Use of Real-Time Spectrum Analysis for EMI Characterization of a Safran Hall Thruster

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Abstract

An extensive effort was undertaken to characterize the EMI emissions from a Safran Hall thruster. Both frequency domain measurements (FDMs) that included RE102 and RE103 and time domain measurements (TDMs) that included Z-Span and LSCX tests were made. In addition, Real-Time Spectrum Analysis (RTSA) providing simultaneous time resolved measurements over large frequency ranges was evaluated during this testing.

This paper will provide some of the results from this test program but will focus on RTSA that was used for the first time to characterize the EMI emission from an EP thruster. This technique uses overlapping FFTs and high-speed memory to provide a 100% probability of intercept (POI) ensuring capture of nonrecurring bursts of emission that are often characteristic of EP thrusters. The test set-up was unchanged from the standard RE102 set-up but uses a real-time spectrum analyzer instead of a signal receiver. For this testing, a selected set of frequency ranges were characterized and generally showed the background prior to ignition, the ignition step, a steady-state period following ignition, a transition to a new operating point, a return to the original operating point and then, in some cases, thruster shutdown. Many new and interesting insights were provided by these data including the ability to correlate thruster operating steps (such as changing gas flow, magnetic field and anode voltage) with the emission activity. The main result of the data presented in this paper is that Real Time Spectrum Analysis will provide an improved characterization of the EMI from EP thrusters.

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I. Introduction

The electromagnetic compliance and interference (EMC/EMI) emissions from a Safran Hall thruster were characterized at The Aerospace Corporation (TAC). The thruster test unit included an XFC (thermo-throttle) used for propellant (xenon) control. The thruster was operated with a PPU emulator developed at TAC. The emulator development included telemetry measurements, fault protection and software control. The thruster was identified as having a ceramic wear profile simulating an intermediate-life condition of 2,000 hours.

A significant component of this testing involved preparation work. The PPU emulator development involved selection and organization of power supplies, preparation of filters (inductors and resistors) to match the characteristics of the PPU, cabling and connectors to meet required specifications, and a detailed telemetry system to accurately characterize the performance of the thruster. In addition, a comprehensive software package was made to control the thruster and the XFC. This allowed the operator to move smoothly between thruster operating points and monitor its behavior. A Load Bank was built to allow testing of the PPU emulator and evaluate the control software. Finally, both fault protection hardware and software were provided to ensure safe operation of the thruster and XFC.

Both RE102 (10kHz to 18GHz) and extended RE103 (18GHz to 52GHz) frequency domain measurements (FDMs) were made at several antenna locations and thruster operating points. Time domain measurements (TDMs) were also made using Zero Span measurements that covered 8 pre-selected central frequencies (CF) and 5 additional CFs selected after the FDMs were obtained. The TDMs also included emission event capture over broad frequency bands, the so-called LSCX measurements. In addition to these baseline measurements, special start-up and steady-state TDMs were made.

In addition, a unique approach to the characterization of EMI from an EP device was evaluated during this testing. This involved Real-Time Spectrum Analysis (RTSA) that provided simultaneous time resolved measurements over large frequency ranges. The test set-up was unchanged from the standard RE102 set-up but used a real-time spectrum analyzer to provide a unique data set that acquired signals over a large frequency range continuously in time.

RTSA uses overlapping FFTs and high-speed memory to provide a 100% probability of intercept (POI) ensuring capture of nonrecurring bursts of emission that often occur with EP thrusters. For this testing, a set of frequency ranges were selected for characterization. The data obtained showed the background prior to ignition, the ignition step, a steady-state period following ignition, a transition to a new operating point and then the return to the original operating point. Many new and interesting insights are provided by these data. These include, the difference in the emission characteristics at and immediately following ignition versus after reaching steady-state, the presence of frequency dependent peaks and valleys that evolve slowly over time, the difference in transition from operating point Ta to Tb versus the transition from Tb to Ta, and the ability to correlate thruster operating steps (such as changing gas flow, magnetic field and anode voltage) with the emission activity. The primary conclusion from this study was that Real Time Spectrum Analysis will improve the characterization of the EMI from EP thrusters.

II. EMI/EMC Test Facility

The measurements presented here were made at The Aerospace Corporation Electric Propulsion EMC/EMI Facility. A detailed description of the facility can be found in Ref. [1], a brief description is presented here.

The facility is made up of a semi-anechoic room which surrounds a dielectric tank in which the test article is installed. The dielectric tank is connected through a 1-meter gate-valve to a large stainless-steel chamber (EP2) that includes the vacuum pumps. The facility is shown schematically in Fig. 1. and a photograph of the semi-anechoic room is provided in Fig. 2.

The EP2 vacuum chamber is pumped with four cryotubs and six re-entrant cryopumps. With the gate-valve closed, a pumping speed of 250,000 l/s (Xe) can be achieved allowing base pressures of ~10^{-8} torr. With the gate-valve closed, the main chamber and the semi-anechoic room can be used for independent testing.

The dielectric tank is made from fiberglass (S2 glass) that allows electromagnetic radiation from the thruster to be transmitted with little absorption to antennas located in the semi-anechoic room. A description of the absorption characteristics of the dielectric tank is available elsewhere[1].

