processing RF measurement from

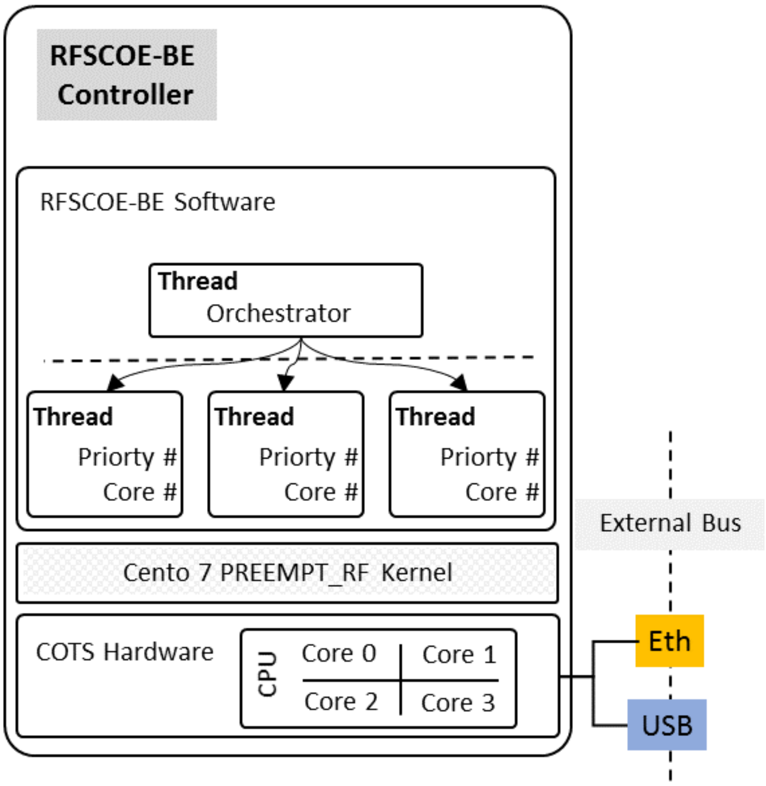

Fig 4: PC Controller Setup

multiple instruments simultaneously. The new GSE orchestrator maps each RF acquisition task (from PPM, DVM, TRP, and RSA) to separate threads allocated on separate physical CPU cores with predefined Realtime priorities as shown in Fig 4.The archiving tasks from the four measurement units are mapped to threads running with lower priority on the same physical core of the corresponding acquisition thread (i.e., DVM acquisition and archiving threads are running on the same physical core). Furthermore, many configurations were updated inside the RFSCOE-BE Controller, such as disable C-States, P-States, hyperthreading, CPU frequency control and options related to power management. Such configurations ensure ultimate processing capabilities of the Intel CPU.

For communication with USB devices, such as the DVM, a key tradeoff must be considered when creating a USB device: does the device need guaranteed bandwidth from the host (known as isochronous transfers) or does it need to send/receive a lot of data (known as bulk transfers)?
Bulk transfers are desirable since they can use nearly the entire bandwidth of the Bus, such that the data can move quickly. Flash drives and other external storage choose this approach. Unfortunately, bulk transfers do not guarantee a minimum bandwidth or latency, so communication can be 'bursty'.
Guaranteed bandwidth is desirable since USB I/O is round-robin controlled from the host - even when another device on the Bus monopolizes the Bus, the host will periodically service an isochronous device. Data acquisition devices, such as the DVM, usually choose this approach since every USB device wants their data measurements to be both as Realtime as possible and without stutters. Unfortunately, isochronous transfers are allowed to drop old data in order to keep giving the host the newest data. The RFSCOE-BE Controller verifies data integrity of USB devices with isochronous transfers at Runtime.

RESULT AND ANALYSIS

After assembling the RFSCOE-BE as illustrated in Fig. 2, additional emulators for the RFSCOE-FE and DCU components were implemented by AtoS Austria to verify the overall system functionality and performance.

