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Efficient Test and Characterization of Space Transmit-Receive Modules Using Scalable and Multipurpose Automated Test System

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Abstract
Transmit-Receive (TR) modules are essential requirements of a space borne Synthetic Aperture Radar (SAR) used in the earth observation satellites with all-weather and day-night applications. Active array space radars use typically hundreds of TR modules in each satellite. These modules need extensive testing to ensure that they are well matched across the array. The TR modules are tested during the multiple stages of the assembly and integration process and traceability is required at every step. The functioning of the onboard radar hugely depends on the TR module test performance and hence the accurate, fast, and reliable testing of such modules becomes critical to their mass production. Each of the TR module has 15 parameters to test with 20 spot frequencies and the tests are repeated at typically 30 stages implying 9000 readings. To realize the automatic testing of hundreds of the C band dual TR modules of a Radar Imaging Satellite, an advanced automatic test system (ATS) is successfully developed. Conventional testing and set up time for each TR module has been brought down from around 5 hours to 30 mins using the ATS which has additional features of testing single and multiple modules at ambient and environmental test phases. The set-up clearance time is reduced by 96% and test engineer requirement is significantly brought down from 448 to 14 engineer-hours. Multiple TR module test capability using this ATS has reduced the requirement of expensive environmental chambers by 75%. The ATS also has the hardware and software features to store, analyze and present the statistical test results of the large-scale data captured for TR modules over their journey prior to the launch of the satellite. In this paper, the need for an automated, reliable, scalable, and multipurpose test solution for large numbers of space TR module testing and characterisation is explained. The measurable improvements in resource utilization, speed, efficiency, productivity, and flexibility are covered in detail. The test parameters and multi-utility features of the automated test station are detailed along with the test philosophy.

Keywords Transmit Receive (TR) Modules · Synthetic Aperture Radar (SAR) · Characterization · Automated Test System (ATS) · Test and Evaluation

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1 Introduction

As against the mechanically steered radars, the active electronically steered arrays (AESA), offer several advantages. The key enabler for this AESA technology is the TR modules that sit behind every radiating element of the array. TR modules form the basic elements of any radar imaging payload of an earth observation satellite. The planar antenna radiation pattern of the SAR system is controlled by dividing the antenna into sub-apertures and controlling the amplitude and phase of each sub-aperture through TR module. Hence, every radar imaging satellite comprises several hundreds of TR modules operating in different frequency bands based on the mission design and payload applications [3, 4, 23–25, 27]. Table 1 gives the list of some of the SAR satellites and their number of TR module.

The TR module comprises of a transmit chain, a receive chain, digital controller and power supplies generating the required voltages to different stages of the RF block [28]. As shown in Fig. 1, a typical TR module comprises a phase shifter, controllable attenuator, TR switch, power amplifier, circulator, LNA and limiting elements. In the transmitter mode, the signal source is amplified by the amplifiers (driver and power) and through a circulator, and transmitted signals reach the antenna. In the receiver mode, the received signal through the circulator is amplified by LNA. The phase shifter translates the control signal to phase variations [18, 19]. Typical test parameters [29, 32] of a space borne TR module are provided in Table 2.

The subsystems of a satellite payload are inaccessible for routine maintenance and repair, and require a thorough testing & characterization on ground, prior to integration with Satellite and launch [6]. Subsequently, they operate in an environment much different from that on ground. The rigorous test and evaluation of these TR modules are most important phases of the realization and delivery of 'ready-to-integrate' radar electronics to the imaging payload of the satellite. To ensure they work reliably in the space environment over the operational life span, testing is carried out in an environment close to the space environment by approaching it as sufficiently as possible. Developing a test system having multiple features like scalability, re-configurability, automation resulting in test time reduction, accuracy and repeatability of the measurements, auto-result-analysis, and ability to test at multiple stages of payload integration is the key success factor for realization of large number of TR modules [2, 8, 11, 16, 20, 26, 31, 39, 40].

In this paper, the testing, Characterization and Verification of space TR module are discussed in detail. The key specifications of the TR module are provided in Table 3.

These TR modules are tested at different stages of its delivery cycle on ground before they get integrated onto the launcher and reach the intended orbit. The modules are taken through one-time detailed test with manual test set-up, to confirm that they meet all the parameters as per specification. This is done with a small set-up with minimum

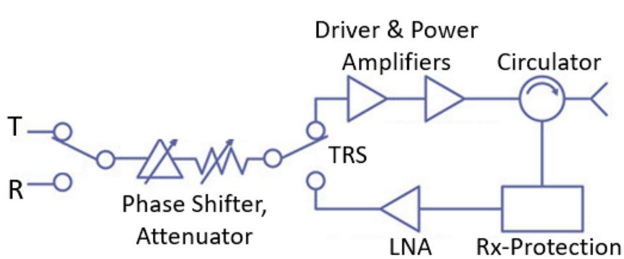


Fig. 1 Block diagram of a TR module

equipment automated to verify the basic functionality of the module. Once results are verified, the modules are taken up for screening and undergo detailed tests 28 times with Automated Test Set-up at different stages of the screening as detailed in Table 4. Their functionality is also verified post launch, in-orbit, before the Payload is delivered to the user. In addition, the qualification model undergoes an additional 2000-hour life test where the detailed measurements are carried out every 250 hours.

Overall organization of this paper is as follows. Section 2 provides the test development scheme for ATS, Sect. 3 provides the hardware and software architectures and before concluding, Sect. 4 provides the details of test results, analysis, and statistical features. This solution has been successfully implemented in large scale test, characterization, and integration of the TR modules onboard radar imaging payload of a satellite.

2 Test Scheme Analysis – an Automated Test System

The TR modules have a major effect on the RF performance of the synthetic aperture radar. To deliver a reliable product, TR module must be tested at every stage of production, either as individual submodule or as an integrated product. To increase the production efficiency, productivity, in different product development and subsequent production stages, ATS is required. Different tests are required to validate DUT performances during the development cycle. There is a need for good quality control during the production phase, through 100% inspection as well detailed test at the integration stage. An Automated Test System (ATS) comprises of instruments that apply bias, Control signal and Stimuli to the DUT and carry out measurement of the outputs accurately under the complete control of a computer [36]. The ATS consists of subsystems such as: electrical (the hardware), the software, where functionality relies [35, 38] and physical (essentially mechanical). Development of an ATS requires the (1) careful assessment of requirements and design approaches [9, 13, 21, 34, 41] and (2) good knowledge of latest test technologies, sensors, equipment, cabling, and interconnects. Interdisciplinary nature of the ATS development, demands the roles for system engineers in SAR satellite payload, specialist engineers and test engineers [23]. Figure 2. gives the team-based approach and their roles for an ATS development.

ATS offers integrated solutions with short testing time by providing the device specific power and control inputs to the DUT and ensures the high throughput required in production [5, 14, 22, 30, 33, 34, 37]. It also allows reconfigurable measurements and flexibility for development phase.

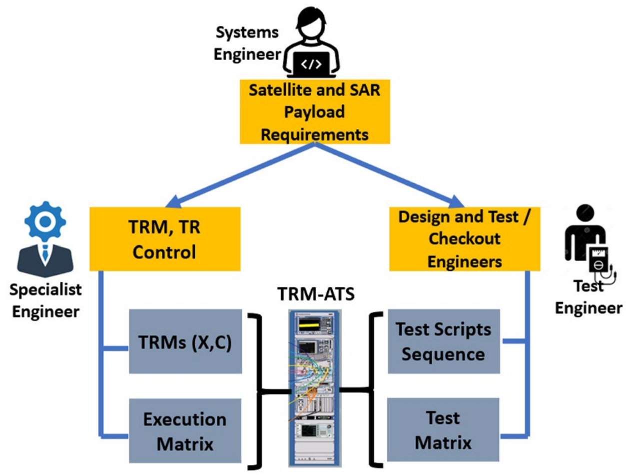


Fig. 2 Team based framework for ATS development

This Advanced Automatic Test System (ATS) addresses multiple challenges. Any TR Module testing calls for making test set and carrying out test for Transmit and Receive path separately, sequentially. This ATS avoids this by hooking together all the TX and RX RF path just by two cables connected to the Input and output port of the TR Module. Bias and Control signals are done just once since well defined bias and signal routing is done through proper design of the harness from power supply and control cards to the multiple TR Modules. These power supplies and control cards are in turn controlled by the Main Computer. The features of ATS described below, help the development of modules, reduction of production cycles and increases efficiency.