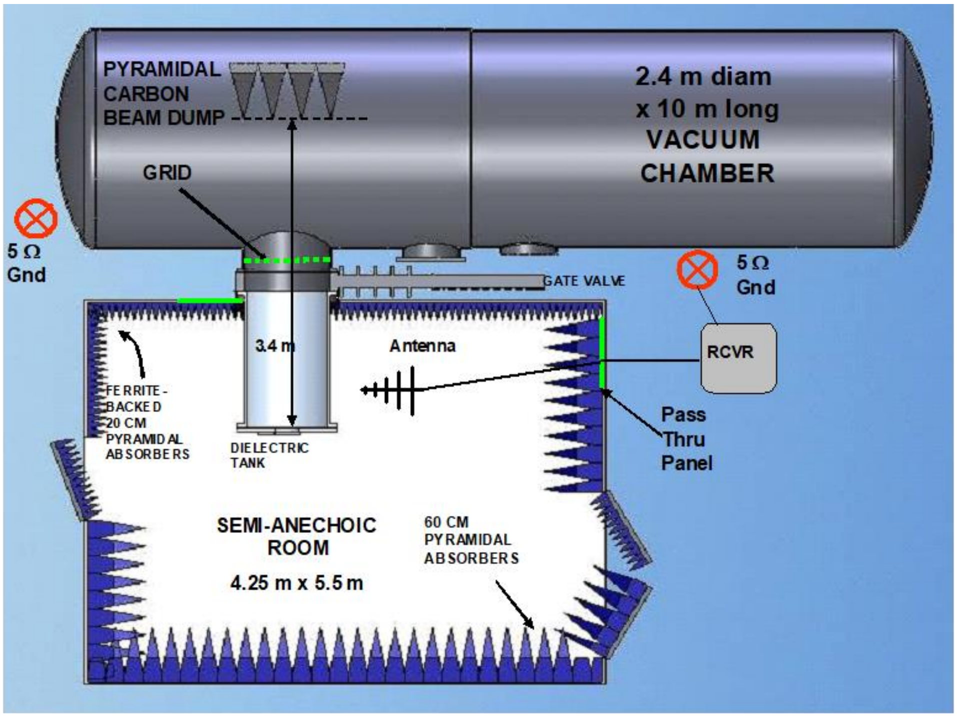


Figure 1. *A sketch of the Aerospace Electric Propulsion Thruster EMI/EMC Test Facility.*

Figure 2. *Photograph of the Semi-Anechoic Room and the Dielectric Tank*

The semi-anechoic room is 5.5m x 4.25m x 3m. It provides >100 dB shielding from 14 kHz – 18 GHz and is designed to be MIL-STD 285 and NSA 65-5 compliant. Analyzers, receivers, and custom-built time-domain instruments (not used in this study), located in a neighboring control room, record the radiation that is emitted from the thruster. Below 18 GHz, the instruments connect to antennas through a panel in the semi-anechoic room using cables and feed-throughs with known attenuation. The series of antennas normally used are: rod antennas from 10 kHz to 30 MHz, bi-conical antennas from 30 MHz to 200 MHz, log-periodic antennas from 200 MHz to 1 GHz and double-ridge horn antennas from 1 GHz to 18 GHz. Above 18 GHz, a smaller receiver situated in the anechoic room connects through one of two short cables to a series of low-noise amplifiers (LNAs) mated directly to octave horn antennas.

To perform EMI testing on an EP thruster that is operating in the small (0.9 m diam. and 1.5 m long) all dielectric vacuum tank, a beam-dump is installed in the main chamber and the gate-valve is opened. The beam-dump is made up of an array of 0.6-meter high aluminum pyramids covered with grafoil to reduce sputtering by the high-energy xenon ions and reduce scattering. The plume of the thruster exhausts into the main vacuum tank, terminating on the beam dump. Pictures of the thruster installed, operating and being tested in the facility are shown in Fig. 3.