DVM Data Acquisition and Processing

DVM measurements are considered the key input for Open-loop and Closed-loop signal conditioning algorithms. The USB-based DVM device was connected to the RFSCOE-BE RT Preemptive Linux Controller and configured to continuously sample and acquire two differential voltage channels *each* with 100KS/s (one for Power Detector output, another for TCM output). Samples were streamed to the RFSCOE-BE Controller periodically in traces of 2000 samples (equivalent to 10ms). Upon reception of a Tx Pulse and an Echoed RF signal, the RFSCOE-BE Controller calculates the required increase in TRP (or Signal Generator) output power to guarantee equal signal powers at the Power Detector

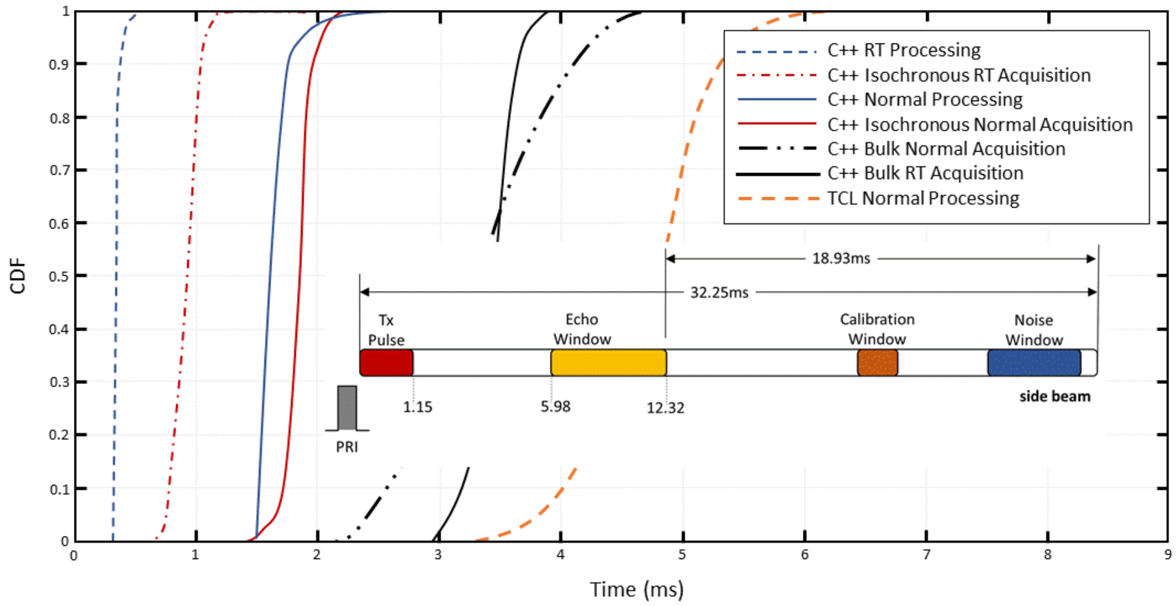

Fig 5: CDF Distribution of Acquiring and Processing Time DVM Samples

input port (see Fig. 2). The acquisition and processing times of different setup configurations are illustrated in Fig 5 by means of Cumulative Distribution Function (CDF).

Result in Fig 5 shows that Isochronous acquisition time with Realtime priority is shorter (i.e., faster acquisition) than without Realtime Priority or Bulk acquisition. Fig 5 also shows C++-based processes threads, which implements the Closed-loop logic, were accomplished shorted (i.e., faster processing) than without Realtime priority or TCL-based processes.

