Electromagnetic Interactions Test Procedure for a Centre-Triggered Pulsed Cathodic Arc Thruster

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Introduction

All electronic systems, no matter their type or technology, generate electromagnetic noise during operation. Conversely, all electronic systems are susceptible to the noise emissions of other systems, where these emissions can induce off-nominal system behaviour, potentially leading to system failure. This drives test procedure standardisation, to ensure confidence in test results, growing confidence in mission success by applying standards such as MIL-STD-461G [1]. However, all standards are based on assumptions which inherently limit their applicability. In the case of MIL-STD-461G, an underlying assumption is that the operating modes of the Device Under Test (DUT) reach steady-state quickly

While this is a valid assumption for most propulsion systems, the cathodic arc propulsion systems produced by Neumann Space are pulsed systems, wherein short, transient bursts of plasma generate thrust [2, 3]. The pulsed ablation of ionised material is driven by pulsed currents, which will generate pulsed magnetic fields and other transient effects; the transience of these phenomena suggest that tests which focus on the frequency domain are not well suited to full characterisation of transient electromagnetic effects.

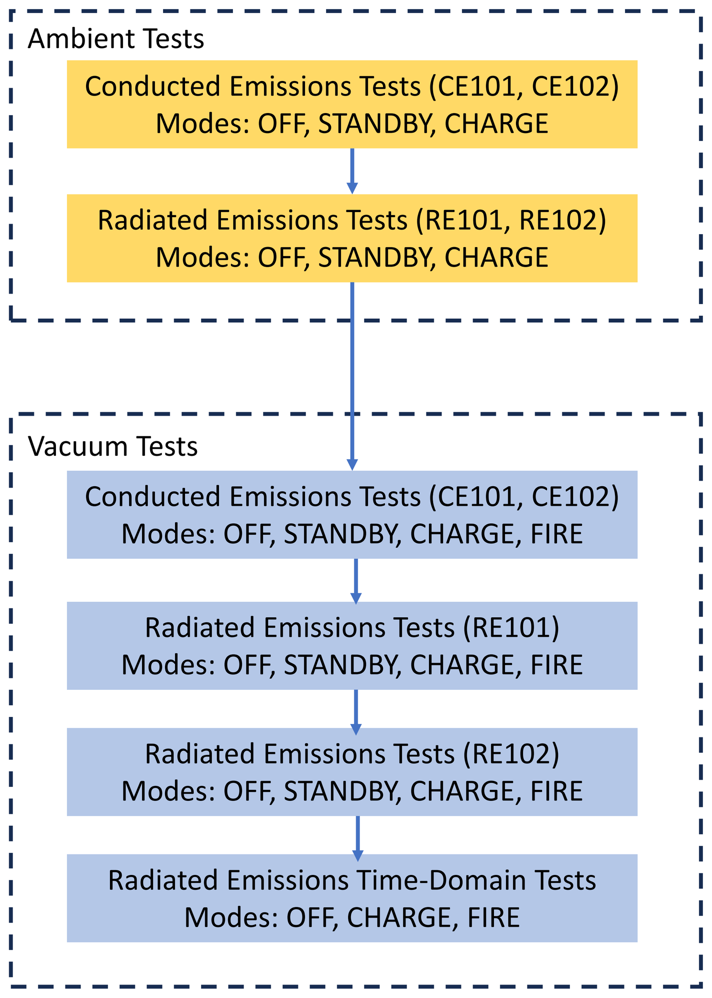
To aid in this characterisation an international collaborative project was begun, involving electromagnetic test expertise from the Centre National d'Etudes Spatiales (CNES) and the NATA accredited test facilities of REDARC, to characterise the electromagnetic emissions from Neumann Space's novel thruster technology. To limit potential scope creep, the tests were kept to emissions tests, and susceptibility of either thruster hardware or other spacecraft electronics was not investigated. In this work we shall describe the tests performed, how they relate to standard tests, and describe the deviations made where appropriate before presenting certain initial results.