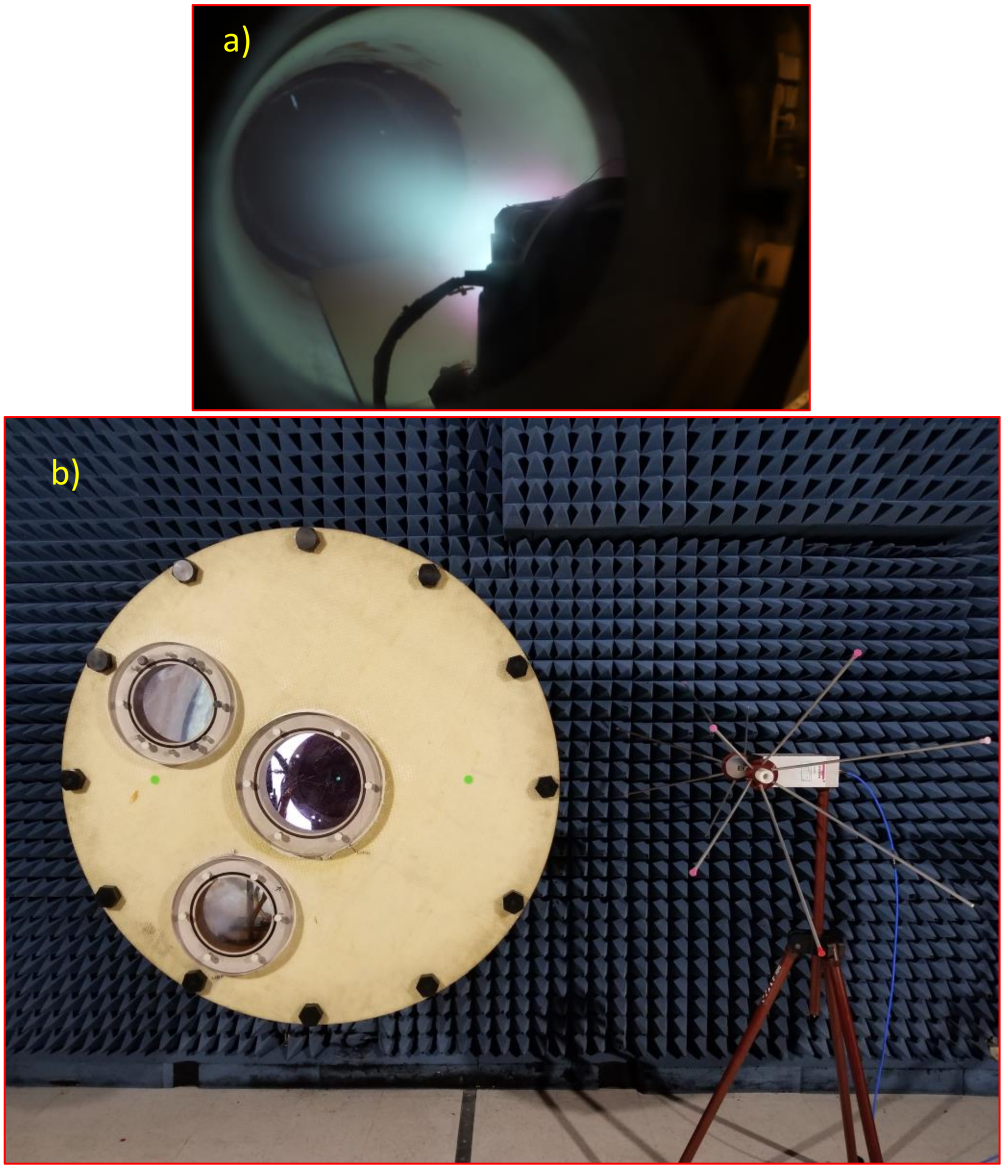


Figure 3. *Pictures of a Safran Hall thruster a) installed and operating in the dielectric vacuum chamber. In b) a Bi-Con antenna is placed in the semi-anechoic room to make emission measurements from the thruster operating in the dielectric chamber.*

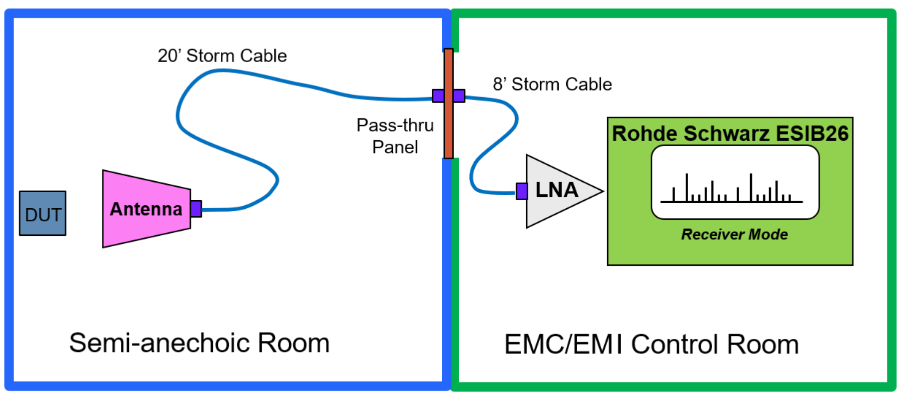
III. Results and Observations

A. Frequency Domain Measurements

The most common aspect of EMI testing[2,3] at The Aerospace Corporation is to determine the spectrum of radiated emissions from an Electric Propulsion (EP) thruster. This is done by collecting the RE102 and, if requested, RE103 data following the MIL-STD 461E. These represent Frequency Domain Measurements or FDMs. The test set-up for the RE102 measurements is shown in Fig. 4. The antennas used to cover this frequency range are shown in the table along with the low noise amplifiers (LNAs) that are used and the resolution bandwidth and dwell time.

A peak hold process is followed so for each frequency range, the receiver starts at the lowest frequency, waits for 15 ms, and returns the maximum detected signal. It then takes a frequency step (1/2 the RBW), and repeats the process, scanning the entire frequency range over several minutes.

Examples of RE102 measurements taken using this Hall thruster are shown in Fig. 5. These data include both horizontal and vertical antenna polarization for 2 thruster operating points (labelled Ta and Tb.)



Antenna	LNA	Frequency Range	Band	RBW/Dwell
Active Rod	-	10 kHz – 30 MHz	LF	10 kHz,15 ms
Biconical	HP 47405A	30 MHz – 200 MHz	HF, VHF	100 kHz, 15 ms
Log Periodic	HP 47405A	200 MHz – 1 GHz	UHF	100 kHz, 15 ms
Double Ridge Horn	Miteq JS32	1 GHz – 18 GHz	L, S, C, X, Ku	1 MHz, 15 ms

Figure 4. *Test set-up used for RE102 measurements. The time needed to complete a full scan is 2 – 5 minutes. A set of measurements for a single thruster operating point and a single test location can take up to an hour.*

