Echo Simulator Systems For Exomars 2016 Radar Doppler Altimeters Tests

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***Abstract*—In the framework of Exomars Mission 2016, test equipment were developed in order to verify the performance of the Radar Doppler Altimeter onboard of the Entry, descent and landing Demonstrator Module before the Radar Field Test campaign. Three Echo Simulator Systems are currently involved into test activities of radar units. Their main task is the simulation of the echoes coming from Mars surface and their injection into the radars to test them in various operating conditions of descent trajectories and terrain behaviors. The Echo Simulator Systems are also used to collect the transmitted radar pulses and auxiliary signals to verify the correct radar transmission sequence in terms of pulse width, power and repetition interval. Echo Simulators Systems are able to simulate echoes in presence of wide terrain backscattering, altitude and attitude variations. The architecture is based on hi-speed Analog to Digital and Digital to Analog Converters commanded by a Field- Programmable Gate Array. A front end from Base-Band to Ka-Band has been designed to interface the equipment with radar and built to assure the required high dynamics and fidelity of signals. Two Echo Simulators are used in open-loops mode, injecting echoes generated by means of pre-processed trajectories to test the radars in standalone mode. The third one is by contrary used in closed-loop mode. It generates echoes using trajectories that are evaluated runtime according to radar units' measurements feedback and simulated maneuvers of the descent module such as aero braking and thrusters' activation. This mode permits to test the radars when integrated with the platform's Guidance, Navigation and Control system.**

Keywords—Aurora, Exomars, Entry Descent and Landing, Radar Doppler Altimeter, Electrical Ground Support Equipment, Automatic Test Equipment, Echo Simulator System;

I. Introduction

ExoMars is the first flagship mission of Aurora Exploration Program led by European Space Agency (ESA) [1] [2]. Its main aim is to develop and improve a long-term plan for robotic and human exploration of our Solar System, preferring some specific subjects like the Moon and Mars. A second aim, not less significant, is to look for evidence of life beyond the Earth. In this context, ExoMars will pursue important scientific and technological goals directed to improve Europe capabilities in the field of planetary exploration and, in particular, to observe Mars planet which, in its environment, can hide the evidence of some form of past life. Two missions have been scheduled in the ExoMars Program: Mission 2016, which foresees the launch of the Trace Gas Orbiter (TGO) and an Entry, descent and landing Demonstrator Module (EDM), and Mission 2018, which includes a rover which will carry a drill and a suite of instruments dedicated to exobiology and geochemistry research. The EDM is covered with a special material that will thermally protect the module and will be equipped with technology capable of controlling the orientation and landing speed [3]. Indeed the module will slow down its velocity by means of a parachute which will open after entering the Martian atmosphere and will complete its descent by means of a close-circuit Guide, Navigation and Control (GNC) system based on a Radar Doppler Altimeter (RDA) and Inertial Measurement Units (IMU) [4] [5]. Thales Alenia Space Italia (TASI) is the industrial Prime of the missions. Among all, it is also in charge of the design, manufacturing and verification of RDA.

Three Echo Simulator Systems (ESS1, ESS2, and ATE) have been provided as part of the dedicated Electrical Ground Support Equipment (EGSE) designed to test the Engineering Model (EM), Engineering Qualification Model (EQM) and Proto Flight Model (PFM) of the RDA. The equipment have been designed, manufactured and verified by the Consortium of Research on Advanced Remote Sensing Systems (Co.Ri.S.T.A.) in Naples (Italy). Co.Ri.S.T.A. supports TASI also in RDA validation and verification activities, including field test campaigns.

