Temporal Characteristics of Radiated Emission from SPT-100 Hall Thrusters in the L, S, and C Bands

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Abstract: Temporal and transient characteristics of radiated emission from four SPT-100 Hall thrusters in the L, S, and C bands (1-8 GHz) are presented. The radiation in these bands was largely pulsed with pulse widths between 10 and 200 ns. A small percentage (< 5 percent) of the pulses occurred in pairs. There was no apparent correlation between pulse amplitude and pulse duration. The pulse rate decreased exponentially with increasing pulse amplitude. In the L band the pulses had a spectral width of approximately 150 MHz. At a frequency of 1600 MHz, the pulse rate appeared to increase with increasing thruster age. Several transient characteristics were observed. Startup emission amplitude and duration decreased with increasing frequency for the measured frequencies of 1400, 1600, 2000, 3000, 6500, and 10000 MHz. Startup transient emission could reach 85 dBμV/m at 1600 MHz (3 MHz RBW) at thruster start but decreased by approximately 25 dB within a few seconds; startup emission appears to increase with thruster age. Small changes in thruster discharge voltages and currents (5 percent) did not change L band emission. There was no change in emission at 1600 MHz due to xenon regulation and feed system pressure surges.

I. Introduction

This paper presents the temporal characteristics of radiated emission from four SPT-100 Hall thrusters in the L, S, and C bands (1-8 GHz). A companion paper presents the spectral characteristics of this radiation.[1] This companion paper describes the motivation for the work, the facility, placement of antennas, the electromagnetic response of the facility as a function of antenna position, the thrusters, and the extent of the measurements. This information will not be repeated here but specialized setups and techniques will be described. Work presented includes: a statistical study of pulse amplitude; measurements of pulse duration and pulse shape; studies of the bandwidth of radiated pulses at specific frequencies; and temporal variation of emission in the L band through startup and pressure surge transients.

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II. Instrumentation

Three different instruments were used in conjunction with various low noise amplifiers (LNAs) to make time domain measurements. The first was a spectrum analyzer or combination of two spectrum analyzers used at fixed frequency (zero span) usually operated at their greatest bandwidth. The 3 MHz (6 dB) maximum resolution bandwidth (RBW) on spectrum analyzer 1 (SA1) was approximately equal to the 2 MHz (3 dB) maximum RBW on SA2. SA1 was more sensitive than SA2 below 1 GHz and SA2 more sensitive than SA1 above 1 GHz. The second was a down-converter (DCv) supplied by Astrium that converted L band emission to a frequency between 55 and 85 MHz with a band-pass of 30 MHz (see Fig. 1). This allowed L band radiation to be studied through a bandwidth characteristic of a satellite transponder. The third was the time domain instrument (TDI) shown in Fig. 2. This comprised two nearly identical low noise amplifiers (LNAs) separated by a wideband variable attenuator followed by an envelope detector and digital sampling oscilloscope (DSO) with a bandwidth of approximately 500 MHz. The TDI was designed to study the L-band radiation without the bandwidth restrictions inherent in the spectrum analyzers and the DCv. The RF pass-band of the TDI was 0.5–2 GHz. These three instruments were used in several configurations, some of which are shown in the Appendix.