Test Philosophy

The assumptions contained in MIL-STD-461G include time-invariance of emission, the physical scale of potential installations of a DUT, the environment required to operate the DUT, and the freedom to place other systems in arbitrary geometries near the DUT. Each of these assumptions apply imperfectly, and so need to be considered in relation to the test philosophy.

A pulsed propulsion system is inherently time-variant; the Neumann Drive has four 'modes': OFF, STANDBY, CHARGE and FIRE. The table below summarises the modes and the modified approach used to measure the Emissions in each one.

Mode	Description	Modification from Standard	Mode	Description	Modification from Standard
OFF	Thruster electronics OFF, any pumps required are on	None – determines noise floor in test environment	STANDBY	Thruster electronics powered, but not operating	None
CHARGE	System on and charging capacitors	(1) Lengthen acquisition time to whole charge period. (2) Take multiple short acquisitions across period	FIRE	Rapid (< 1ms) discharge of capacitors	Tailored acquisition time across multiple pulse firings.



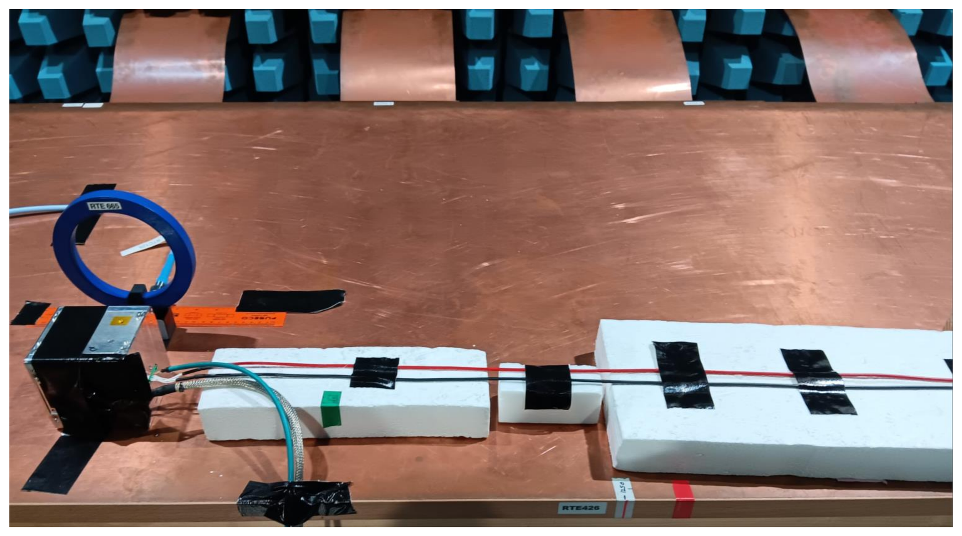
The DUT was a CubeSat scale integrated propulsion system, which implies proximity to spacecraft power management systems. The line impedance stabilisation network (LISN) design in the standard includes a 50μH inductor, implying a significant length of transmission line upstream of the DUT, as well as 2m of line for metering in the conducted emissions tests [1]. As these are far larger than what can be reasonably expected, we opted to use a LISN with 1μH of inductance to enhance network stabilisation, as well as 1m of line for metering and distancing. Circuit simulation, backed up with in-situ impedance testing, ensured that resonance conditions were avoided by the correct choice of LISN capacitor.