1. Ability to test at multiple stages (multipurpose)

   The ATS can test the TR modules at different stages with changing RF input, output, monitoring port as well as control port cabling and test configurations. For example, the external cable lengths and their corresponding cable attenuation, phase variation over temperature at active temperature cycling test or characterization & verification, thermo-vacuum test are different from that of a bench test. Under these configurations of test, the S2P files of these cables need to be saved and the same is considered during the test. Hence the ATS has provisions for all additional hardware and software combination to address the effects of external environment of the test set up.

2. Scalability

   - The ATS rack can increase functionality to test sub-RF modules both active and passive.
   - Auto test sequence can facilitate testing of multiple TRMs (like 8 Nos) using 24 / 72 ports with sequential measurements.
   - RF measurements to achieve short test time of typically 30 minutes to complete one T/R module characterization.
   - Over-The-Temperature (OTT) tests, can be conducted for 24 TRMs (extendable up to 30)

3. Test and Characterisation of DUT(s)

   Ability to characterize the DUTs over the temperature range -10deg to + 60 deg in steps of 10 degrees.

4. Customisation capability with software modifications

   Testing of subsystems or their submodules such as TRM, sub-stage-amplifier, can be customized with adaptable software for different test plans.

5. Test results analysis and report customisation

   By changing the software modules, the test results are customized to different formats. At the end of all tests, multiple stage test summary could be extracted from the system.

3 Hardware and Software Architecture

An Automated testing of TR module is mandated to carry out system testing, data recording and processing, with minimum manual intervention and present the data in the desired formats. The overall blocks associated with the ATS are given in Fig. 3. The blocks involve programmable power supply to power the DUT, measuring instruments like Vector Network Analyzer (VNA), Spectrum Analyzer, power sensor and inputs such as noise source, RF switch matrix, control unit. All these are interfaced with the user through a versatile e-platform.

During the transmit operation of the TR modules, the pulsed RF signal is amplified by the amplifiers deciding the radiated power of the radar. Due to pulsed operation, the pulse parameters of the output of the TR module are measured. During the receive operation of the TR modules, the LNA determines the system noise figure. The ATS is effectively used to carry out the RF measurements [1, 7, 10, 12, 15, 17] as shown in Table 5. The integrated ATS with DUT and its associated cabling for the test set up is shown in Fig. 4.

3.1 Hardware Architecture

As shown in Fig. 4, the power source supplies the input raw power to the power conditioning and processing unit which in-turn generates the secondary voltages required

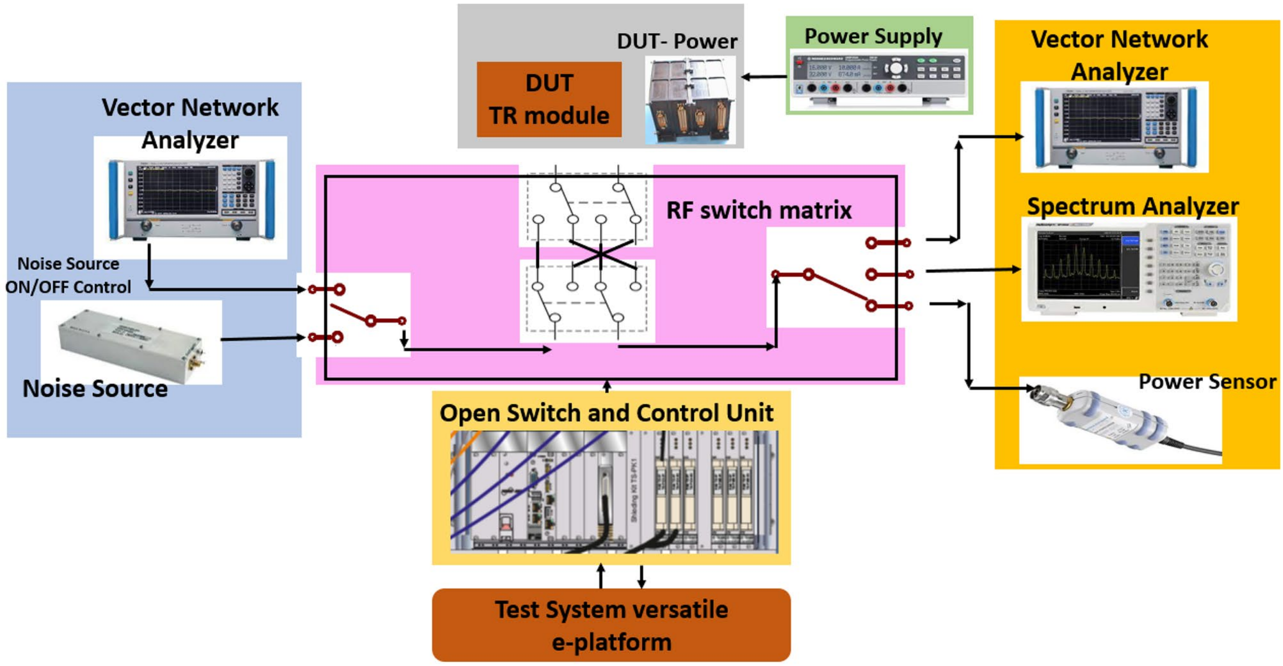


Fig. 3 Blocks of ATS for the TR module testing and characterization

for the different parts of the TR module. The test channel and modes of operation are selected by the control computer using the RF switching matrix and the control instrument. The measurement instrument section covers the low/high pass filters, spectrum analyzer, power analyzer, vector signal generator. The overall specifications of the ATS are met using the hardware stacked into the rack.

- 24 /72 port RF Switch Matrix: for connection of up to 8 / 24 TRMs with coupled ports (3 port TRM – Tx, Rx

Fig. 4 Measurement platform the TR module with ATS

& Coupled port) & pulsed power handling capability of up to +42 dBm.

- 24 /72 port RF Switch Matrix: for connection of up to 8 / 24 TRMs with coupled ports (3 port TRM – Tx, Rx & Coupled port) & pulsed power handling capability of up to +42 dBm.
- Vector Network Analyzer: Calibrated and high-speed measurements of RF S-parameters (both CW and Pulsed), compression point measurements & Power Added Efficiency Tests from 1GHz to 40 GHz.
- Wideband Spectrum Analyzer: For measurement of Harmonics, Isolation Tests, Noise Figure, Pulse profiling & system response times with 2 Hz - 43 GHz & 320 MHz Analysis Bandwidth.
- Power Supplies: 4 nos. 50W/32V power supplies and 1 no. 760W/80V & 1 no. 1500W/30V power supplies for the DUT.
- Digital Control Platform: The platform also includes a 90 pin multiplexer and Voltage & current measurement card. The inbuilt control software/sequencer is state-of-the-art for fast repeatable measurements & documentation of results (on a Server Database). This uses 64 input and output channels for DUT control.
- Accessories: 40 GHz Auto Cal Unit, Power Sensor, 24 VNA Grade RF Cables, Smart Rack, PC etc.
- Noise Source, up to 24GHz, which with the help of Noise Figure Application support in Spectrum Analyzer, carries out the Noise Figure Measurements of the receivers.
- Peak and Average power Sensors up to 24GHz, meant for absolute RF power level measurement and used for the RF Calibration of the ATS.

3.2 Software Architecture

The architecture of the system software is the critical factor affecting the usability of the ATS. Modularity and hierarchical designs are implemented in the software architecture that helps in achieving many of the features intended. The software system manages the automation test, device manager and self-tests. The overall specifications of the ATS are met using the following software features.

- The library software enables automation of RF subsystem characterization tests. This library covers all tests which are common for components, modules, and subsystems.
- Module control is implemented using an open C# interface.
- Speedy testing of different DUTs is enabled by preloading command sequences and test controls from a single source. Proper test sequencing helps in optimizing the TR module testing speed.
- Control implementation and software parametrization are carried out locally. The ATS library has an open control plug-in programmed in C# and has code samples. The user can adopt this code to communicate to module-specific hardware or software.
- Many times, RF subsystems require complex trigger sequences. These trigger signals are controlled. All communication interfaces such as RS485, RS 422m TTL, LVTTL and LVDS are available in combination with flexible and multiple triggers.
- ATS is developed on the TS Run, which uses modular Codes written in C# language for user-defined test runs.