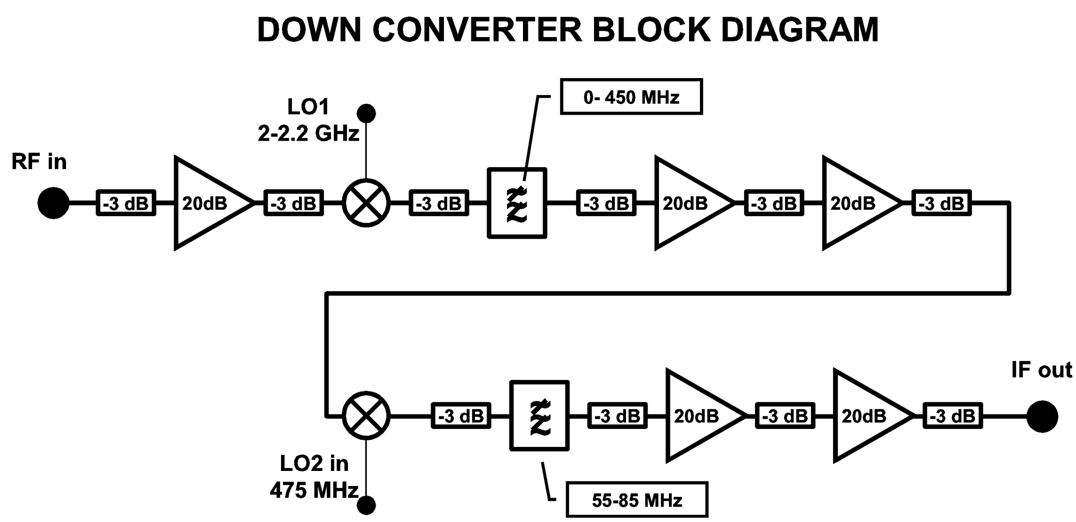

Figure 1. Block diagram of down-converter.

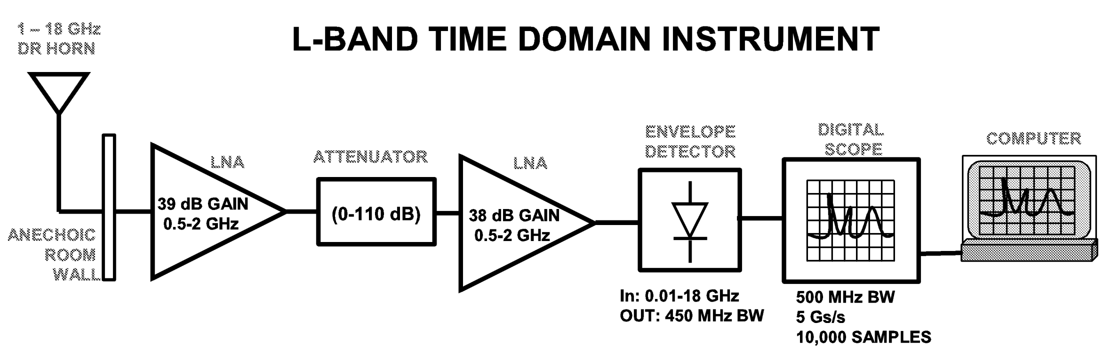

Figure 2. The L band time domain instrument.

III. Temporal Characteristics

Several sets of exploratory measurements were made to discover characteristics of the strong radiation in the L band. In one set, zero span spectrum analyzer data of duration 50 and 100 ms were acquired at 1645 MHz with RBWs of 3 MHz, 1 MHz, 300 kHz, and 100 kHz. With the exception of the 3 MHz RBW trace, the number of pulses recorded was not great enough to allow statistical analysis. The background noise in these data decreased about 10 dB per decade decrease in RBW, as would be expected for incoherent noise. However, the peak pulses decreased 15–20 dB per decade decrease in RBW, indicating that the emission is largely coherent, as would be expected for pulsed radiation with a spectral width greater than 3 MHz.

In another set of measurements the TDI was configured in parallel with SA1. The DSO was connected to display both the TDI output and the SA1 video out. Data were taken with the antenna in position 2 to verify correlation between pulses in TDI and SA1 set at a center frequency 1.6 GHz and a 3MHz RBW (zero span). Using this setup it was observed that: every pulse in the 3 MHz channel had a corresponding TD instrument pulse; many TDI pulses had no corresponding pulse in the 3 MHz RBW channel; and the level of the TDI pulse was not correlated to the level in the 3 MHz RBW channel pulse. These results are consistent with pulses occurring at random frequencies in the 0.5–2 GHz band of the TDI and therefore not always "significant" in the 1600 ± 1.5 MHz spectral region of the HP. The pulse width on the TDI output ranged from a few 10 ns to more than 100 ns. Using the trigger level, real-time observations found no clear correlation between pulse amplitude and pulse duration.

Subsequently, time domain measurements were taken with the signal from the antenna in position 2 evenly split between the TDI and a 25 dB gain LNA connected to the input of the DCv. The output of both instruments was sent to separate channels on the DSO, which was triggered on the TDI. A group of four pulses from the DCv is shown in Fig. 3. These traces are viewed on a linear (volts) scale to observe their temporal shape through the 30 MHz band pass of the DCv instrument. A set of six single pulses from the TDI pulses converted to dBμV/m is presented in Fig. 4. These six pulses display a variety of pulse shapes and durations.