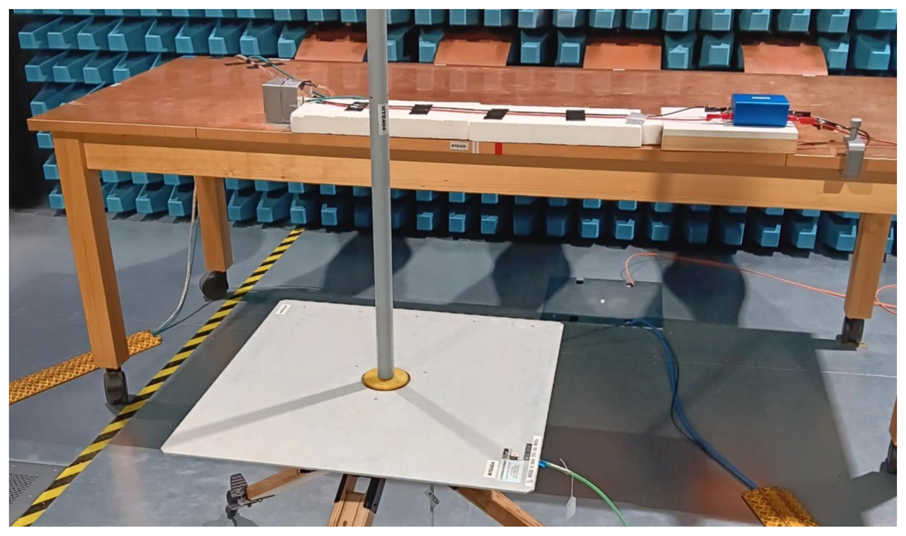
While measurements of the DUT while OFF, at STANDBY, or while CHARGE can be done at atmospheric pressure, measurements taken while FIRE must be done in a vacuum chamber transparent to magnetic fields and across the RF spectrum. Since polymethyl-methacrylate (PMMA, commonly referred to as acrylic) meets these requirements, a cuboidal acrylic chamber was designed and built for these tests. To prevent contamination of the chamber walls via deposition, the interior of the chamber in direct line of the plasma plume was covered by sheets of cellulose acetate. While the acrylic chamber was being commissioned, what tests could be performed at atmosphere were done, so that test philosophies and processes could be verified.

Due to the time-variance of emissions matching poorly with the acquisition times required by the standard, the acquisition times were altered to ensure proper capture of emissions. This was done in CHARGE mode to characterise any change in emission during the charging process, and FIRE mode. Since each plasma pulse is less than a millisecond long, the acquisition time was kept long, and many pulses were queued to so that the system firing would "walk" through the frequency bands being sampled by the acquisition hardware

To make the standard more generally applicable, radiated emissions measurements are mandated for all emitting surfaces of the DUT, to determine the vector of the greatest emissions. This is not particularly relevant or feasible for electric propulsion systems; it is often assumed that the noisiest environment will be downstream of the thruster, thus the measurement equipment would need to be in-line with the exhaust. Additionally, spacecraft hardware does not get placed in the exhaust plume due to the erosive effects of the plume, thus the standard test procedure and its assumptions is not directly applicable. We chose to test in the direction of the plume, since the EMI transparent acrylic chamber enabled this, denoting this the +z direction; we also tested orthogonal to this direction in the +x and +y direction, as this will be more relevant to spacecraft integrators and operators.