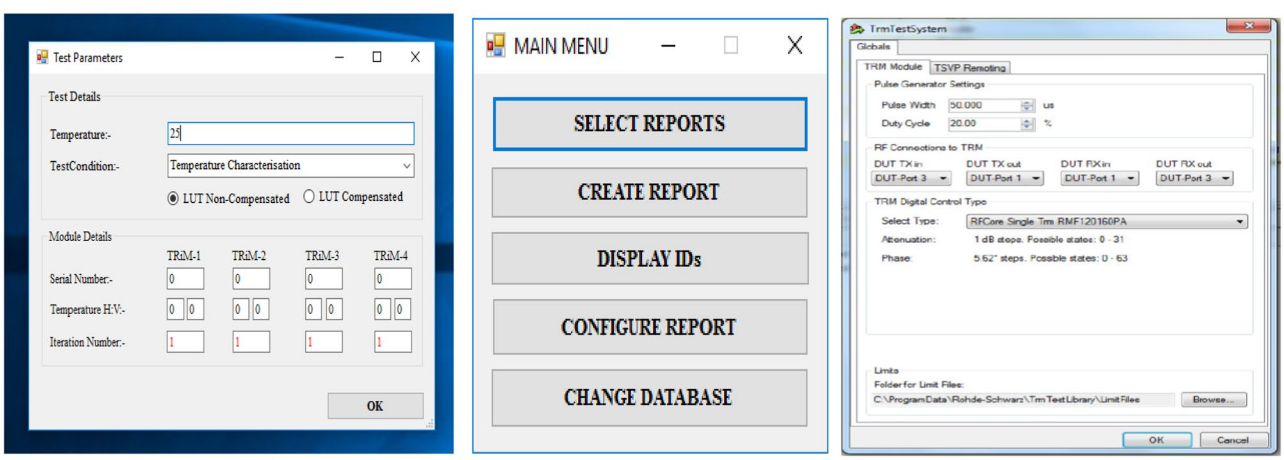


Fig. 5 GUI for test stage selection, report generation and test condition

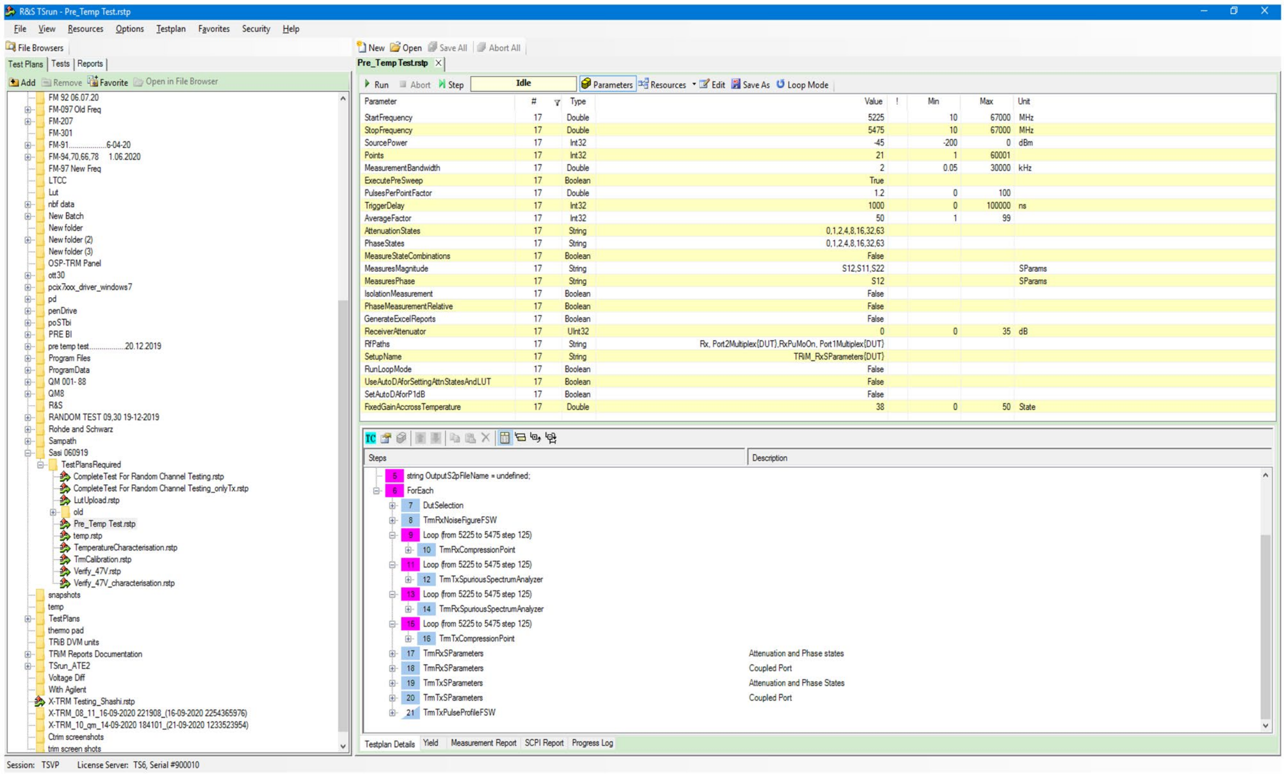


Fig. 6 GUI test parameters and test case selection

The end user interfaces, and the GUI for the test stage selection, report generation, test condition, parameters and test stage selection are shown in Figs. 5 and 6.

4 Test Results and Discussions

This section provides the details of the successful implementation of the ATS which is scalable, and used at multiple stages of the test, characterization, and integration of TR modules onto the satellite payload. The traditional manual test solution and the ATS based solution are compared for speed, accuracy, and efficient way of production testing of large TR modules.

4.1 Parametric Test Results of One DUT

4.1.1 Pulsed S-parameters Measured Using the Point in Measurement of VNA

The point-in-pulse technique is used in measuring accurately the S parameters. In this technique, the monitoring of the pulse is done only during the "on" phase of the RF bursts. The sampling time (Tspl) to acquire an S-parameter is smaller than the pulse width, t-on (Fig. 7)

The sampling time is determined mainly by the measurement bandwidth of the receiver. The minimum sampling time and measurement bandwidth is defined as Tspl = 1/IFBW. Shorter pulses can be analyzed using the increasing measurement bandwidths where the sampling time decreases. Good VNAs generally implement IF filters digitally for measurement bandwidths up to 600 kHz, and hence the sampling time is 1 us or more. Some of the Network analyzers with IF bandwidths of 5 MHz or more, allow sampling times as fast as 400 ns. The VNA is used in "point-trigger mode", implying that data sampling for every measurement point starts after the detection of