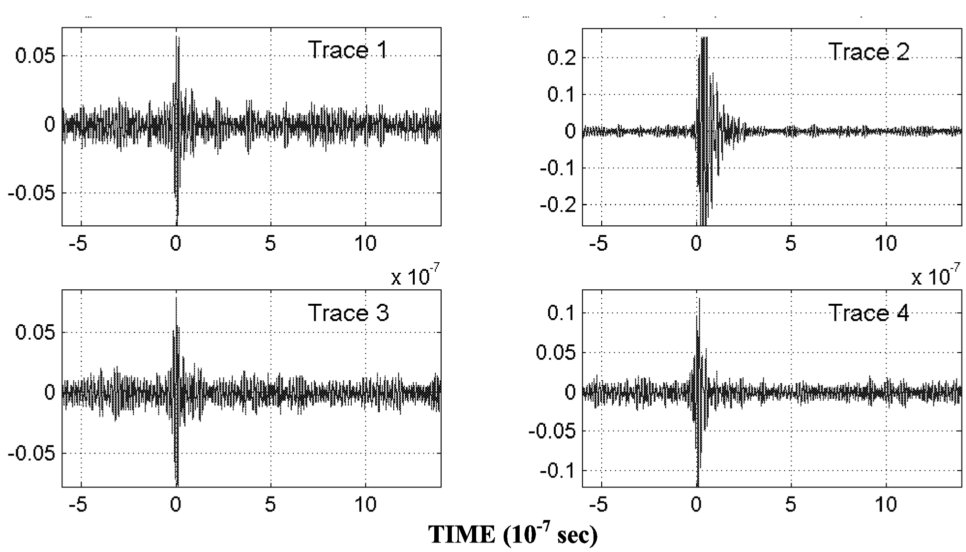

Figure 3. Four 2-μs segments of single pulse DCv data from SN10. Vertical axis is amplitude in volts.

TIME (10^{-7} sec)