RSA Data Acquisition and Archiving

The SCA Tx Pulse signal has a bandwidth of 2MHz (i.e., 5355MHz ± 1MHz). For a wider signal characterization and further processing, an RF bandwidth of 4MHz at *8MS/s rate* is recorded (i.e., 5355MHz ± 2MHz). An RSA pre-defined internal memory of 2^{17} Samples (each is a 16bit integer) is allocated for recording the 4MHz IQ data. At 8MS/s rate, the memory is filled in 15.625ms. Once the memory is filled, it will be available on an RSA socket interface. The RSA starts immediately overwriting the pre-allocated memory. Hence, the RFSCOE-BE Controller has to acquire the 2^{17} IQ Samples within 15.625ms to fulfil the (quasi)-Realtime requirements.

By means of CDF distribution, result in Fig 6 shows recording and accusation to disk required time of C++-based and TCL-based processes. As shown in Fig 6, C++-based implementation can fulfil the (quasi)-Realtime requirements, whereas the TCL-based implementation cannot. However, not a substantial improvement was observed between the Realtime priority and normal priority processes.

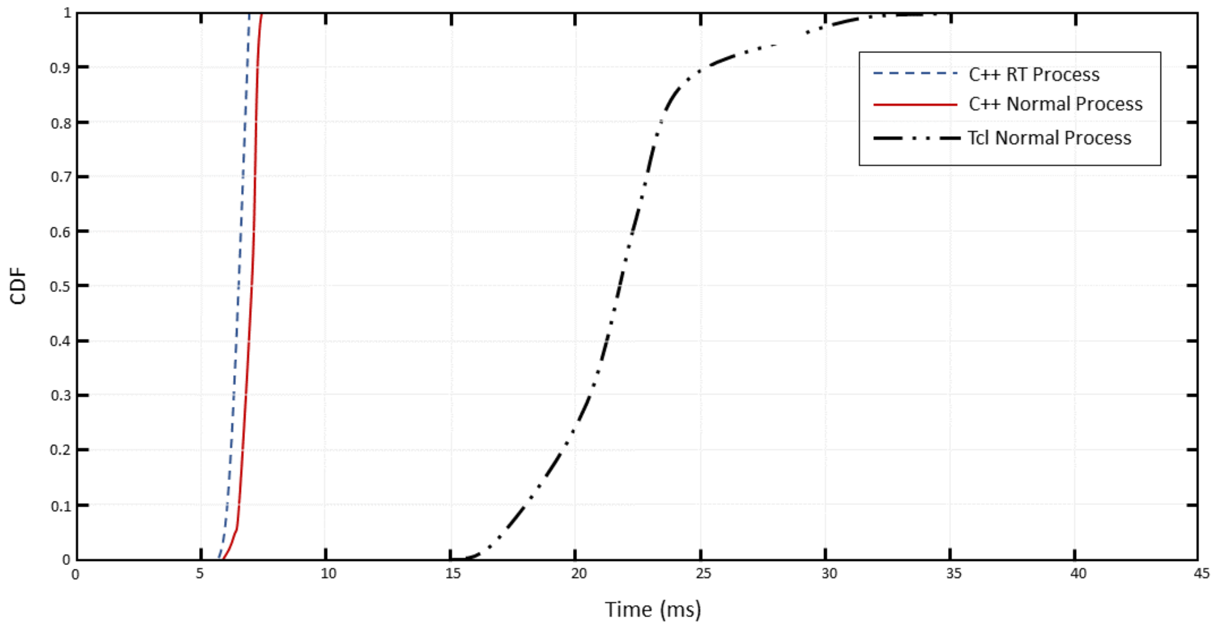

Fig 6: CDF Distribution of Acquiring and archiving RSA IQ data

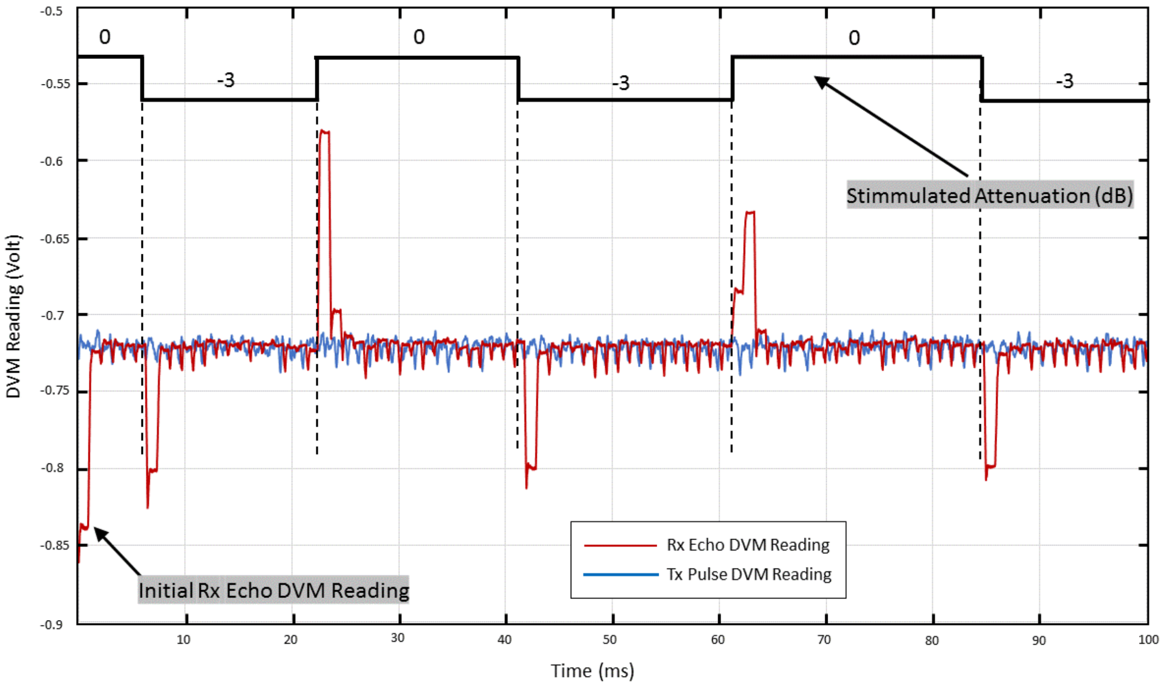

Figure 7: End-to-End Closed-loop Results

End-to-End Closed-loop Performance

To measure the overall system performance, the Closed-loop setup was considered (i.e., the Rx Echoed RF signal should have an equal power level to the Tx Pulse signal at the Power detector input port). An attenuator inside the RF matching and switching unit was used to interrupt the Echoed