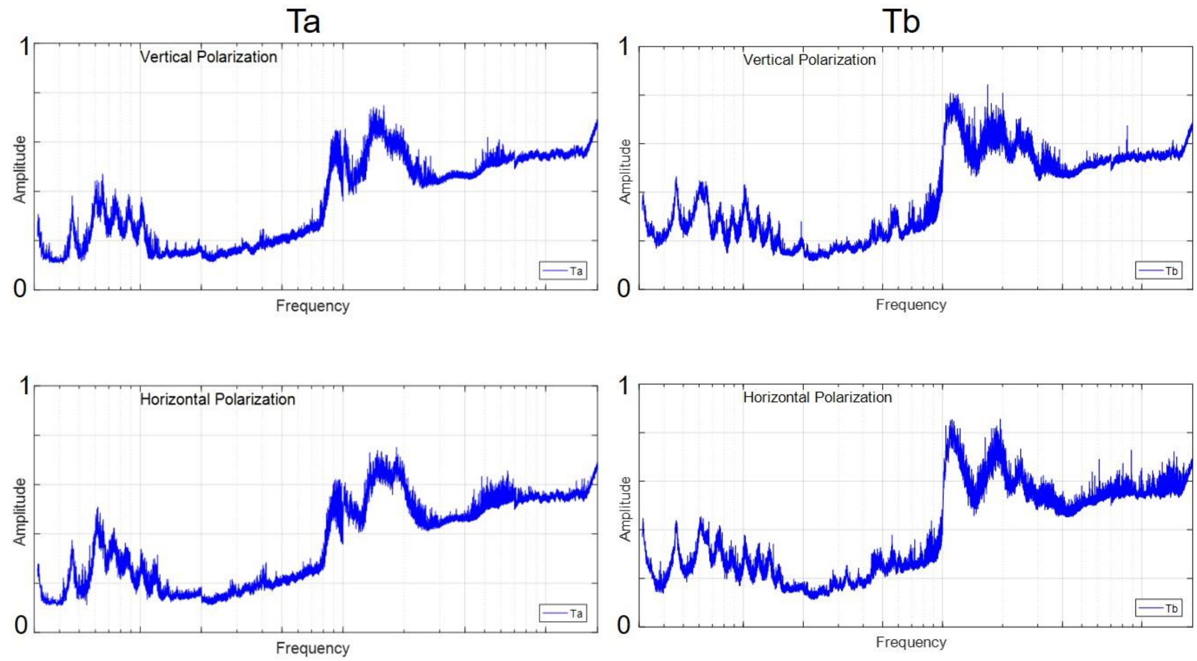


Figure 5. *RE102 emission data at 2 different operating points Ta (on the left) and Tb (on the right).*

The first set of these FDMs measurements were taken at four specified locations and the main three thruster operating points. With these data the location with highest emission (LWC) was determined. The second set of FDMs were taken at LWC for three additional thruster operating points.

From this complete set of frequency domain data, the emission signature of the Hall Thruster was characterized. The thruster emission as a function of frequency was found to be very dependent on location and thruster operating point. The emission was highest with horizontal polarization, especially at higher frequencies. At frequencies above the S-Band the emission was characterized by transient spikes that had the highest density and magnitude with higher anode voltage.

Finally, in the frequency domain, comparative data was taken for specified frequency notches in the UHF, L, S, C, X and Ku Bands with various resolution bandwidths (RBW). In many cases the signal level in the notch was at background levels and the response to the change in RBW was to increase and decrease with it in an expected manner. For notches having significant transient emission, it was necessary to increase the dwell time by the same factor that RBW was decreased to match the probability of capturing the transient events.

Background levels were taken at all test locations before, during and after the Test campaign. There was no significant dependence on location and the background levels remained constant throughout.

B. Time Domain Measurements

Typically, a thruster does not only emit continuously, but also in transient "bursts" or "events". Typically, Zero-Span and/or LSCX methods[4,5] are used to capture these events. These tests are called Time Domain Measurements or TDMs.

With Zero-Span a central frequency and bandwidth are set on a Spectrum Analyzer and emission is captured as different time periods are scanned. Statistical analysis allows an estimate of bit error rate to be made at the specified frequency. The test set-up for the LSCX measurements is shown in Fig. 6. Four frequency bands of emission are evaluated. The LSCX measurements involve compromises with how the data is collected and used. A diode can be used and the statistical behavior over several seconds can be examined but the ability to capture specific frequency information is lost. Instead the signal can be sent directly to the scope and high-resolution data obtained over a very short period but because of the short data acquisition time and the long storage time, only very few events are actually captured. An example of the LSCX measurements taken in this direct manner is shown in Fig. 7.

All TDMs were taken at the worst-case location. The Zero-Span measurements were taken at specified central frequencies and referred to as narrowband or NB TDMs. The LSCX measurements were taken with a horn antenna "farm" and then directed to 4 separate scope channels. They were referred to as broadband (BB) TDMs and taken both during steady-state for all operating points and for start-up. Additionally, BB TDMs were made for a limited window in the UHF band.

The TDMs indicated that transient emission was very dependent on the frequency region being examined and the anode voltage of the thruster. Based on the degree of asymmetry of the distribution of the binned data, higher levels of transient emission were observed for horizontal polarization in the C-, X- and Ku-Bands and with the thruster operating with higher anode voltages. The BB TDMs showed similar dependencies. The LSCX start-up data showed the most significant emission in the L-Band with weaker in the S- and C-Bands. In general, the steady-state LSCX data also showed the strongest emission at L-Band and reduced emission at higher frequency bands. Again, the most significant test parameter affecting the transient emission level was the thruster anode voltage.