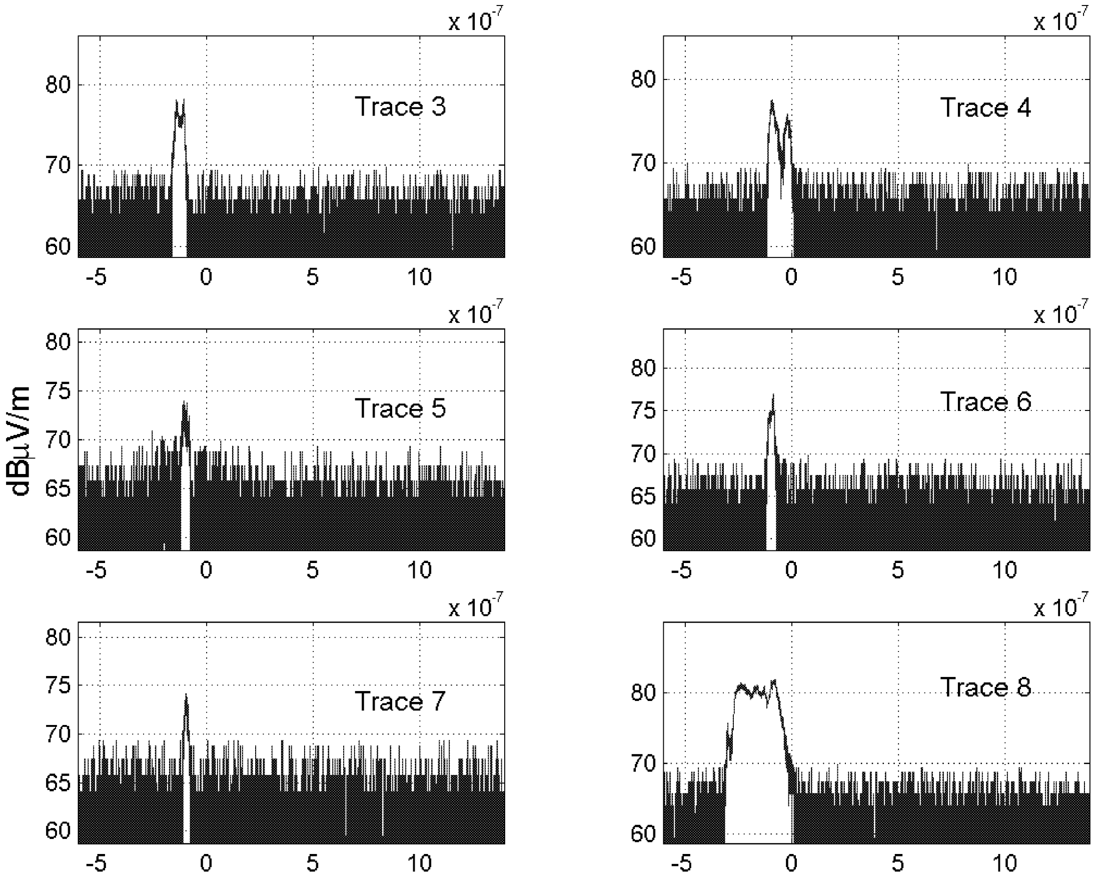

Figure 4 Six 2-µs segments of single pulse TDI data from SN10. Vertical axis is Electric field.

The pulse rate of the thruster emission as a function of amplitude was measured by putting the output of the TDI into an analog oscilloscope and setting the trigger level to select the pulse amplitude. The sweep gate-out of the oscilloscope was sent to a pulse rate-meter. The average rate of pulses higher than the trigger level could then be measured. The results are shown in Fig. 5 where the trigger level is converted to electric field sensed at position 2 for both the TDI and DCv. The pulse repetition rate decreases exponentially with pulse magnitude expressed in dB. Note that the pulse rate from the TDI is approximately 50 times that of the DCv at small amplitudes where the Gaussian instrument noise dominates—as would be expected because the bandwidth of the TDI is approximately 50 times that of the DCv. However, for amplitudes where thruster emission dominates, the DCV pulse rate (14 Hz) is approximately half that of the TDI (26 Hz). This is likely a result of the pulse bandwidth being greater than the 30 MHz bandwidth of the DCv