The three test equipment have been designed to fulfill the following main tasks: (a) simulation of the echoes coming from Mars surface and their injection into the RDA to verify radars performances in various operating conditions of descent trajectories and terrain behaviors, (b) to collect transmitted radar pulses and auxiliary signals to verify their characteristics in terms of pulse width, power and repetition interval. Echo Simulators Systems are able to manage the entire descent phase that is characterized by wide altitude and attitude variations. Descent profiles can be assigned as input through dedicated files (ESS1 and ATE) or runtime through a reflective memory (ESS2). The architecture is based on hi-speed Analog to Digital and Digital to Analog Converters commanded by a Field-Programmable Gate Array (FPGA). A dedicated front end from Base-Band to Ka-Band permits to interface the equipment with the radars and to assure the required high dynamics and fidelity of the signals. ESS1 and ATE inject echoes to RDA generating them using pre-processed descent trajectories. They are used in an open-loop mode permitting to test radars in standalone configuration. ESS2 generates echoes in closed-loop mode using trajectories evaluated runtime on the basis of RDA measurements feedback and EDM simulated maneuvers such as aero braking and thrusters' activation. This mode is aimed to test radar models with operative EDM equipment and with the support of several Special Check Out Equipment (SCOE).

II. Architectures

Three independent Echo Simulator Systems have been built to serve different facilities involved in radar models (EM, EQM, and PFM) testing activities. Main subsystems composing the equipment are reported in the following:

- Rack Power Distribution Unit (RPDU), that distributes electric power to all subsystems; RPDU is powered by Main Power Distribution Unit (MPDU) that is common to all EGSE involved into RDA tests;
- Ethernet Switch, that allows to command and to transfer data between the subsystems;
- Off-Line Processor (OLP), that simulates echoes by taking into account a statistical description of terrain and its electromagnetic response as well as RDA characteristics such as the antenna pattern, the attitude and the trajectory;
- Data Archive (DA), that stores simulated echoes and acquired data transmitted by RDA;
- Signal Reference Distribution Unit (SRDU), that manages all useful synchronization signals and information coming from RDA and distributes them towards equipment;
- Acquisition and Generation Section (AGS), that generates the simulated digital echoes and acquires the transmitted pulses from RDA both in Base-Band according to radar timeline; it also manages the UDC IF and RF variable attenuators to guarantee the entire output power dynamic;
- Up & Down Conversion (UDC), that converts the Base-Band echoes to Ka-Band and the RDA pulses from Ka-Band to Base-Band;
- Radio Frequency Front End (RFFE), that receives the simulated Ka-Band echoes, generated by UDC, and transmits them to the RDA Beam Router; it is also devoted to receive the Ka-Band pulses from the RDA Beam Router Sub Assembly (BRsA) and to transmit them toward UDC.

A. ESS1 Architecture

ESS1 provides echo signals to RDA in open-loop mode (*Fig. 1*). It is intended to test radar models in standalone mode and it is constituted by: RPDU, Switch, OLP, DA, SRDU, AGS, UDC, and RFFE.

OLP is a software that runs on a dedicated workstation in a Windows 7 SP1 x86-64 environment. It uses the MATLAB Compiler Runtime (MCR). The workstation is located in a dedicated module of the rack and its hardware is selected for the CPU parallel computing. This allows to build the software with a hi-level parallel computing instructions set, i.e. Matlab Parallel Computing Toolbox. The OLP includes the Terrain Model, the RDA Model, and the Calibrated Model. The Terrain Model is OLP module in charge of generating synthetic Martian surfaces, representative of real scenarios. The simulated surface is schematized as the sum of two processes: a large scale deterministic and a small scale stochastic. The large scale process is a deterministic model used to simulate smooth topographic variations of Mars surface that occur at large scale (tens of kilometers). It is defined as a bilinear interpolation of a low resolution digital elevation model (DEM) on the basis of the grid computed by RDA Model taking into account the EDM position and attitude w.r.t. the surface. DEM can be: (a) Mars topographic maps obtained with MOLA or MOC instruments; (b) Earth topographic maps (c) Plane with bidirectional slope with superimposed features (like crater with different shape and size). The small scale process takes into account small stochastic topographic variations of Mars surface up to the wavelength scale, i.e. it simulates the overall surface roughness by means of fractals surface modelling [6]. The RDA Model is the OLP module that simulates the echoes received by the RDA from the Mars surface modelled by the Terrain Model. It takes into account EDM trajectory and attitude during the descent as well as RDA main parameters [7]. The front shield and back shell are also included in the received echoes simulation. The Calibrated Model performs the crucial task of ensuring that, at the RDA antenna interface, the