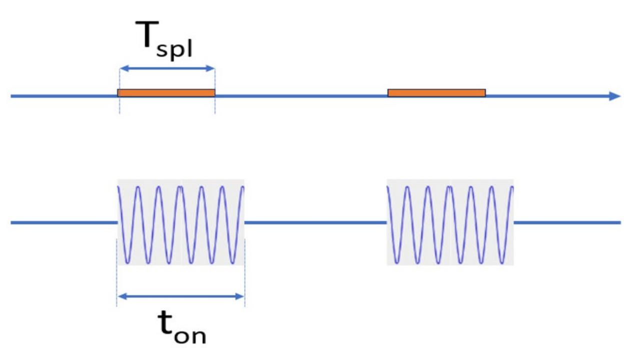


Fig. 7 Point in pulse measurement

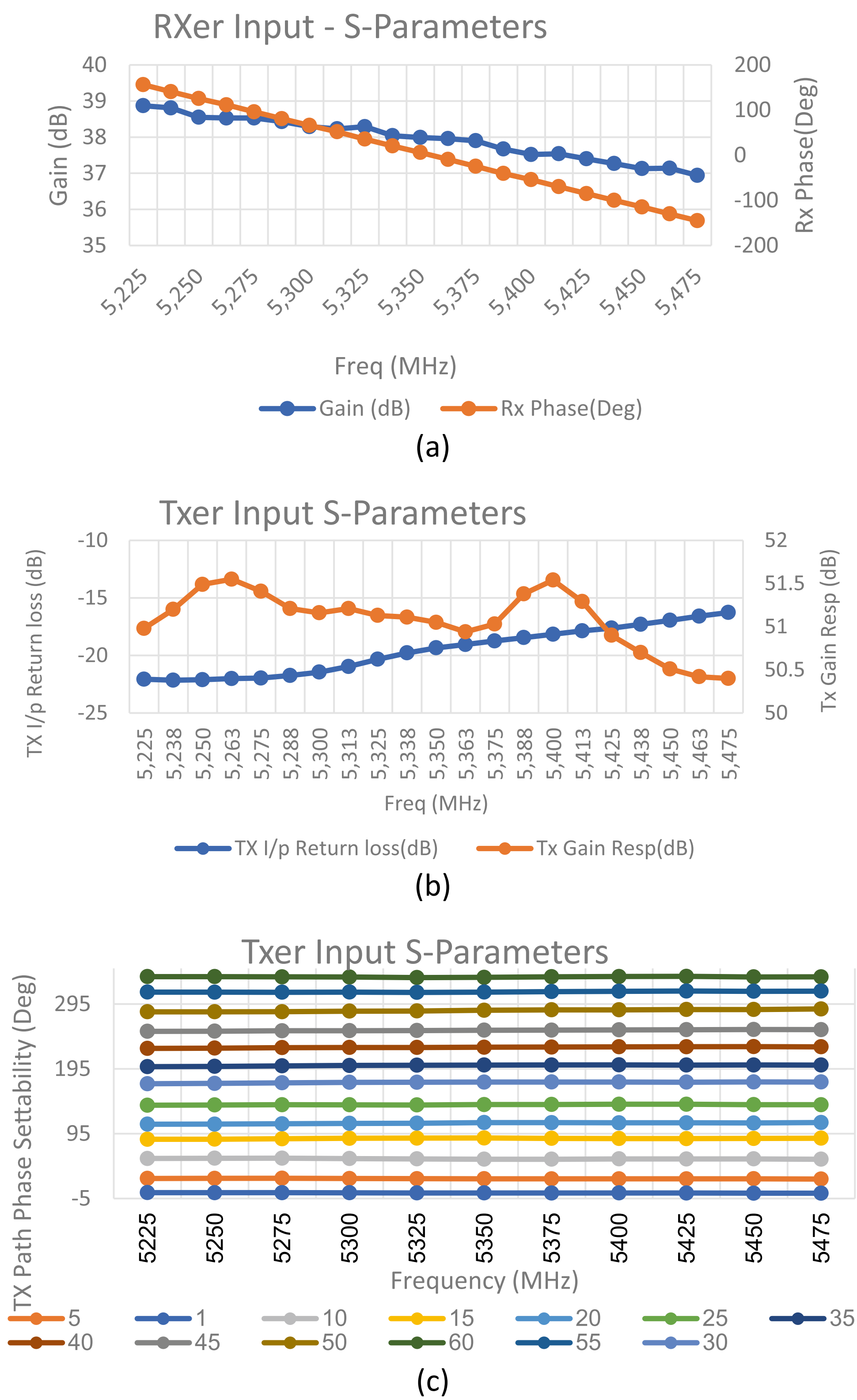


Fig. 8 (**a**) Receiver input S-parameter versus frequency. (**b**) Transmitter input S-parameter versus frequency. (**c**) Transmitter path phase settability versus frequency

a trigger event. This 'point in pulse' technique eliminated the dynamic range dependency on duty cycle and allows the data acquisition moment within the pulse to be shifted. However, this comes at the cost of the need for an expensive instrument VNA with larger measurement bandwidth.

Figure 8(a) to (c) provides the S parameter test results.

4.1.2 Noise Figure Measurements

The noise figure measurement of a pulsed mode amplifier is different from the continuous mode since the measurement of the hot and cold power must be done only during the active part of the periodic pulse. The data sampling takes place during the active period of the burst mode RF using the gated sweep mode of the spectrum analyzer. The firmware application from R&S FSW-K30 adds functionality to carry out noise figure measurements. Noise source is used for measuring the noise figure with Y-factor method that indicates the uncertainties and quality of measurement tolerances. In this technique, the DUT power is measured with the noise source turned on (hot power) and the noise source turned off (cold power). The Y-factor is a ratio of N_{on} and N_{off} where N_{on} is the Noise power in dB with noise source on and N_{off} is Noise power with noise source off.

The receiver noise figure plot using the TR module using the test method referred above is shown in Fig. 9.

From the above plot, it is clearly seen that the Receiver noise figure is within the limits of 5 dB at ambient, over the frequency range of operation.

4.1.3 Gain and Power Measurements

Receiver is fed with RF small signal where it operates in the linear operating point. Corresponding RF Output is measured. The difference between the input and output signal provides the gain of the Amplifier. This test is carried out over the frequency range of operation of the amplifier and results are plotted. Similarly, a Transmitter test is carried out at a small signal. The P1dB is derived by feeding large signal, where the Power Amplifier gets into saturation. The point where the Gain reduces by 1dB is declared as the 1 dB compression point.

The receiver small signal gain plots are shown in Fig. 10(a). The corresponding return losses at input and output are also plotted. It is seen that the gain flatness over the entire frequency range is within 2 dB.

The transmitter small signal gain plots are shown in Fig. 10(b). The corresponding return losses at input and output are also plotted. It is seen that the gain flatness over the entire frequency range is within 2 dB.

The P1 dB plots for the power amplifier are provided in Fig. 10(c). The curves clearly repeat for three different spot frequencies of 5.225GHz, 5.35GHz and 5.475 GHz.

4.2 Multiple DUT (TR Modules) Test Results

One of the important features of the ATS developed is the scalability. With the same ATS, one or more TR modules can be tested simultaneously. The following plots explain the different parameters measured for four modules. The repeatability of the test results of multiple TR modules and a single TR module on multiple ports of the ATS is provided in the Table 6.

The average output power measured for four channels are plotted in Fig. 11(a). Within a variation of 0.8 dB the close performance of four modules is clearly seen.

The Noise Figure for four channels are plotted in Fig. 11(b). Within a variation of 0.5 dB the close performance of four modules is clearly seen.

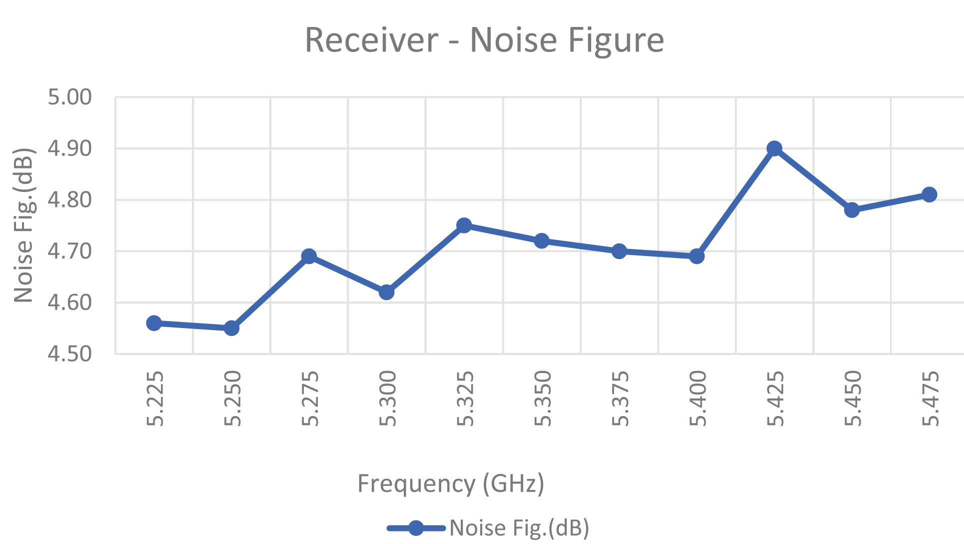


Fig. 9 Noise Figure test results of C band TR module.