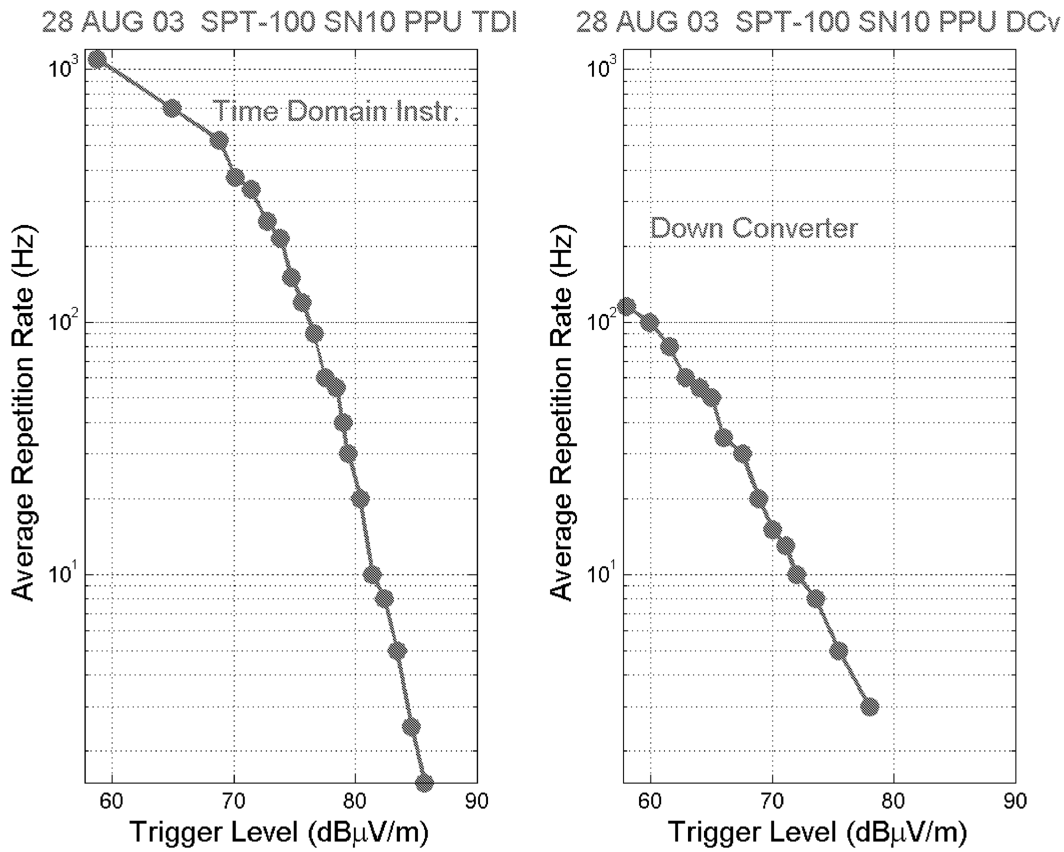

Figure 5. Pulse rate verses trigger level for pulses viewed from position 2 for the TDI and DCv.

The TDI could be used to generate data sets with enough pulses to allow statistical analysis of the pulse heights. Figure 6 shows a statistical analysis of the pulse magnitudes of 2 seconds of data observed from position 2 of SN90 (the thruster with only 30 hrs of accumulated operation time). The upper plot in this figure is the distribution of the pulse amplitudes, whereas the lower plot is the cumulative sum of all amplitudes above the amplitude indicated on the abscissa. Note that both ordinates in these plots are logarithmic. For this type of data one would expect the distribution to be a skewed Gaussian: the low amplitude being a Gaussian distribution of the thermal noise of the receiver and the high amplitude tail of the distribution the pulse emission from the thruster. In these data, the low amplitude distribution will appear skewed because all voltage values from the oscilloscope that were lower than the lowest calibrated amplitude were set to the lowest calibrated value. All pulses greater than the highest calibrated value were set to the highest value. Additionally, the TDI was calibrated at its maximum gain frequency, close to 1.5 GHz. For a pulse occurring at a different frequency, the TDI gain is lower and the signal level is underestimated as the assumed gain is higher than the actual gain. The pulses were converted to logarithmic field strengths by interpolating between the measured calibration points.