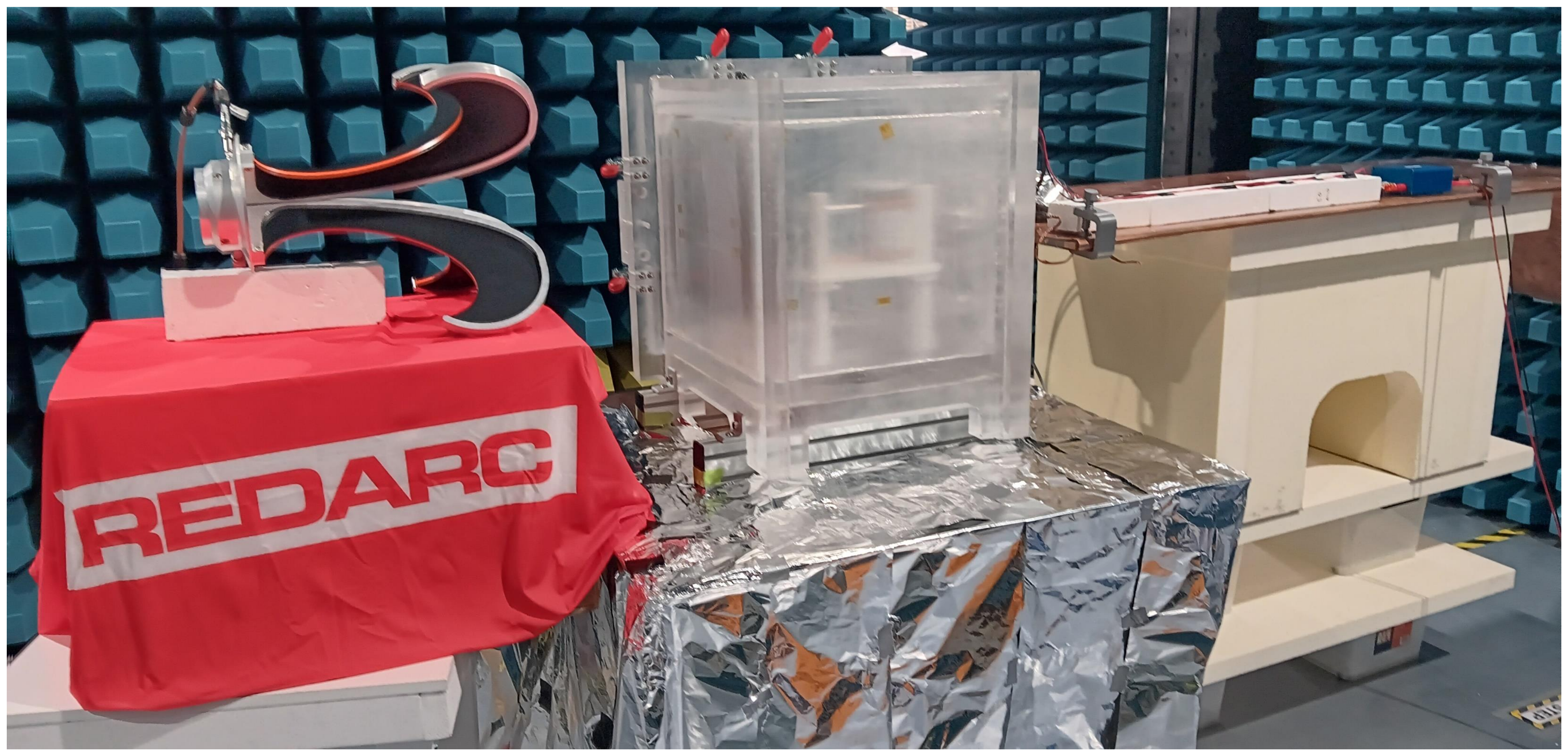
As an additional control over artefact, chamber wall thickness attenuation measurements were performed using a comb generator and the assorted RF antennae used for the radiated emissions tests. These measurements were performed for bare PMMA walls, as well as for PMMA walls covered by molybdenum-coated cellulose acetate sheets, to investigate any change in artefact that might occur during the progression of the tests. An indication of test flow is shown in the diagram above.





References:

1. MIL-STD-461G, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, digitized at https://quicksearch.dla.mil/qsDocDetails.aspx?ident_number=35789 , retrieved 8th April 2024
2. Andre Anders, "Cathodic Arcs: From Fractal Spots to Energetic Condensation," Springer Series on Atomic, Optical and Plasma Physics #50, 2008
3. Neumann et al, APL v109 094101 (2016)