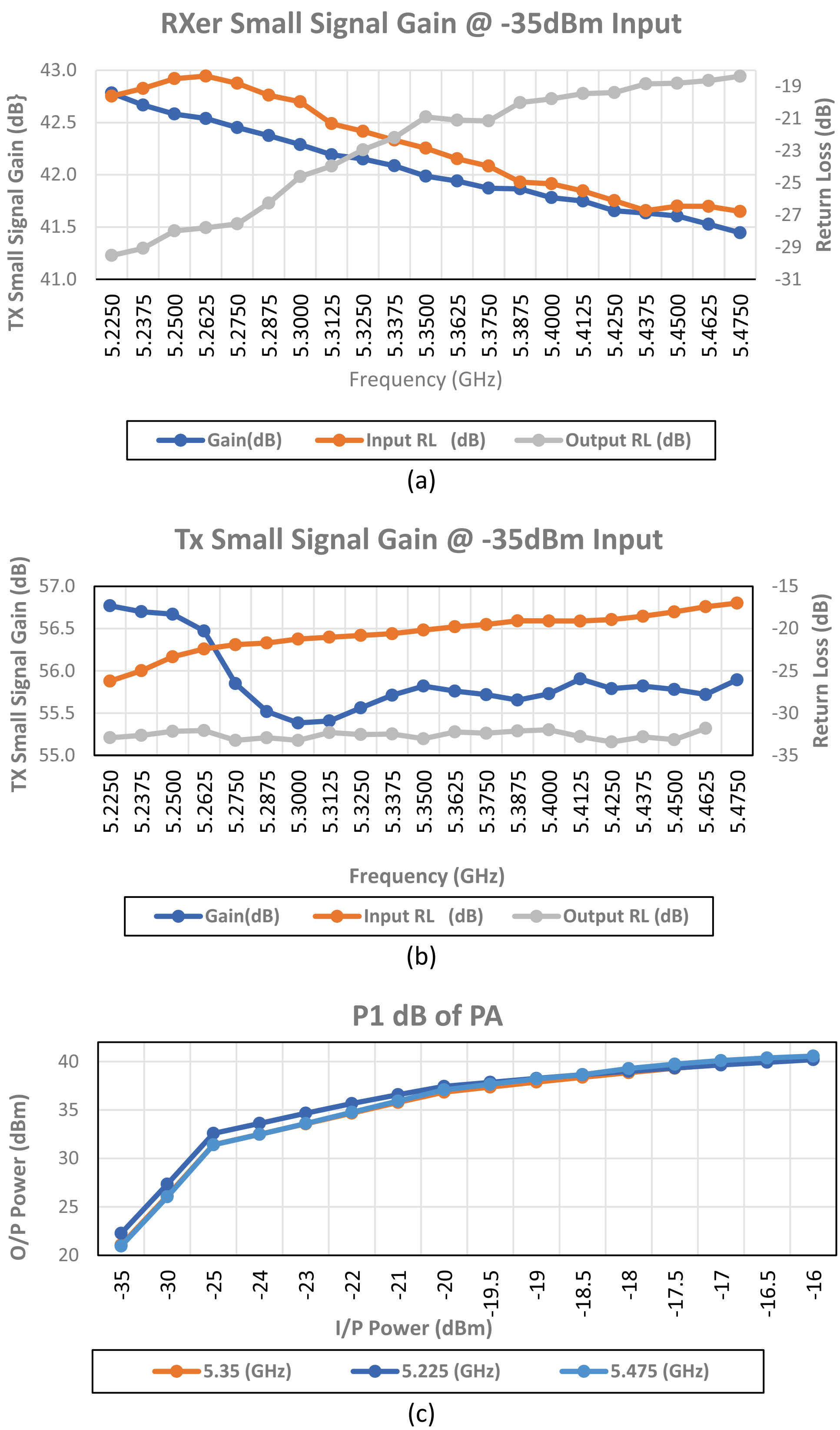


Fig. 10 (**a**) Receiver small signal gain versus frequency for C band TR module. (**b**) Transmitter small signal gain versus frequency for C band TR module. (**c**) Power and gain related test results of C band TR module

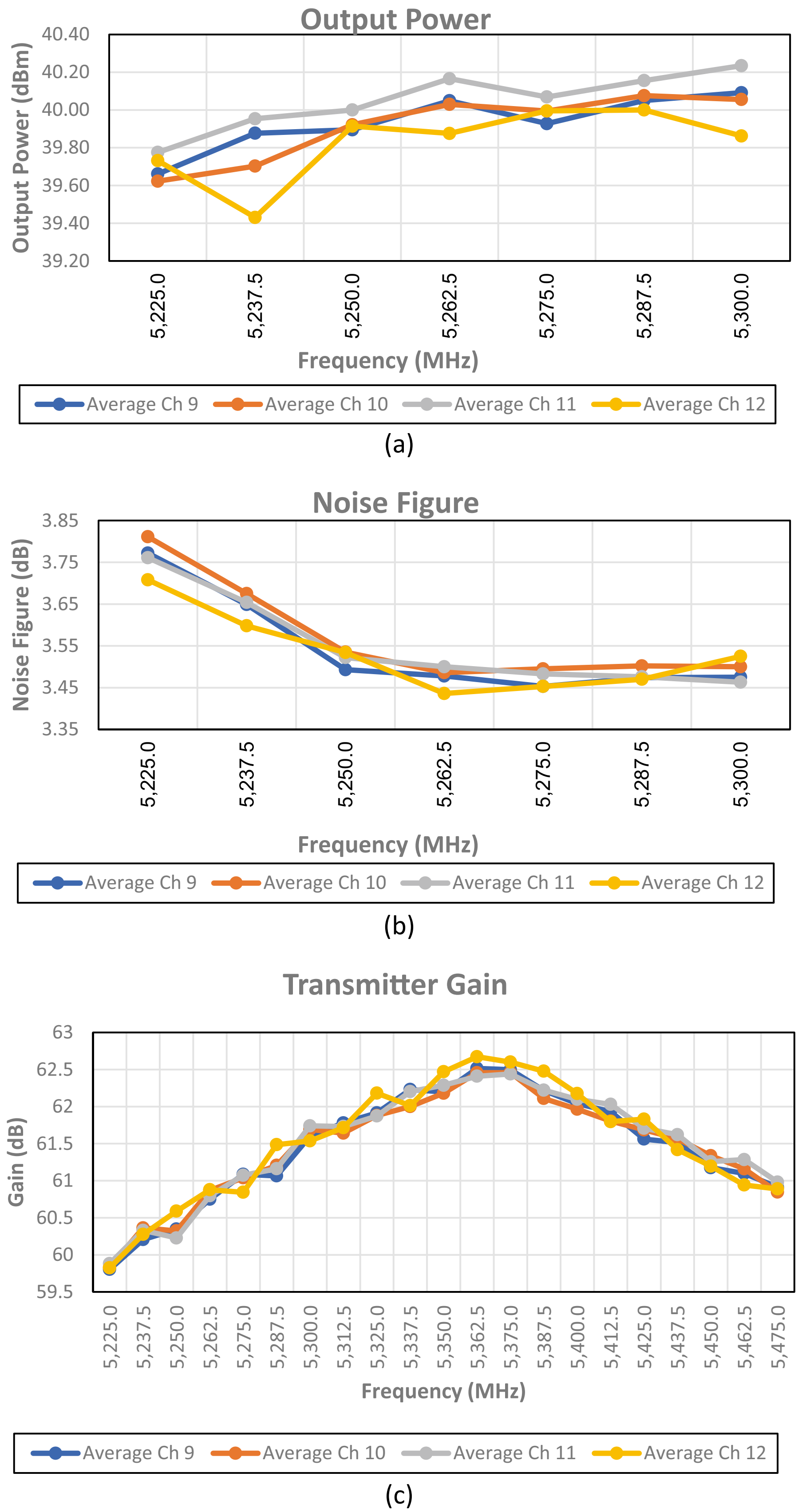
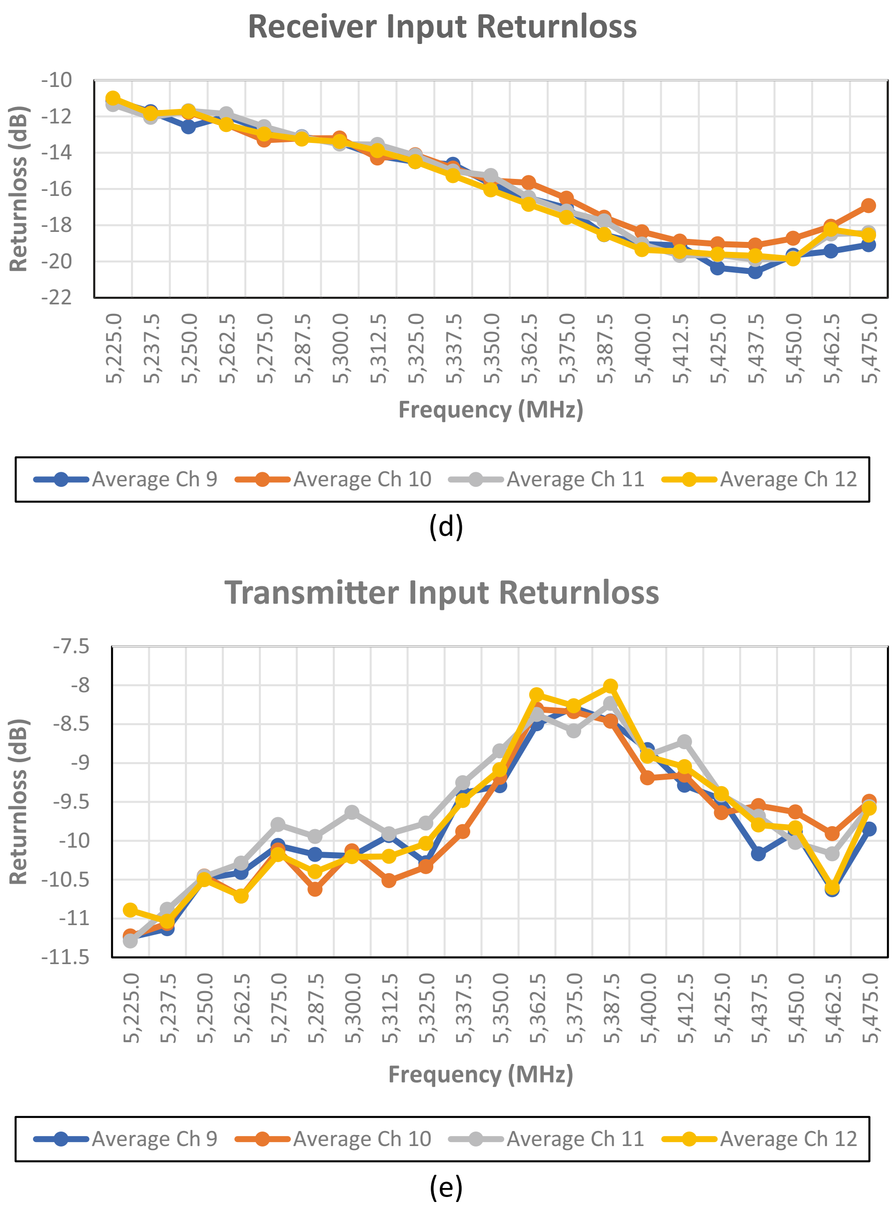