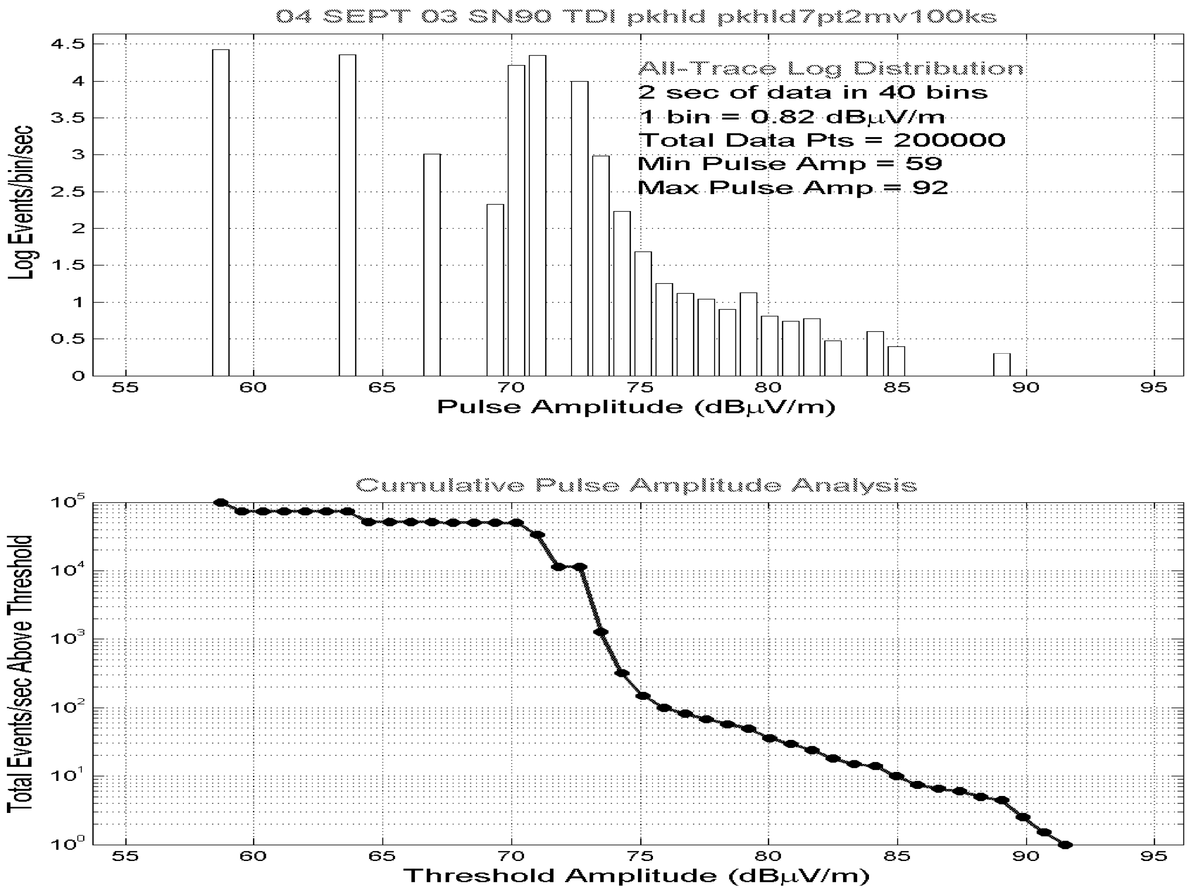

Figure 6. Pulse amplitude analysis of 2 seconds of TDI data from SN90.

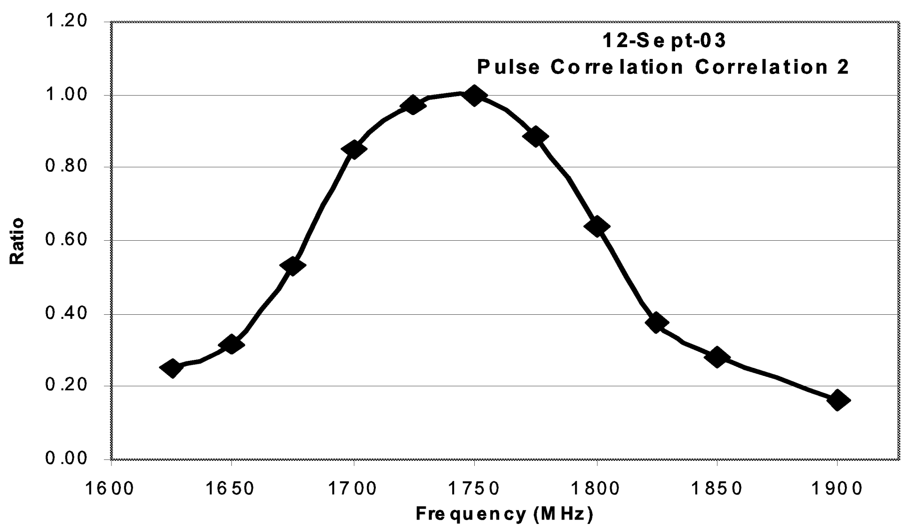

Figure 7. Pulse correlation analysis at 1750 MHz from SN09.

A pulse correlation instrument was configured to determine the spectral width of the pulses emitted near 1600 MHz. This configuration equally split the output from the antenna between two spectrum analyzers (see Fig. 10 in the Appendix). One analyzer frequency was fixed at 1750 MHz, whereas the second analyzer changed frequency in 25-MHz steps (RBWs = 3 MHz). The video outputs of the analyzers were sent to the two channels of the DSO and the fraction of pulses appearing in both channels were recorded at each frequency. When both analyzers were at the same frequency the correlation was 100 percent for a ratio of 1.0. An example of these data is shown in Fig. 7. This and similar measurements indicate the spectral width of the pulses at 1750 MHz (at the 50 percent correlation level) is about 150 MHz. This corresponds to an average pulse width of about 65 ns, which is consistent with the traces seen in Fig. 3.

The statistical and bandwidth data in Figs. 5 and 6 are useful for determining the worst-case effect of Hall thruster emission on the bit error rate (BER) of a satellite receiver. If an L band receiver channel has a bandwidth narrower than the 150 MHz, then a fraction (= receiver bandwidth/150 MHz) pulse rates shown in Fig. 6 will be register in that channel. This is approximate because the pulse can be anywhere in the 450 MHz bandpass of the TDI. If the receiver channels are in the S or C bands, other rates will apply but can be estimated from the relative strength of the emission seen the 1 – 10 GHz spectra (see Ref. 1). Similarly, thruster age and conditions will play a role in modifying the pulse rates and amplitudes. The definitive method is to measure the BER caused by the thruster emission through the exact receiver channel.