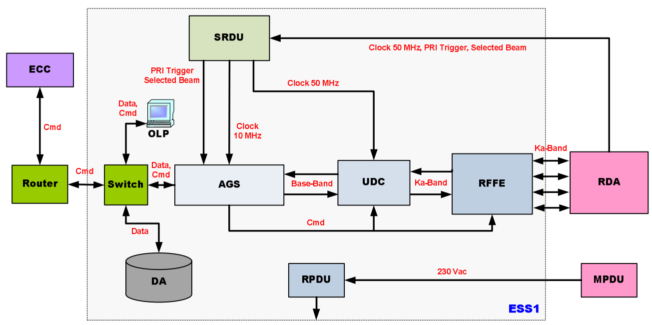

Fig. 1 - ESS1 Architecture

echo power, delay and shape are preserved by any alteration introduced by the AGS, UDC and RFFE.

Simulated data are stored in the DA and they are locally loaded by Echo Generator Command and Control (EGCC) software on OLP and then read by the AGS high speed reading channel during real-time test. DA is integrated into OLP workstation and it is composed by a dedicated raid controller with 8 Hard Disk Drives (HDDs) of 2 TB of capacity. Controller is set in Raid 5 configuration permitting an effective storage capacity of 14 TB and one HDD failure tolerance.

SRDU manages synchronism signals and information coming from RDA (PRI Trigger, 10 MHz and 50 MHz Clock Signals, and Beam Selection) and distributes them to equipment subsystems to ensure machine operations timing coherence [8] [9] [10]. SRDU is equipped with an internal auxiliary 50 MHz oscillator for internal debug that can be switched on and loopback connected for internal testing. The internal oscillator is totally disabled during RDA operations. The subsystem interfaces RDA with AGS and UDC subsystems.

AGS is constituted by: Controller and Data Memory (CDM), Analog to Digital Converter (ADC), Digital to Analog Converter (DAC), Disk Array Controller (DsAC), Mass Memory (MM), and System Controller (SyC) [11] [12] [13] [14]. The ADC digitizes the input pulses transmitted by the RDA that are converted to Base-Band by the UDC. The DAC performs a digital-to-analog conversion of simulated echoes samples read from dedicated MM by means of AGS Read channel. The CDM subsystem manages the timing of ADC and DAC. It also provides two digital signals to UDC: Attenuation ID and Autocheck command. SyC manages the DsAC to store and read data from MM according to EGCC commands sent to SyC by means of TCP/IP protocol. These commands can be locally sent on OLP using the EGCC GUI or remotely sent on EGSE Command Computer (ECC) by means of Ethernet connection using a dedicated protocol. In this case EGCC only manages the communication between ECC and SyC. Typical commands are the saving of calibrated acquired data from MM to DA and the preloading of the selected scenario from DA to MM. The DsAC is introduced to improve the data rates of writing and reading channels. The writing of RDA transmitted pulses (Acquisition Phase) and the reading of simulated echoes from mass memory (Generation Phase) are executed in parallel by two different FPGAs. ADC and DAC operations are synchronous with the external clock provided by SRDU.

UDC interfaces AGS with RFFE. It performs signal frequency conversion between Ka-Band and Base-Band, and signal conditioning by means of amplifiers and variable attenuators. It is composed by four parts: Tx Up Converter, Rx Down Converter, Autocheck Unit, and Clock Distribution Unit. Main guidelines in designing and manufacturing UDC are: (a) usage of as much Commercial Off-The-Shelf (COTS) components as possible to facilitate maintenance and reduce development cost, risk and delay, (b) minimum number of active elements such as amplifier in RF pathway to increase reliability and calibration stability, (c) simple RF architecture in order to easily expand test capability, and (d) minimum interface Voltage Standing Wave Ratio (VSWR) to reduce mismatch and improve accuracy and repeatability of the test system.