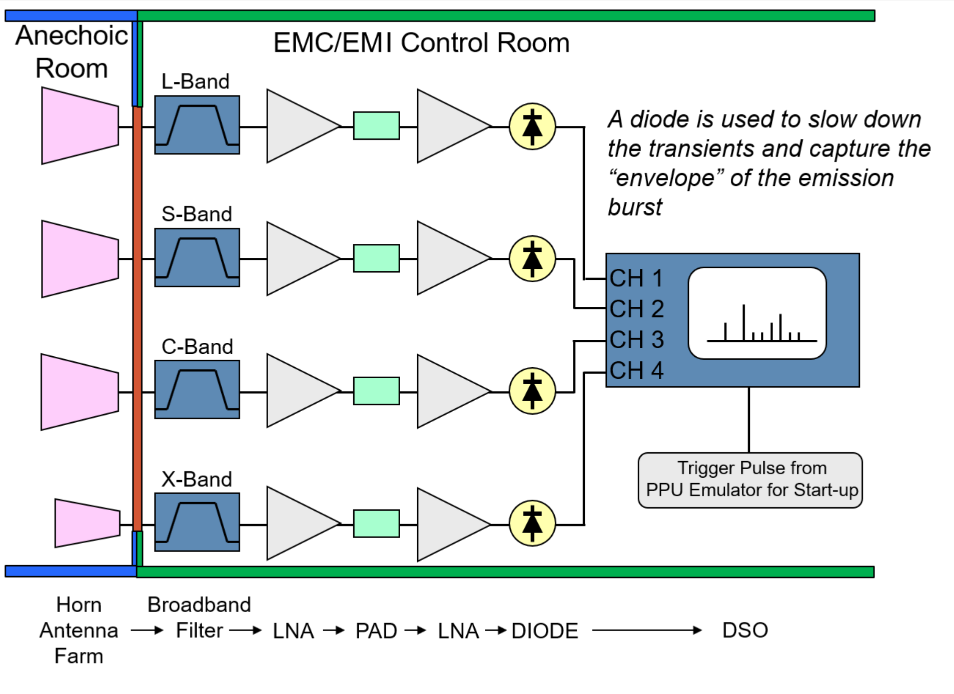


Figure 6 *LSCX Test Set-up*

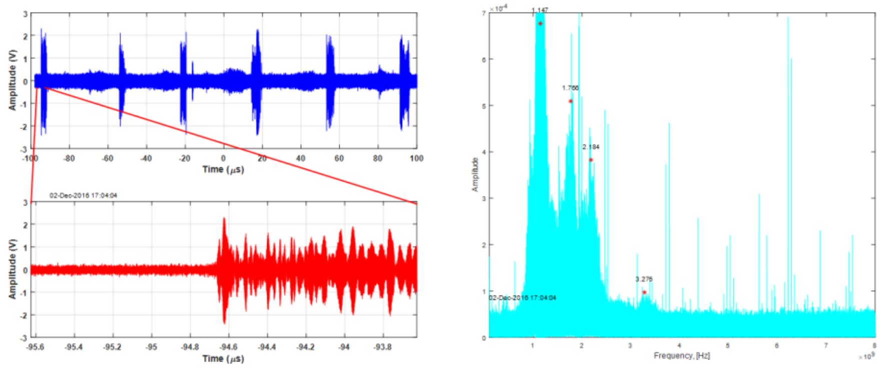


Figure 7 *An example of LSCX measurement data showing the time domain scope capture for the L-Band input and the FFT result.*

C. Real Time Spectrum Analysis

Because of the significant level of transient emission that typifies the EMI from an EP device, a new approach to characterizing this emission called Real-time Spectrum Analysis (RTSA)[6,7] was evaluated during this test campaign. RTSA leverages overlapping FFTs and high-speed memory to have a 100% probability of intercept (POI) which provides a much stronger characterization of the thruster emission than either the FDMs or the TDMs discussed earlier.

Effectively this technique makes use of wide bandwidth analog-to-digital converters (ADCs), high-speed memory, fast processors, and efficient Fast-Fourier transforms (FFTs), to process at least hundreds of megahertz of instantaneous bandwidth as fast as it is received. For the measurements shown in this paper, a Keysight PXA 9030A Signal Analyzer with Real Time, capable of providing data from 3Hz to 50 GHz, was used.

The test set-up is shown in Fig. 8-a) along with an example of the data provided from RTSA. There is no change in the test set-up as was used to obtain the standard RE102 measurements. What is clear, however is that this new tool provides new ways to look at the thruster emission.