VI. Transient Characteristics

Startup transients were studied for the thrusters at six frequencies using a spectrum analyzer in zero span mode. Fig. 8 shows typical 100-second time traces for SN09 for the two highest frequencies. The emission decreases with increasing frequency for the six frequencies studied. For SN09, the initial transient is comparable to that of SN10, but the emission decreases within a few seconds to a value near 40 dBμV/m.

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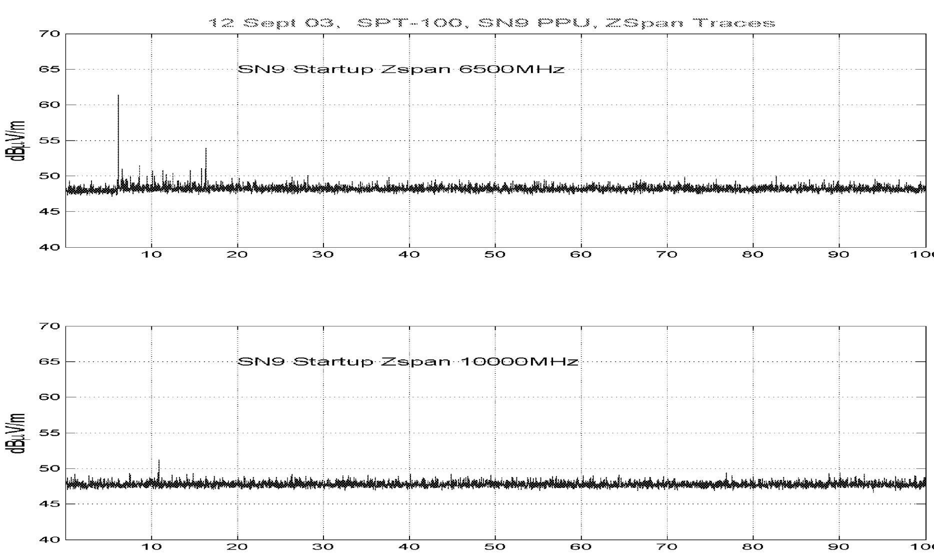

Figure 8. Two 100-second startup zero span traces at 6500 and 10000 MHz.

V. Conclusion

This paper presented a subset of the data acquired in the study of four SPT-100 thrusters of differing ages. In general the study indicates that the radiation in the L, S, and C bands from the SPT-100 Hall thruster is primarily pulsed with pulse lengths from a few tens of nanoseconds to several hundreds of nanoseconds. There is no apparent correlation between pulse amplitude and pulse duration. A small percentage (< 5 percent) of the pulses occur in pairs. The pulse rate decreases exponentially with increasing pulse amplitude. The time-averaged studies of the L band radiation measure a bandwidth of approximately 150 MHz. Such characterization was used by EADS Astrium and their customers to estimate the perturbation of signal on the payload receiver, subsequently proved robust through the in-orbit test.

The pulses can have intensities as high as 90 dBμV/m, however, instruments with band widths less than 150 MHz will register maxima less that this value; these instruments sample only a portion of the radiation and that portion will likely be not centered on the center frequency of the pulse. There is evidence that rate of these pulses increases with total accumulated operating time of the thruster. However, it is not possible from this study to discern the role that contamination plays in this increased rate. That is, measurements were not taken periodically with a single thruster as it accumulated operating time but with a series of four thrusters that had operated in a variety of facilities with different background (contaminating) fields. None of these environments approached the relatively pristine vacuum of space.

When this study was made, only one investigation had addressed this 1 – 8 GHz radiation.[2] That investigation found a significant increase in emission with increasing thruster age and identified this emission with anomalous erosion of the wall of channel insulator. Subsequently, two more studies have been published. The first considered the effects of this radiation on satellite transponders[3] and the second presents a more convincing case for identifying the source of this radiation with the cathode.[4] The data taken on the four SPT-100 thrusters during this campaign is consistent the conclusion that the origin of the radiation is the cathode. Studies of emissions the Hall thruster cathodes are planned to investigate this topic further.