RFFE interfaces UDC with RDA. It receives the four Ka-Band signals, nominally going from BRsA to the RDA antenna, and transmits each of them toward the UDC down converter, complying with the BRsA transmission sequence. Vice versa the RFFE receives the simulated Ka-Band echoes, provided by the UDC up converter, and transmits them to the four beams (B0, B1, B2, and B3) of the BRsA. Moreover the RFFE provides dedicated outputs to monitoring the system signals with laboratory instrumentation such as Scope, Power Meter and Analog Spectrum Analyzer. The four RFFE paths were characterized in terms of shape distortion, amplitude and delay using standard laboratory instruments. Characterization results are stored into dedicated files then used by the OLP Calibrated Model and Acquired Pulses Calibrator (APC). The Ka-Band echoes from UDC, split into four parts by a power divider, are input to RFFE. Each output signal coming from power divider is sent in a circulator to avoid problems of reflection and mismatch and to permit signal circulation in several directions. When the radar is in receiving mode, signal circulation is from UDC output to radar, while when the radar is in transmitting mode signal circulation is from radar to UDC input.

B. *ESS2 Architecture*

ESS2 provides echo signals to RDA in closed-loop mode (*Fig. 2*). The simulated echoes are not pre-processed by OLP but they are provided by a real-time firmware on AGS. To save time execution, the firmware evaluates echoes features at each pulse repetition interval according to a simplified model. The evaluation is based on terrain backscattering and real-time trajectory. ESS2 is composed by: RPDU, DA, SRDU, AGS, UDC, and RFFE.

ESS2 DA is a server with dedicated raid controller that manages 2 HDDs of 2 TB of capacity. Controller is set in Raid 5 configuration to permit an effective storage capacity of 2 TB and one HDD failure tolerance.

ESS2 AGS differs from ESS1 version for the lack of DsAC. In this case in fact, echoes are not pre-processed: no storage in DA and AGS reading tasks are necessary. ESS2 uses

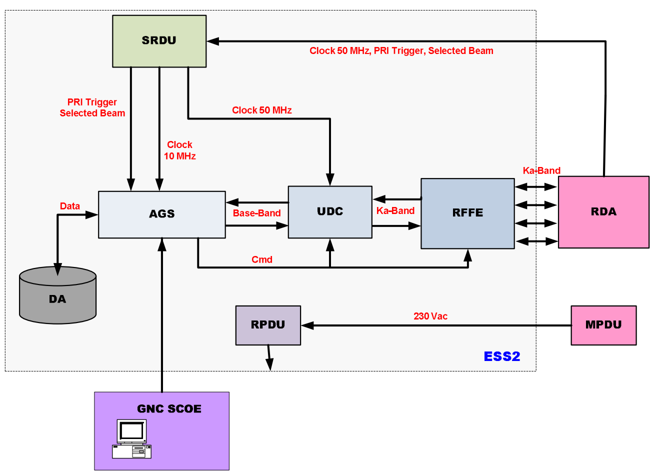

Fig. 2 - ESS2 Architecture

a Reflective Memory (RM) to receive real-time kinematic data provided by GNC SCOE through fiber optics. Unlike ESS1, ESS2 is not remotely commanded, since commands are locally executed on AGS.

RPDU, SRDU, UDC and RFFE are identical to ESS1.

C. *ATE Architecture*

ATE provides echo signals to RDA in open-loop mode, but without BRsA (*Fig. 3*). It has been manufactured to provide one unidirectional output and one unidirectional input waveguide instead of four bidirectional waveguide as per ESS1 and ESS2. It is composed by only AGS and UDC, but functionality and configuration are kept the same as for ESS1.

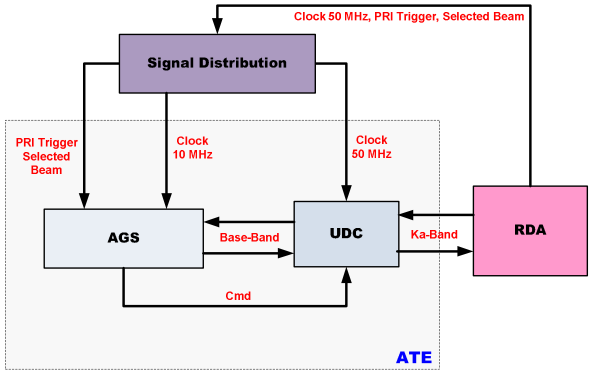

Fig. 3 - ATE Architecture

III. Specifications

Echo Simulator Systems have been designed according to RDA specifications. They are Ka-Band Radio Frequency (RF) pulses receiver from RDA and echoes transmitter to RDA (TABLE I).