Test Environment and Setup

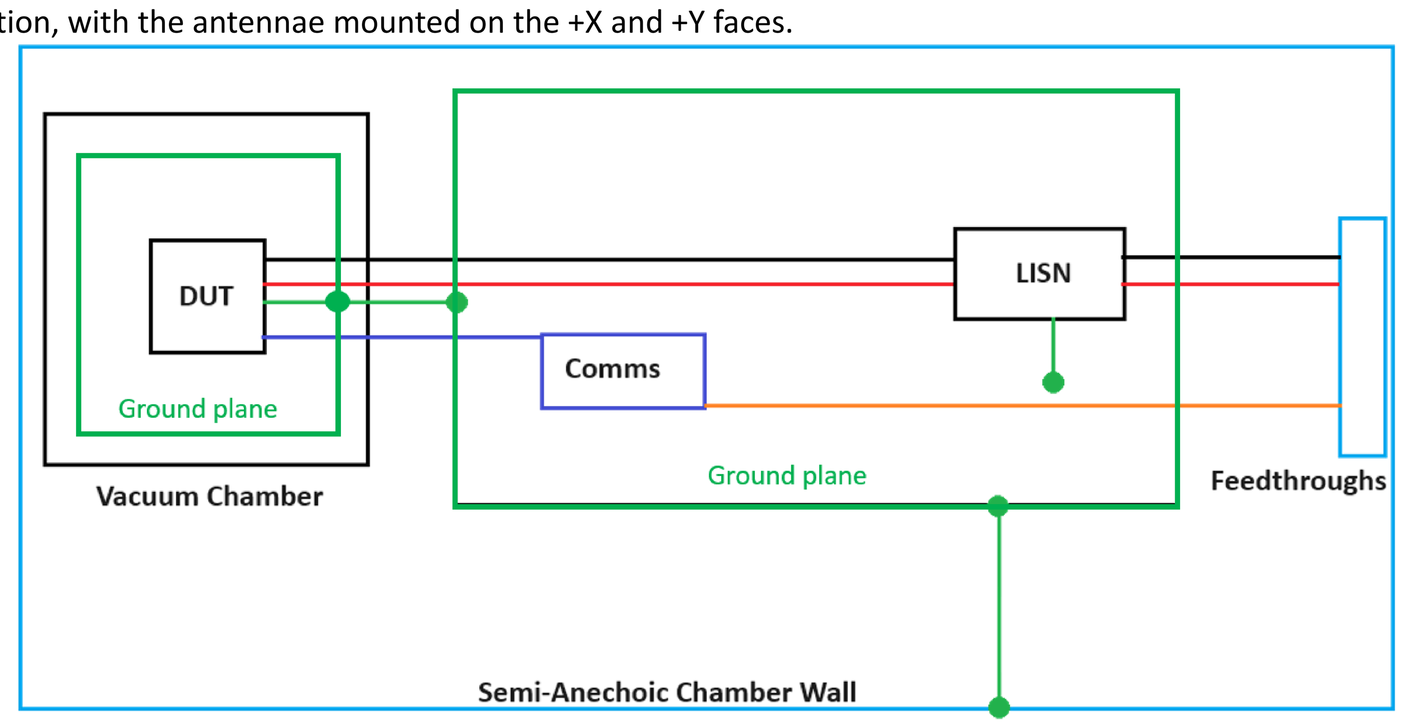
Tests were performed inside a NATA-accredited semi-anechoic chamber (SAC) at REDARC Technologies, an electronics manufacturer in Lonsdale, South Australia, represented schematically in the figure below. The SAC walls were grounded, and the DUT and LISN earths were tied to this ground appropriately, via the NATA-standard copper topped support table. DC power was provided to the LISN via shielded and EMI-filtered feedthroughs, while DUT communication was via RS-422 to fibre-optic converters powered by appropriately scaled battery packs with low emissions; the converter and battery pack inside the SAC is represented by the "Comms" box in the schematic, and was covered with aluminium foil secured, and electrically connected to, the same RF Grounded copper-topped table that held the LISN. Separation of the positive and negative power leads from each other and from the copper tabletop was as per standard. Initial testing in atmosphere had the DUT placed directly on the copper tabletop and connected to the LISN, as shown in the two photographs at left. Tests carried out in vacuum used a chamber built from 40mm thick PMMA plates with an interior cuboid volume approximately 400 mm on a side. The interior surfaces were shielded from propellant deposition by cellulose acetate shielding, and the chamber was pumped by a Pfeiffer HiPace 700 turbopump, roughed by a Pfeiffer HiScroll12 oil-free scroll pump. All tests were conducted at pressures below 5×10^{-5} mbar, as verified by a Pfeiffer PKR361 gauge. Chamber hardware, including pumps and gauges, were powered and grounded via filtered and shielded leads, while shielding from radiated emissions was achieved by use of a copper ground-skirt bonded to the pump port, as well as the use of aluminium foil to reflect emissions away from the antenna locations, as shown in the photograph above.