Appendix
Instrument Configurations

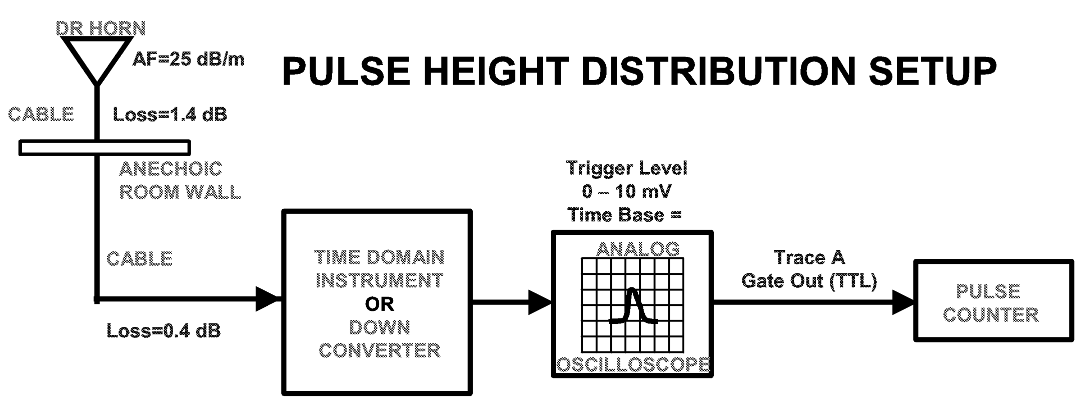

Figure 8. Pulse height distribution using the TDI or DCv.

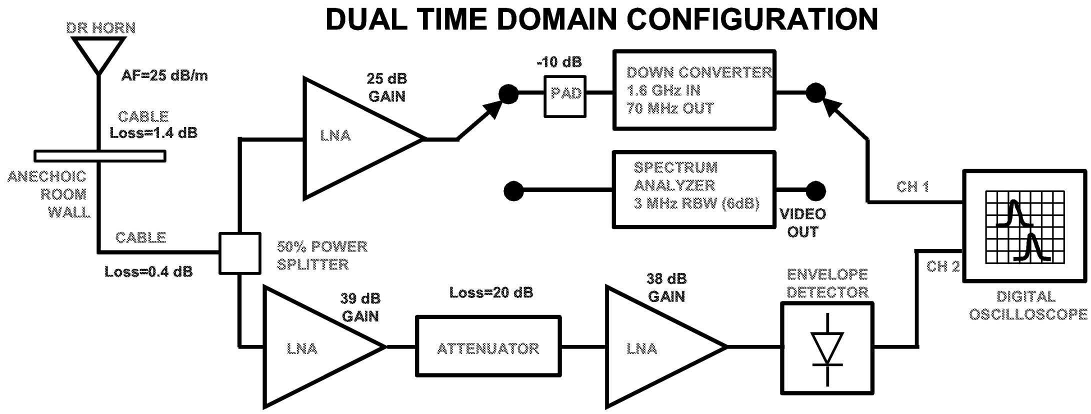

Figure 9. Dual TDI and DCv/SA1 measurements.

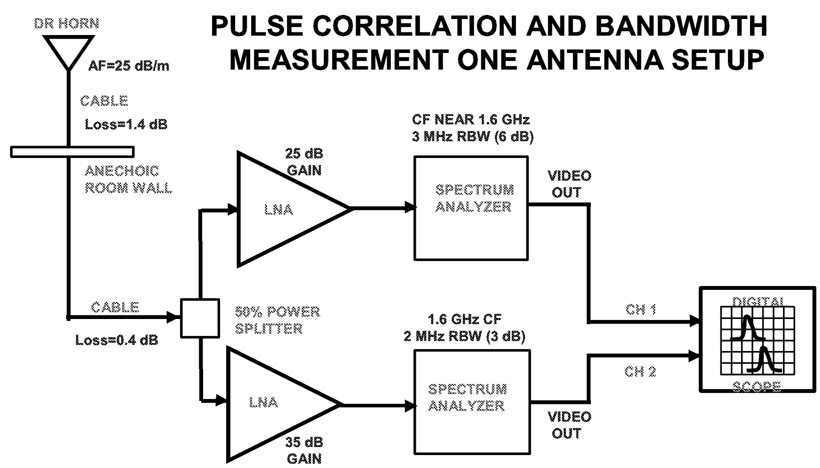

Figure 10. Pulse height distribution.using the TDI or DCv.

References

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