Their primary goal is to guarantee the generation of echoes in a wide dynamics of EDM altitude and attitude that means a wide power dynamics that is accomplished by means of (a) AGS DAC dynamic, (b) UDC IF and RF variable attenuators commanded by AGS, and (c) UDC RF manual attenuator. The use of variable and manual attenuators ensures a minimum Signal to Noise Ratio (SNR) in any simulated condition. The I&Q modulation permits to manage echoes with half of the necessary sampling frequency related to signal bandwidth.

The secondary goal is to acquire pulses that, transmitted by RDA, are characterized by a low power dynamic and zero delay. All power dynamic is accomplished by AGS ADC: no variable attenuators are installed while manual RF attenuator is set to avoid ADC saturation. The I&Q demodulation allows to manage pulses with half of the necessary sampling frequency related to signal bandwidth.

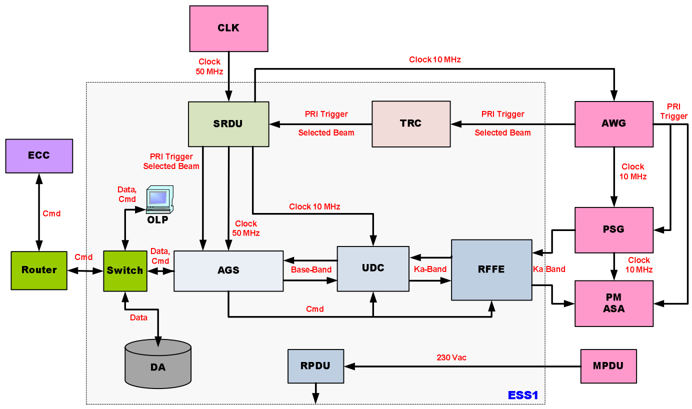

Fig. 4 - ESS1 Calibration Architecture

IV. Calibration

Echo Simulator Systems are calibrated in order to satisfy accuracy requirements of the pulses acquired from RDA and echoes transmitted to RDA in terms of delay and amplitude. This is accomplished by specific setups involving the following instruments: (a) Synthesizer (CLK) that provides master clock, (b) Arbitrary Wave Generator (AWG) that provides PRI Triggers, (c) Pulse Signal Generator (PSG) that provides input pulses to Echo Simulator Systems, (d) Power Meter (PM) and Analog Spectrum Analyzer (ASA) that measure transmitted echoes, and (e) TTL to RS422 Converter (TRC) that converts PRI Triggers and Selected Beams from TTL to RS422 standard.

The ESS1 calibration setup is shown in *Fig. 4*. Two calibration steps are performed: the first step evaluates the parameters required to compensate the delay introduced by the Tx/Rx paths and the UDC/RFFE RF fixed attenuations on four bidirectional ports setting the UDC variables attenuators to zero attenuation; the second step evaluates the eight levels of UDC IF/RF variables attenuators crucial to guarantee the required accuracy on the entire power dynamic.

TABLE I - Echo Echo Simulator Sistems Specifications

Parameter	***Values***
Carrier Frequency	35.76 GHz
Intermediate Frequency	1.86 GHz
Sampling Frequency	200 MHz (DAC) 250 MHz (ADC)
Bandwidth	200 MHz
Pulse Repetition Interval	10.01÷245.03 µs
Pulse Width	0, 20, 640, 2560 ns
Pulse Power	0, 30 dBm
Echo Width	0÷8750 ns
Echo Delay	0÷230780 ns
Echo Power	-98÷7 dBm
Echo Doppler	0÷35 kHz
Minimum SNR	20 dB

The required accuracy of measurements performed during the verification of systems calibration is ±5 nsec for time measurements and ±1 dB for amplitude measurements.