power level and test the system response time.The result in Figure 7 shows that the Closed-loop process has successfully adjusted the TRP output power every time the RF path was interrupted with a different attenuation value (changing between 0dB and -3dB). The overall system response time, which includes DVM samples acquisition, processing, and TRP amplitude commanding, varies between 1.2-1.6ms. This represents an outstanding performance given the PRI period of 32ms.

CONCLUSION

RFSCOE systems provide a set of automated calibration and RF measurements, which are key components in a Satellite development lifecycle. Radar RFSCOEs are challenged to provide periodic precision RF measurements in time-constraint test scenarios for Radar hardware and software subsystems. In this paper, a description of the TCL-based AtoS' EGSE solution was presented including its limitation in performing parallel and Realtime operations. A new C++-based EGSE system, which is under continuous development, was presented to offer parallel and Realtime test operations to Radars' manufacturer engineers at a competitive price. A comparison between the two solutions was performed within the ESA's MetOp-SG-SCA project. Finally, an End-to-end evaluation of the SCA RFSCOE-BE response was presented, which shows 1.2-1.6ms latency within 32ms valid response window. Experience and lessons learned during the SCA RFSCOE-BE project will be transferred to Biomass RFSCOE-BE (a new ESA mission), which require Realtime operations within a 250µs PRI window.

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