Conducted RF emissions CE101 tests were conducted with a current clamp in position as per the standard. For CE102, the measurement ports on the LISNs were used as per the standard [1]. Sensor leads carried signals to a Rohde & Schwarz ESW26 EMI Receiver in all tests for processing and archiving.

Radiated magnetic field measurements were taken as per RE-101, with the DUT placed in the vacuum chamber so that it was near a vertex of the interior cuboid, enabling the loop antenna to be placed 70mm from the exterior walls of the 1U sized DUT [1]. These measurements were taken in the +Z direction, where the loop antenna was face-on to the vector of the plasma plume, as well as in the +X and +Y directions, those being of more interest to integrators.

Radiated RF emissions were measured as per RE-102, with the DUT placed in the orthocentre of the cuboid [1]. Standard antenna types were used, with vertical and horizontal polarisations measured as required. Measurements were taken in the +Z and +X directions, with the DUT in the centre of the antenna pattern at 1metre distance as per the standard[1]. Limitations imposed by equipment mounts precluded testing in the +Y direction without alteration of the test environment.

Additionally, and in addition to the standard tests, a QH400 quad-ridge horn antenna from MVG was used to capture time-domain data during the tests, as were two COTS cubesat patch antennae. This was performed to investigate time-dependent signals radiated by the thruster, including the plasma pulse, and to compare pulses to each other. The QH400 was placed on the DUT X-Z plane, 2m outwards from the thruster at 45 degrees to both the X- and Z-axes, while the two patch antennae were mounted onto a 1U cubesat frame bonded to the DUT and groundplane, immediately adjacent to the DUT in the –Z direction, with the antennae mounted on the +X and +Y faces.



Initial Results

Initial results from the atmospheric tests performed to confirm the feasibility of the test procedure were successful; conducted and radiated emissions were measured during the STANDBY & CHARGING modes using procedures close to that prescribed by the standard. These tests enabled the isolation of noise being coupled along communications lines thought to be shielded, thus mandating the switch to a fibre-optic converter, and enabled users to identify emissions consistent with these two modes.

Tests performed in vacuum showed results consistent with the previous atmospheric tests of the STANDBY and CHARGING modes of operation. Since the capacitors must charge before firing the arc, measurement of emissions from the FIRING mode included emissions from the charging mode; the previous atmospheric tests enabled user identification of signals captured during the arc firing.

Signals captured by the QH400 showed very short duration transient emissions, which the more standard acquisition methods transformed into the frequency domain as high-powered broadband emissions. Detailed investigation of these transient signals continues, but the initial spike in emissions is sub-microsecond in duration, and rings down rapidly. Thus, while these transients are high powered, their very short duration means that their energy transfer is very low. Similar, but weaker, spikes were seen by the patch antennae, indicating that these signals were outside of their peak ranges. While not a rigorous susceptibility test, the fact that there were no microprocessor reboots or dropped communications packets in this test indicates that thruster hardware components, likely to be in the harshest thruster-derived EM environment, were unaffected by thruster emissions during operation, suggesting that other systems shall be similarly robust to the emissions of this thruster.

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