TABLE II summarizes the relevant data acquired during the first step of ESS1 calibration. First column identifies the four Tx/Rx ports, second column reports delay compensations, third column outlines errors measured after the verifications of calibration, and fourth column specifies delay requirement. The following three columns reports the same data but related to amplitude calibration. The results confirm the RFFE equalized design w.r.t. delay and attenuations on all bidirectional ports. The calibration accuracy is compliant with the required one.

TABLE III outlines the eight levels of UDC IF/RF attenuators measured during the second step of ESS1 calibration. Hi-Speed pin diode attenuators are used so that AGS is able to set a specific attenuation level at each PRI Trigger according to the required echo amplitude. First column identifies the eight attenuation steps. Second column reports measured values of the four steps (4 bits) of IF attenuator sequentially engaged from ID 0 to 3 and repeated from ID 4 to 7. Third column reports the measured values of two steps (2 bits) of RF attenuator set with its unique attenuation value from ID 4 to 7. Fourth column reports the total attenuations according to the described command sequence. The OLP is programmed to skip the attenuations ID 2 and ID 3 (fifth column) to easily manage the entire dynamic by monotonically increasing the attenuation from ID 0 to ID 7. This does not introduce any loss of performance because ID 2 has a total attenuation similar to ID 4 while ID 3 has a total attenuation similar to ID 5. The *Fig. 5* shows measured echoes amplitudes in all Tx power dynamic range before and after attenuator ID changes. The errors are compliant with the required accuracy.

Calibration setups of ESS2 and ATE are identical to ESS1. Only one Tx and one Rx calibration is foreseen for ATE due to unique unidirectional input port and unidirectional output port instead of four bidirectional ports (beams) of ESS1 and ESS2.

V. Tests Results

The Echo Simulator Systems had been tested in standalone mode with a setup similar to the calibration configuration. Three categories of tests were conducted: 1) static acquisition and generation tests, 2) dynamic loop tests, and 3) timeline tests.

The required accuracy of measurements performed during the systems tests is ±5 nsec for time measurements, ±1 dB for amplitude measurements, and ±0.2 m/s for Doppler velocity measurements.

A. Static Acquisition and Generation Tests

Aim of static tests is the verification of the correct pulses acquisition and echoes generation with fixed values of PRI Triggers, RF Pulses amplitude, delay and width. Several tests were executed to cover a wide range of cases: different amplitudes, delays and widths had been used accordingly to RDA timeline. Systems performances resulted compliant with the required accuracy in all test conditions.

TABLE II – ESS1 First Step Calibration Results

Beam ID [-]	***Delay Cmp. [ns]***	***Delay Err. [ns]***	***Delay Req. [ns]***	***Amp Cmp. [dB]***	***Amp Err. [dB]***	***Amp Req. [dB]***
0 (Tx)	30	0	±5	-20.5	-0.5	±1
1 (Tx)	30	5		-20.5	-0.3	
2 (Tx)	30	4		-20.6	-0.7	
3 (Tx)	30	2		-20.4	-0.7	
0 (Rx)	44	4		-24.0	-0.6	
1 (Rx)	40	1		-24.3	-0.2	
2 (Rx)	36	4		-23.9	-0.6	
3 (Rx)	44	0		-24.2	-0.1	

TABLE III – ESS1 Variable Attenuators Calibration Results

Tot. Att. ID [-]	***IF Att. Value. [dB]***	***RF Att. Value. [dB]***	***Tot. Att. Value. [dB]***	***Adp. Att. Value. [dB]***
0	0	0	0	0
1	-15.7	0	-15.7	-15.7
2	-32.2	0	-32.2	*Not Used*
3	-48.8	0	-48.8	*Not Used*
4	0	-34.5	-34.5	-34.5
5	-15.7	-34.5	-50.2	-50.2
6	-32.2	-34.5	-66.7	-66.7
7	-48.8	-34.5	-83.3	-83.3