Fig. 11 (**a**) Output power versus frequency for four TR modules. (**b**) Noise Figure versus frequency for four TR modules. (**c**) Transmitter Gain variation over frequency for four modules. (**d**) Receiver Input Return Loss over frequency for four modules. (**e**) Transmitter Input Return Loss over frequency for four modules

Fig. 11 (continued)



The Transmitter Gains of four channels are plotted in Fig. 11(c). Within a variation of 2.5 dB gain flatness, the close performance of four modules is clearly seen.

The close tracking of Receiver and Transmitter input return losses is evident from the plots shown in Figs. 11(d) and (e). These plots indicate the ability of the ATS to measure accurately and repeatably, different parameters for multiple TR modules simultaneously.

4.3 Environmental Testing: Thermo-Vacuum Test Case

RF systems for satellites go through one of the most important and critical tests on ground where thermal and vacuum conditions are simulated in a specially designed chamber. A typical thermo-vacuum test cycle is given in Fig. 12. and there are initial and final major cycles of longer duration

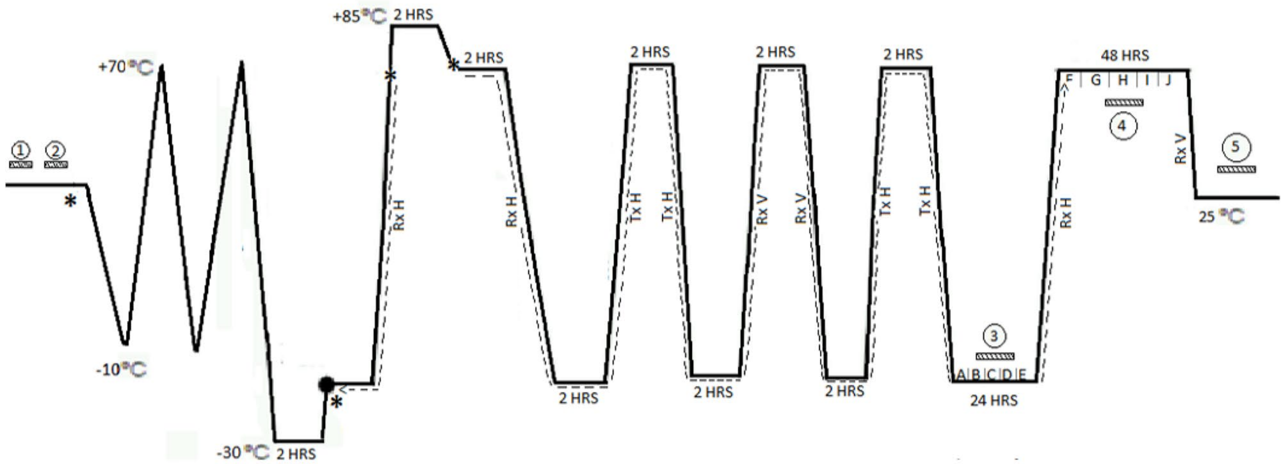


Fig. 12 Thermo-vacuum test profile for RF space subsystems

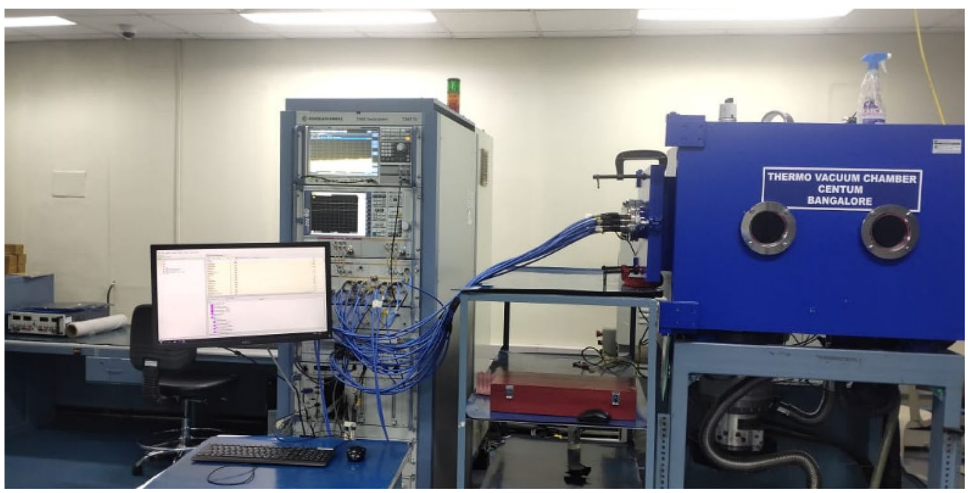


Fig. 13 ATS in testing TR modules at Thermo-vacuum facility

Table 1 List of some SAR satellites and their number of TR modules

Space Agency / Country	SAR Satellites and their TR Modules details	
	Satellite	No. of TR modules, Frequency
Indian Space Research Organization - ISRO	RISAT-1	576 (C band)
	NISAR	24 (S band), 12(L band)
	RISAT-1A	576(C band)
European Space Agency - ESA	Envisat	320 (C band)
	Sentinel	280 (C band) + 280 (C band)
Japan Aerospace Exploration Agency - JAXA	ALOS-1, 2	80 (L band), 180 (L band)
Canadian Space Agency - CSA	RADARSAT-1,2	512 (C band)
Deutsches Zentrum für Luft- und Raumfahrt e.V. – DLR - Germany	TerraSAR-X	384 (X band)
Comision Nacional de Actividades Espaciales – CNIE - Argentina	SAOCOM	105 (L band)
Instituto National de Técnica Aeroespacial (INTA) - Spain	PAZ	32 (X band)