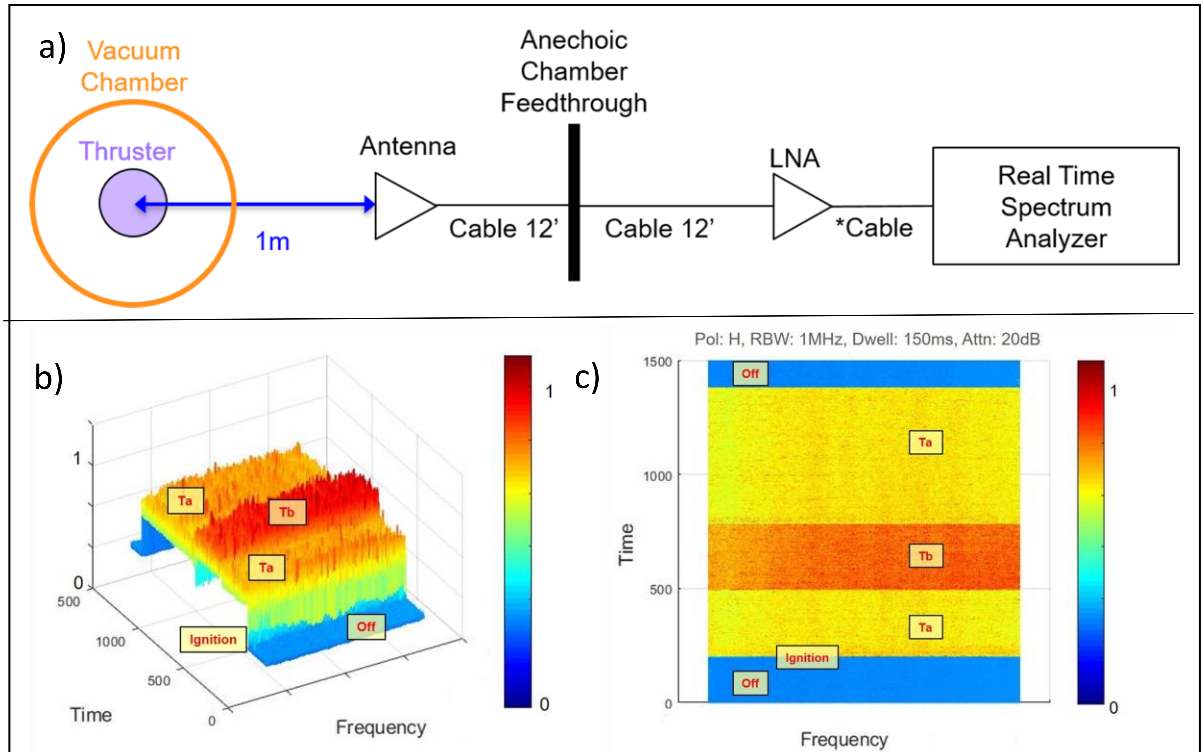


Figure 8. *The RTSA test set-up, a), and an example of the Safran Hall thruster emission showing both b) 3-D, and c) 2-D data representations.*

The 3-D map in Fig. 8-b) shows the initial background level (blue section at the bottom right) jumping dramatically with the thruster ignition to operating point Ta. The map follows the emission at this operating point for several minutes and it can be seen to reduce and stabilize. Then a transition is made to operating point Tb and the increased emission now displayed as a red color is clearly observed. After a few minutes the transition back to Ta is made and finally the thruster is turned OFF. In many ways, the view of the data is even better when it is shown as a 2-D map as provided in Fig. 8-c). In this case the immediacy of the changes in emission when the thruster ignites and then transitions to different operating points is obvious. In addition, the presence of frequency dependent emission can be seen as periodic vertical regions of darker and lighter colors. While the data is being obtained, this 2-D map can be viewed as a waterfall display where each sweep is colored based on signal strength and stacked sequentially to show the changes in time. This gives the operator an opportunity to identify regions of interest as the data is being taken.

Fig. 9-a) and 9-b) show the 3-D, 2-D along with a 1-D time map of thruster emission in 2 different frequency regions of the L-Band. At the lower frequencies in Fig. 9-a, the sharp contrast in the emission between the two operating points is remarkable. In the 2-D map, the vertical bands showing frequency dependent emission is much more significant than in Fig. 8-c and appears to grow with the change in thruster operating point. The lower 1-D plot is generated at a specific frequency and is basically a Zero-Span plot and, of course, can be generated for any frequency specified in the sweep. What is clear in these 2-D and 1-D plots is that the transition from operating point Ta to Tb is very different from the transition from Tb to Ta. The Ta to Tb transition appears instantaneous but from Tb to Ta there is clearly a different process being used. This difference in the transition behavior is even more clear in Fig. 9-b) which also has the major change in behavior in that the emission at Tb is weaker than at Ta.