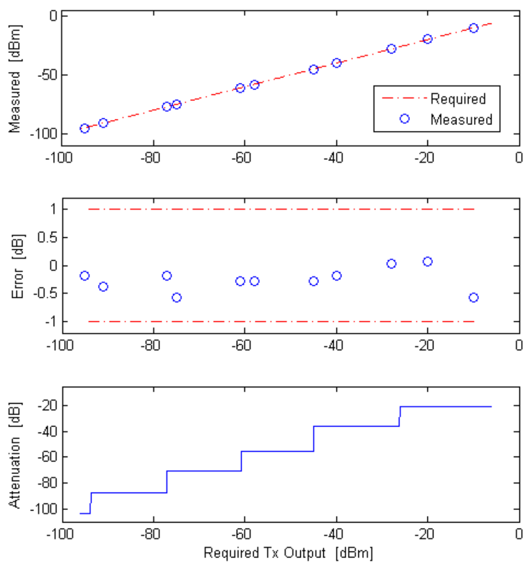

Fig. 5 - ESS1 Second Step Calibration Results

B. Dynamic Loop Tests

The ability to acquire and generate signals in static conditions allows to run a second category of tests: the dynamic loop tests. They are intended to stimulate the systems managing a dynamic sequence of signals with a fixed delay and PRI Triggers but with different amplitudes and Doppler velocities. These tests are performed without PSG and PM/ASA: the transmitted echoes are acquired by means of four short circuits installed on bidirectional ports of ESS1/ESS2 and by connecting the output unidirectional port with unidirectional input port of ATE. The performances of the systems are compliant with the required accuracy in all test conditions.

C. Timeline Tests

Final tests are performed using the same setup of loop tests but programming the AWG to generate three RDA subsets with same number and value of PRI Triggers and fixed amplitude, delay and width, and zero Doppler velocity. These tests represent the closest simulation of Echo Simulator Systems operations with RDA. Also in this final standalone tests, the performances of the systems are compliant with the required accuracy in all test conditions.

VI. RDA TESTS

ESS1 has been used into preliminary RDA EM tests at TASI facility in Rome (Italy). It has transmitted echo signals opportunely computed in terms of amplitude, shape and Doppler to the RDA EM. A landing scenario has been pre-processed by taking into account radar requirements and realistic descent paths obtained by mission simulation. The EDM altitude and attitude has been identified in order to check the preliminary performances achievable by the RDA design in the worst case conditions. According to the selected trajectory, ESS1 has generated signals toward RDA by simulating the received echoes in the descent envelope along with acceleration, jerk and false target in the antennas field of view. Exomars RDA preliminary test results show that range and velocity measurements are compliant with the required accuracies [15].

VII. CONCLUSIONS

The Echo Simulator Systems architectures are described in this paper together with the tests configurations. Standalone and RDA test results validate the systems designed and manufactured by Co.Ri.S.T.A. as accurate and versatile instruments able to verify the demanding performances of RDA units manufactured by TASI in the framework of ESA ExoMars 2016 Mission. The systems are able to stimulate RDA with echoes that are computed taking into account complex EDM maneuvers, including Front Shield and Back Shell, both jettisoned during the descent path. Computations take also into account various backscattering curves and landing areas with uniform roughness. The functionalities and performances of Echo Simulator Systems confirm that they are the best solution for the complex indoor RDA tests since standard instruments, like PSG, cannot take into account the complex phenomena computed by the equipment.

The Echo Simulator Systems are characterized by a great versatility and flexibility, permitting them to be considered suitable test equipment for radars that require simulations of complex environmental interaction. The task can be easily accomplished by implementing different timelines on OLP inside the ESS1 and ATE systems or developing different firmware on AGS inside the ESS2 system.

Future design of Echo Simulator Systems can be improved in terms of OLP echoes computation by including all the environmental interactions detected during the scheduled RDA outdoor campaign. Improvements can be achieved computing the echoes as a result of received signals from areas with different backscattering. The range resolution can be improved by using DAC with higher sampling frequency or opportunely fitting the echoes computed by OLP. The latter option leads to heavier computations that imply higher off-line processing time. This can be reduced by increasing the parallel computing capability of OLP upgrading both Matlab environment and the workstation hardware. Source code optimization or GPU processing can also be considered to speed-up the off-line processing. Improvements on AGS echoes generation can be achieved by increasing the Tx data rate. This enhances the maximum separation between multiple echoes inside the RDA sampling windows associated to each PRI Trigger.

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