Table 2 Typical test parameters of a space borne TR module

TR module section / path	Key measurements
Transmitter	Output Power, Gain, VSWR versus frequency Pulse profile: width, rise and fall times, amplitude. Spectrum: Harmonics, Intermodulation and Spurious Transmit Power Amplifier P1dB operation through Variable Attenuator control
Receiver	Gain, VSWR versus Frequency, Noise figure Spectrum: Harmonics, Intermodulation and Spurious Attenuation and Phase shift over the Frequency of operation P1 dB compression in receiver path
Others	Current, DC Power consumption CAL port Return loss Telemetry ON/OFF status

Table 3 Key specifications of the TR module

Parameter	Specification Units
Frequency	5400 MHz
Bandwidth	± 45 MHz
Transmit path specifications	
Peak output RF Power	+40 dBm min.
Transmit pulse width	20µs max./3.5KHz PRF typ.
Receive path specifications	
Noise Figure	4.0 dB nom.
Rx Path gain	35 dB min.

with three minor cycles of shorter duration between major cycles. Quick tests are carried out in minor cycles and detailed tests and characterization are performed in major hot and cold cycles. Figure 13 shows the thermo-vacuum test set up along with the test cables.

Table 5 RF measurements from ATS

TR Modules Test Configurations		
Test Cases	Mode of Testing	Test Condition
S-Parameter	Receive, Transmit	Continuous, Pulsed
Compression Point (1dB, 2dB)	Receive, Transmit	Continuous, Pulsed
Spurious Emission	Receive, Transmit	Continuous, Pulsed
Pulse Profile (rise time, fall time, power droop)	Transmit	Continuous, Pulsed
Noise Figure	Receive	Continuous, Pulsed
Out-of-band Rejection	Receive, Transmit	Continuous, Pulsed
Harmonics	Receive, Transmit	Continuous, Pulsed
Power Added Efficiency (PAE)	Transmit	Continuous, Pulsed
Intermodulation	Receive	Continuous, Pulsed

4.4 Test Data Summary Over Multiple Stages of Testing

The summary test data for TR module for 33 test parameters over different phases of test such as initial bench, post-cold-storage, post-hot-storage, post humidity, post mechanical shock tests are provided in Table 6. The summary table is extended up to post EMI tests and multiple steps of thermo-vacuum tests.

4.5 Repeatable Test Results and Statistical Assessment

By testing the TR modules in one channel for multiple number of times, the repeatability assessment of the ATS is performed. These tests are repeated with the same TR module on different channels. Using this technique, channel-to-channel repeatability and overall measurement repeatability assessments are carried out. The statistical assessment such

Table 4 Stages of TR module testing and characterization

Stage of testing	Number of times	Stage of testing	Number of times
Initial Bench Test (IBT)	1	Pre-Ambient before Vacuum	1
Post passive cycling	1	Post Ambient after Vacuum	1
Pre-burn-in	1	Thermo-vacuum Cold soak	1
Post burn-in	1	Thermo-vacuum Hot soak	1
Over the temperature (OTT)	3	Ambient with Vacuum	1
Characterization	8	Post Thermo-vacuum	1
Verification	3	Post EMI/EMC Test	1
Pre vibration	1	Final Bench Test (FBT)	1
Post vibration	1	**Total**	**28**

Table 6 Multistage test data summary

Parameter	Spec	Initial Bench Test	Post Cold Storage	Post Hot Storage	Post Humidity Storage	Temp Op Test @75	Temp Op Test @-15	Temo Op Test @25	Post Mechanical Shock	Post EMI-EMC
Rx I/P Return Loss	-13	-18.510	-18.220	-18.190	-18.070	-17.080	-19.970	-15.530	-16.410	-15.780
Rx O/P Return Loss	-13	-16.650	-16.610	-16.520	-16.420	-19.160	-17.240	-14.610	-18.270	-17.620
Rx Gain	38.5±0.75	42.960	43.190	43.280	43.230	38.150	37.730	38.550	37.980	38.200
Rx Phase		105.560	107.460	109.440	107.740	5.220	2.610	58.710	12.460	11.500
Rx Flatness	1.5dB	1.480	1.350	1.390	1.370	1.180	1.390	1.480	1.370	1.370
Rx PSE	5	1.852	1.839	1.913	1.836	4.305	3.251	2.679	2.701	2.755
Rx Gain Variation With Phase	0.5	0.161	0.155	0.156	0.154	0.357	0.181	0.404	0.286	0.297
Rx P1dB	5	1.400	1.350	1.530	1.620	-1.970	-1.975	-0.400	-0.350	0.690
Rx Noise Figure	4	3.990	3.850	3.880	3.890	4.590	3.480	3.590	3.850	3.780
Rx Spurious	50	54.780	54.100	53.460	54.790	54.510	55.120	52.390	53.000	53.230
Rx Cal Port I/P R/L	-13	-15.120	-15.200	-15.220	-15.270	-15.780	-16.080	-16.000	-15.890	-16.200
Rx Cal Port O/P R/L	-13	-16.950	-16.970	-16.870	-16.860	-19.130	-16.770	-14.560	-19.630	-19.190
Rx Cal Port Gain	23	24.530	24.660	24.770	24.700	19.490	19.200	20.130	19.550	19.700
Rx Coupling Flatness	1	0.290	0.290	0.300	0.280	0.300	0.300	0.290	0.200	0.260
Tx I/P Return Loss	-13	-16.430	-16.520	-16.590	-16.430	-18.290	-15.780	-13.500	-16.740	-16.670
Tx Gain		54.710	54.980	55.340	55.200	51.180	52.360	51.710	51.460	51.300
Tx Flatness	1.5dB	1.890	1.850	1.720	1.800	0.870	0.910	0.700	0.690	0.710
Tx P1dB	5	-999.000	-999.000	-999.000	-999.000	-999.000	14.160	-999.000	-999.000	-999.000
Tx Spurious	50	57.540	56.690	57.340	57.280	66.800	66.470	63.230	68.420	68.510
Tx Cal Port I/P R/L	-13	-16.320	-16.350	-16.160	-16.200	-18.310	-17.520	-14.750	-16.740	-16.690
Tx Cal Port Gain	23	35.470	35.740	36.070	35.920	32.060	33.130	32.880	32.730	32.800
Tx Coupling Flatness	1	0.670	0.840	0.770	0.810	0.850	0.930	0.610	0.780	0.840
Tx Coupling Phase		175.400	178.910	172.230	167.710	172.690	172.550	166.270	163.290	166.420
Tx O/p Power		0.000	0.000	0.000	0.000	40.108	41.169	40.791	40.596	40.679
Tx Rise Time		0.000	0.000	0.000	0.000	0.140	0.132	0.144	0.143	0.134

Table 6 (continued)

Parameter	Spec	Initial Bench Test	Post Cold Storage	Post Hot Storage	Post Humidity Storage	Temp Op Test @75	Temp Op Test @-15	Temo Op Test @25	Post Mechanical Shock	Post EMI-EMC
Tx Fall Time		0.000	0.000	0.000	0.000	0.133	0.135	0.124	0.134	0.133
Tx Droop		0.000	0.000	0.000	0.000	0.181	0.096	0.119	0.147	0.107

as the standard deviation, average value over the multiple iterations is done using the software features of the ATS and the TR modules. The deviation from the manual reading is analyzed and found to be well within the tolerance limits of the measurement equipment.

To establish the repeatability and reliability of the test results from the ATS, measurements have been repeated 10 times over the frequency band of operation for different parameters and is evaluated as shown in the Table 7.

The sequence of repeatability test is also to connect TR modules to the ATE, where tests are carried out one channel after another for all the parameters. This is repeated 10 times. Then, the same TR module is moved to the next channel and again verified there 10 times. This process is repeated over the next channels. Thus, repeatability performance of a channel as well channel to channel repeatability is derived and ensured it is within the limits. Table 8 shows port to port and each port repeatability of the tests results carried out. The 3-sigma results for 4 channels repeatability are evidenced from the tabulated results.