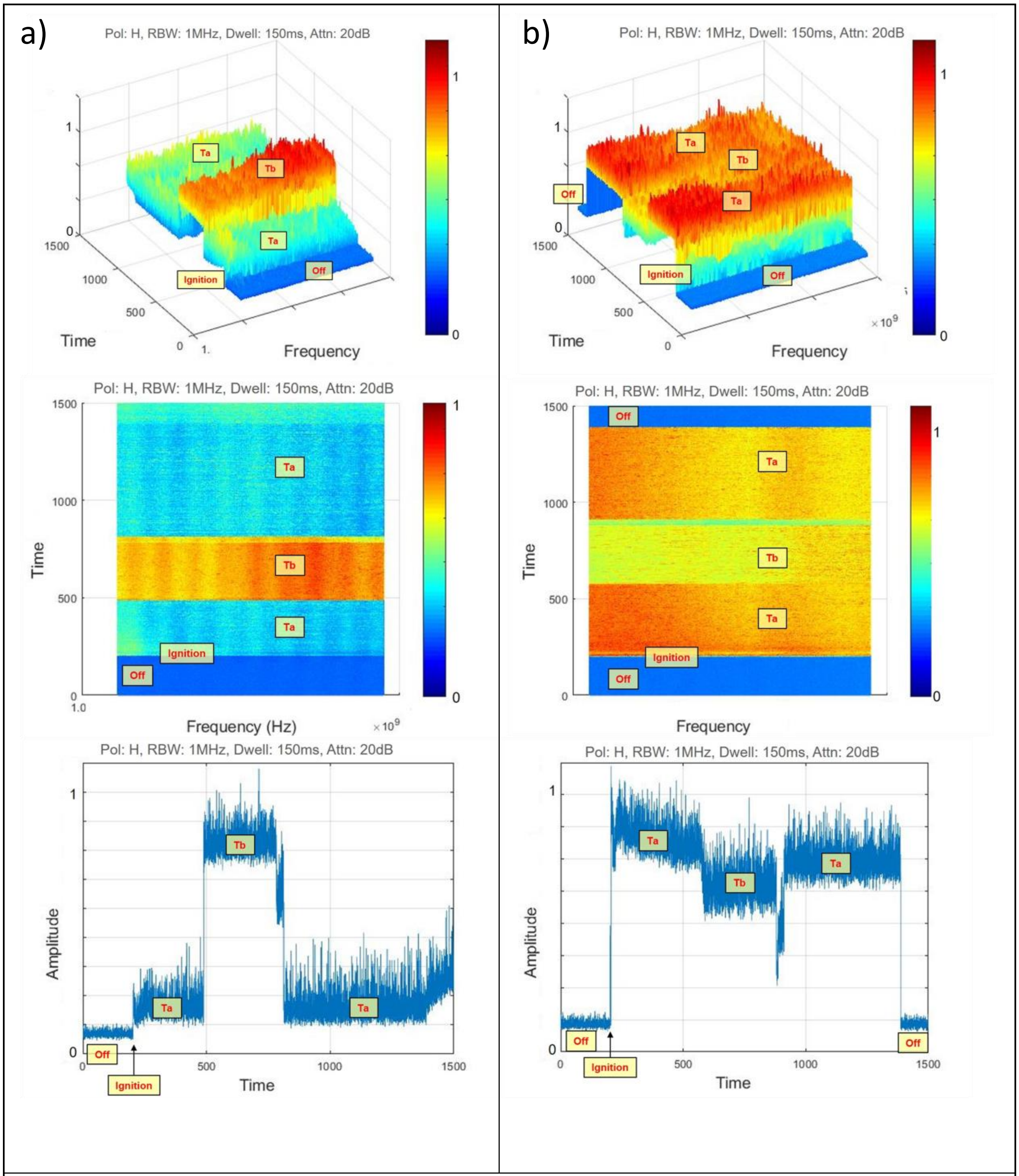


Figure 9. *Two examples of L-Band thruster emission from the Safran Hall thruster with 3-D, 2-D and 1-D data representations*

Fig. 10 examines this Tb to Ta transition more closely. For the Tb to Ta transition, the anode voltage and anode current are changed before the magnetic current is changed. This exposes three distinct changes in emission. There is a sharp decrease in emission when the anode voltage is changed. Then as a result of the change in anode flow rate the anode current slowly steadies and the emission slowly increases. Then when magnetic field configuration is changed, there is a sharp change in emission. Correlation of emission to thruster parameters may enable tailoring of thruster procedures during EMI-sensitive operations

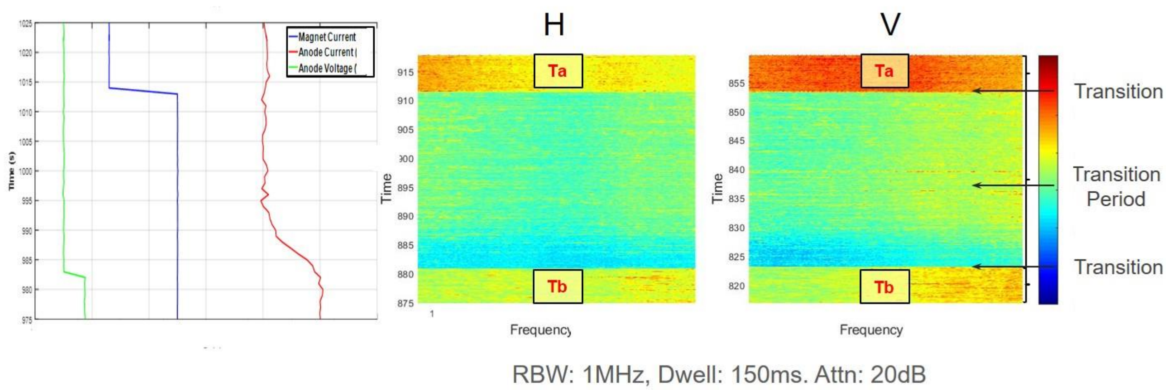


Figure 10. *Real Time Spectrum Analysis in both horizontal and vertical polarizations examining the transition emission behavior from thruster operating point Tb to Ta.*

Finally, in Fig. 11 two RTSA data sets are shown that are well outside the L-Band (previously shown). In Fig. 11-a) the frequency range is in the VHF-Band. The variation in the background prior to ignition suggests the presence of unwanted noise. With ignition and Ta operation, there is only weak emission with slightly higher emission at the higher frequencies. With the transition to Tb there is very strong growth in emission at certain frequencies. Following this transition there are also several occurrences of strong emission resembling a red forest. In the 2-D representation it becomes clear that the red forests are very short emissions of radiation. It is also clear that this is not thruster-related emission since it is observed after the thruster has been turned OFF. The source of this noise was not identified but may be amplified background or associated with the vacuum system operation such as cryopump valves.

In Fig. 11-b), the frequency range is in the X-Band. While bursts of emission were apparent in the L-Band data, the emission here is very “transient” in both time and frequency. Using a RE102 Test Receiver, longer dwell times would have to be used to try to capture the largest emission. With LSCX or Z-Span one would have to be very lucky to capture it. With RTSA – it can’t be missed.