4.6 Enhanced Efficiency, Productivity, and Reliability of the Test Solution

The successful implementation and deployment of the ATS for TR modules onboard a satellite has demonstrated the enhanced testing efficiency, productivity, and reliability of the test data. It would have taken 16 test-engineer-hours (2 engineers X 8 hours) for manual set-up clearance, confirming cable losses, configure the test equipment, and record the test readings. This is achieved with the ATS in 0.5 test-engineer-hours (1 engineer X 0.5 hour) a reduction of 96% time. For the total journey of the TR module testing, the automation has brought down the 448 test-engineer-hours (2 test engineers X 28 times X 8 hours per test) to just 14 test-engineer-hours (30 min per test). In addition to this, ATS enabled simultaneous testing of 4 TR modules and 8 TR modules at a time resulted in the 4 or 8 times less utilization of the expensive chambers. Thus, there is major saving in effort, time taken and cost savings even in terms of the chamber utility and operation.

Complex RF switch matrix which has 24 RF ports, allows feeding 8 TR Module Input from Network Analyzer or Noise Source and routing output to Spectrum Analyzer or Network Analyzer or Power Meter/Sensor. This helps in putting 4 TR Modules simultaneously for characterization & verification over cold and hot temperatures within temperature Cycling Chamber as well as Thermo-vacuum test. Thus, it saves the requirement of multiple resources, effort in terms of making multiple set-ups and operating temperature cycling chambers multiple times, resulting in effective utilization of the man-machine resources. Either manual testing or simple automation for single channel complete measurement, would have taken few months to carry out all the measurements. With the ATS, they are completed within 3 days.

Table 7 Repeatability performance of the ATS

TX Gain in dB	**Freq (MHz)**	***5225***	***5275***	***5425***	***5475***
	Avg Ch 9	*59.804*	*61.087*	*61.562*	*60.911*
	Avg Ch 10	59.831	61.039	61.685	60.846
	Avg Ch 11	59.882	61.073	61.707	60.981
	Avg Ch 12	59.824	60.844	61.831	60.889
	Std Dev	*0.028752174*	*0.097842667*	*0.095423726*	*0.048828142*
	Average	*59.83525*	*61.01075*	*61.69625*	*60.90675*
	Manual Readings	59.600573	60.872213	61.37797	60.634072
	Deviation	*0.234677*	*0.138537*	*0.31828*	*0.272678*
TX input Return Loss	**Freq (MHz)**	***5225***	***5275***	***5425***	***5475***
	Avg Ch 9	-11.241	-10.063	-9.465	-9.851
	Avg Ch 10	-11.226	-10.121	-9.641	-9.495
	Avg Ch 11	-11.292	-9.793	-9.411	-9.564
	Avg Ch 12	-10.894	-10.18	-9.395	-9.584
	Std Dev	*0.157364823*	*0.148068185*	*0.097616597*	*0.135433563*
	Average	*-11.16325*	*-10.03925*	*-9.478*	*-9.6235*
	Manual Readings	-10.485021	-9.3088245	-9.5957375	-9.6959038
	Deviation	*-0.678229*	*-0.7304255*	*0.1177375*	*0.0724038*
RX Gain in dB	**Freq (MHz)**	***5225***	***5275***	***5425***	***5475***
	Avg Ch 9	40.002	39.801	38.953	38.732
	Avg Ch 10	39.921	39.715	38.912	38.69
	Avg Ch 11	40.113	39.778	38.994	38.795
	Avg Ch 12	39.97	39.839	38.943	38.797
	Std Dev	*0.07054254*	*0.045024299*	*0.029312966*	*0.045024993*
	Average	*40.0015*	*39.78325*	*38.9505*	*38.7535*
	Manual Readings	39.899541	39.601421	38.733978	38.485331
	Deviation	*0.101959*	*0.181829*	*0.216522*	*0.268169*
RX i/p Return Loss	**Freq (MHz)**	***5225***	***5275***	***5425***	***5475***
	Avg Ch 9	-11.122	-12.575	-19.034	-19.662
	Avg Ch 10	-11.036	-11.784	-18.366	-18.727
	Avg Ch 11	-11.352	-11.692	-19.05	-19.82
	Avg Ch 12	-10.997	-11.721	-19.351	-19.863
	Std Dev	*0.137686918*	*0.366398008*	*0.360177994*	*0.462775864*
	Average	*-11.12675*	*-11.943*	*-18.95025*	*-19.518*
	Manual Readings	-11.193815	-11.981859	-19.20122	-17.922205
	Deviation	*0.067065*	*0.038859*	*0.25097*	*-1.595795*
Noise Figure	**Freq (MHz)**	**5225.00**	**5266.67**	**5391.67**	**5475.00**
	Avg Ch 9	3.772	3.649	3.453	3.475
	Avg Ch 10	3.811	3.675	3.495	3.5
	Avg Ch 11	3.761	3.654	3.483	3.463
	Avg Ch 12	3.708	3.598	3.453	3.525
	Std Dev	*0.036789944*	*0.028293109*	*0.018493242*	*0.023857651*
	Average	*3.763*	*3.644*	*3.471*	*3.49075*
	Manual	3.701	3.564	3.438	3.49
	Deviation	*0.062*	*0.08*	*0.033*	*0.00075*
Output Power in dB	**Freq (MHz)**	**5225.00**	**5266.67**	**5391.67**	**5475.00**
	Avg Ch 9	39.66105054	39.87707032	39.92758073	40.09171279
	Avg Ch 10	39.62287784	39.70246319	39.99450201	40.05579788
	Avg Ch 11	39.77526854	39.95369973	40.06905552	40.23481184
	Avg Ch 12	39.73167884	39.43092255	39.99535744	39.86230279

Table 7 (continued)

Std Dev	*0.059399025*	*0.200866505*	*0.050048491*	*0.132911039*
Average	*39.69771894*	*39.74103895*	*39.99662392*	*40.06115632*
Manual	*39.58*	*39.82*	*39.92*	*40.12*
Deviation	*0.11771894*	*-0.07896105*	*0.076623925*	*-0.05884368*

Table 8 Port to port variation and repeatability test performance.

Parameter	**Measurement Accuracy**	**Port to Port variation (3σ)**	**Repeatability over 10 sets of data on a given port**			
			Channel 9 (3σ)	**Channel 10 (3σ)**	**Channel 11 (3σ)**	**Channel 12 (3σ)**
Tx Peak power	**< 0.3 dB**	0.345997078	0.125322403	0.054506534	0.114374576	0.063063996
Tx Pulse t_r	**< 10 ns**	0.010809196	0.022029275	0.010481547	0.024108861	0.006879296
Tx Pulse t_f	**< 10 ns**	0.002849088	0.007495948	0.007152428	0.006749006	0.006741912
Rx Gain	**< 0.5 dB**	0.315414014	0.455209842	0.464409302	0.438256774	0.363990384
Rx NF	**< 0.3 dB**	0.110369833	0.135665029	0.100399203	0.195368882	0.103749699
Tx Return Loss	**< 1 dB**	0.910680069	0.775144503	0.901224167	0.96288317	0.604006622

5 Conclusion

In this paper, a framework for the large-scale testing and characterization of space TR modules is explained. Following the standard guidelines for the design, development and commissioning of an automated test system and involving the multidisciplinary team of subject specialists, test engineers, and system engineers, an ATS is successfully deployed for the test and characterization of space TR modules in large numbers. The hardware and software architecture of the ATS has features of flexible sequencing of testing using reconfigurable switch matrices enabling speedier, multi-utility and scalable test solution. With set up times significantly reduced by 96%, engineer- hours brought down from 448 to 14, expensive environmental test chambers requirement reduced by 75%, the ATS has significantly improved the accuracy, repeatability and dramatically increased the throughput to test larger volumes of TR modules. This test system has produced 9000 readings per module and for 500 modules that have been statistically analyzed. The scalability and multi-utility features of the ATS enabled flexibility to the test engineers. The quality agencies and decision makers have used the ATS results to clear the TR modules for onboard use on a satellite.

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Data Availability All the data required for assessment of the manuscript is included in this file itself. There is no separate data to be archived.

Declarations

Conflict of Interest The authors declare that there is no conflict of interest in this manuscript.

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