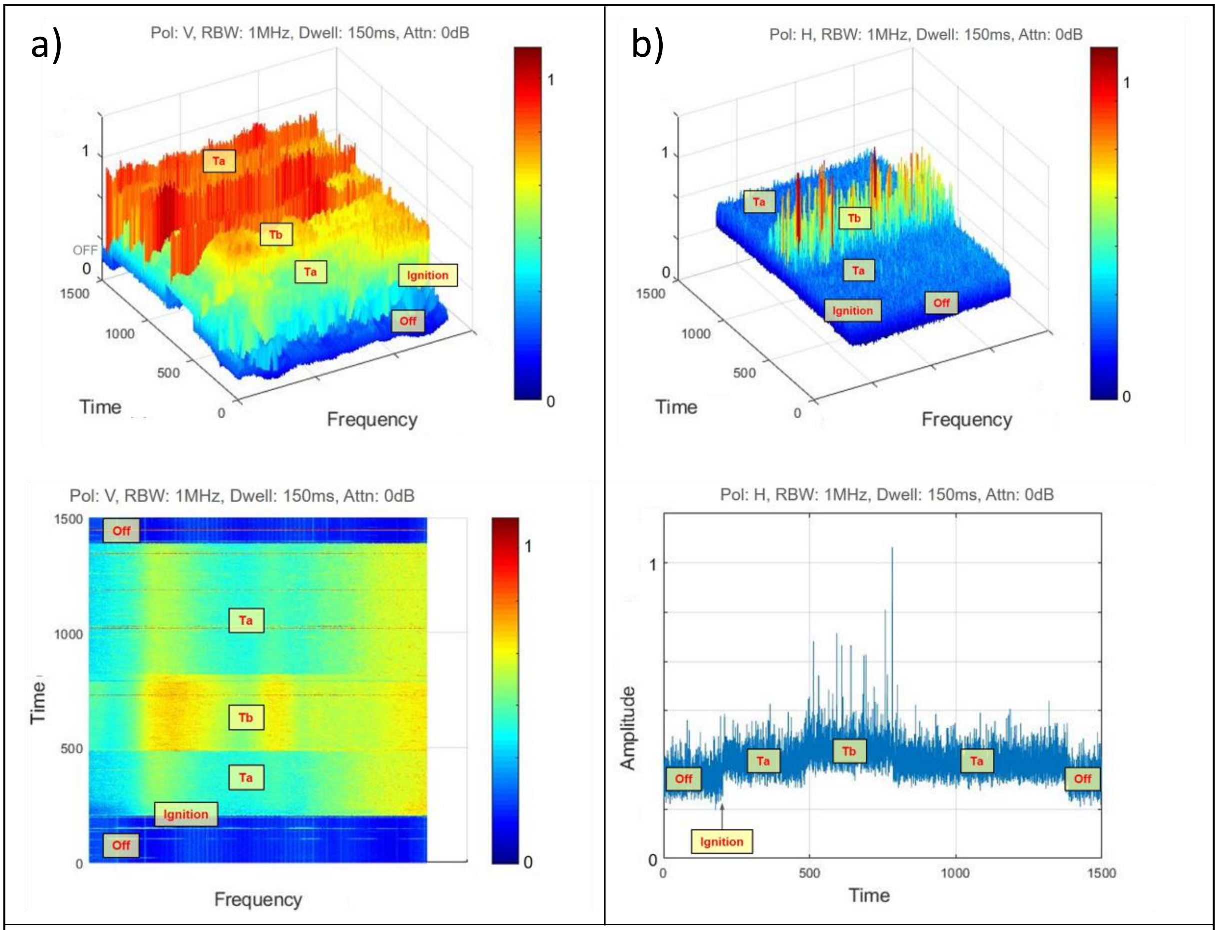


Figure 11. *Two examples of RTSA data using thruster emission from the Safran Hall thruster. The RTSA data in 11-a) is in the VHF-Band and shown as 3-D and 2-D data representations. The data in 11-b) is in the X-Band and shown as 3-D and 1-D data representations.*

IV. Summary and Discussion

Frequency Domain Measurements involved spectral scans of radiated electric fields emitted by a Safran Hall thruster was recorded from 10 kHz to 52 GHz following MIL-STD 461E RE102 and RE103 specifications. Thruster emission as a function of frequency was found to be very dependent on location and thruster operating point. As is typical for thruster plume emission, the signal was generally stronger for horizontal polarization. It was also noted that emission depended on the thruster operating voltages.

Time Domain measurements were made using 2 different procedures. In one case, Zero-Span measurements were made for a predefined list of central frequencies and a series of frequency performed using the LSCX instrumentation. Transient effects associated with thruster start-up were recorded using the Aerospace Corporation LSCX instrumentation. TDMs indicated that transient emission was dependent on the frequency region being examined. The Z-Span measurements (NB TDMs) showed more significant transients in the C-, X- and Ku-Bands. The Z-Span data also showed more transient emission at operating points with higher anode voltages and with horizontal polarization. The LSCX data showed the most significant emission in the L-Band with weaker in the S- and C-Bands with the most significant test parameter affecting the transient emission level being the thruster anode voltage.

Real Time Spectrum Analyzer technology is new and improving every year. It will be particularly valuable for characterizing EMI transient emission and that is very typical of Electric Propulsion (EP) Thrusters. In many respects RTSA may be the tool of choice to test characterize the EP EMI. It provides a new way to look at EP EMI data and will probably replace Zero Span and LSCX data. By taking a slice in time and stepping through frequencies, an RE102 map could be built but this will simplify as the available bandwidth increases. In a generation or 2 of device development, RTSA may replace the RE102 frequency data set. One significant concern is that RTSA is not entirely compliant with standards (for e.g. MIL-STD 461E) but the European standards (CISPAR) have made significant additions to the time domain measurements and RTSA equipment is gaining acceptance in these standards. However, it may not be unreasonable to consider new EMI measurement standards for EP thrusters especially if testing shows that RTSA provides the best way to characterize this emission.

On the negative side, RTSA produces a huge amount of data, so we’ll have much more information and generate much larger reports.

Acknowledgements

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