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Summary of Experiments Performed to Investigate the Effects of Ion Thruster Plumes on Microwave Propagation

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SUMMARY OF EXPERIMENTS PERFORMED TO INVESTIGATE THE EFFECTS OF ION THRUSTER PLUMES ON MICROWAVE PROPAGATION

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ABSTRACT

Electric propulsion systems have now reached a level of maturity where they are being used on operational spacecraft. One concern for the designers however, is the effect of the ion exhaust plumes produced by the systems, on microwave communication with the spacecraft. To better understand these effects, a number of propagation experiments were performed at the NASA Glenn Research Center with an operating ion thruster. This report describes the experiments and presents the results of the data obtained.

INTRODUCTION

Electric thrusters are being considered for a variety of space missions because of the significant propellant savings that result from the use of high performance, electric propulsion technologies. The impact of electric thruster plasma plumes on microwave propagation is an important integration concern for planners of this generation of spacecraft. Arcjets were the first electric thrusters to be considered for operational missions. Ling, et al. [1], studied the effect of arcjet plumes on propagation. Arcjets produce a lightly ionized plume and Ling's analysis predicted that the plume would have a negligible effect on communication. Arcjets are now operational on the AT&T Telstar 401 satellite, and the analysis has been validated by in-space operations.

Plumes from the higher performance ion thrusters being developed exhibit higher ionization levels, plasma temperatures and particle velocities than arcjets. Therefore, there was a need to determine the effects of these plumes. To address this need, the authors designed and performed a series of experiments to examine attenuation and phase changes of an electromagnetic wave as it passes through the plume of an ion thruster.

The challenge with these experiments was that they had to be performed in the operational environment of the thruster. The thruster operates in a vacuum and therefore these experiments had to take place in, a metal vacuum chamber capable of maintaining the low-pressure conditions of space. The metal chamber, however, presents a potential large source of error to the propagation measurements due to the corruption of the desired data from multiple reflections within the chamber.

The effect of the chamber was minimized by a pulsed, continuous wave electromagnetic transmitter and receiver [2]. This system, based on an HP8510 Network Analyzer, uses external hardware time gating to eliminate the clutter of the spurious reflections. Additionally, high gain antennas were used in the measurements to ensure that minimal amounts of energy were transmitted/received in undesirable directions. A schematic of a basic test is shown in Figure 1.

The measurements took place in Vacuum Facility 5 of the Electric Power Laboratory at the NASA Lewis Research Center. This facility utilizes a cylindrical, stainless steel, vacuum chamber, which is 18.3 m long and 4.6 m in diameter. A description of the features of the facility can be found at http://www.grc.nasa.gov/WWW/EPL/vf5.htm. For the tests being described here a 30 cm diameter, xenon ion thruster was used. The thruster provided between 500 W and 2.3 kW of operating power. The thrust provided by the ion engine increases with increasing power level thereby increasing the electron density of the plume. The thruster was mounted axially in the chamber near one of the ends as shown in Figure 1.

Three separate test configurations were used. Each corresponded to a different placement of the transmit and receive antennas with respect to the plume. These configurations were a direct path measurement through the plume, a slant path measurement through the plume and a linear probe measurement along the axis of the plume. A description of each measurement follows along with a discussion of the results.

DIRECT PATH MEASUREMENT

In the direct path measurement, two pairs of broadband horn antennas were mounted inside the vacuum chamber, near the side walls, such that a signal could be transmitted through the plume and received. The horns were mounted such that the direction of propagation was normal to the axis of the plume. One pair of horns operated from 6.5 GHz to 12 GHz. The second pair operated from 12 GHz to 18 GHz. Each of the transmit and receive horn pair were separated by approximately 4 m, with the centerline of the plume approximately halfway between them. The low band and the high band horns were mounted next to each other, so that at both bands, the test was taken looking through the same cross section of the plume. A photograph of this arrangement may be viewed at http://www.grc.nasa.gov/WWW/EPL/experime.htm.

The density of the plasma is a function of the downstream distance of the plume from the plume exit plane and the thruster operating power level [3], [4], [5]. These provide the independent variables for the tests. Since the antennas were fixed in position, the thruster was mounted on a stand that allowed it to be moved axially. This provided for continuous movement of the thruster, albeit manually, but measurements were only taken at three distances: 0.5 m 1.0m and 1.5 m. At each location, four operating points were used: 0.5 kW, 1.0 kW, 1.5 kW, and 2.3 kW. The horns were oriented for vertical polarization.

Measurements were taken over the respective frequency bands in 8 MHz intervals. At every frequency, 64 measurements were taken and averaged to minimize random errors within the measurement system. A single measurement across a frequency band involved 92,000 pulses to be transmitted and received and took approximately 2 minutes to complete. A pair of measurements was taken for each thruster power level. First a reference level was established by taking a measurement with the thruster off. A second measurement was taken while the thruster was being operated at the desired test conditions. The amplitude and phase of the received signal was recorded as a function of frequency and compared to its value at the thruster off condition.

Figure 2 shows the attenuation and phase shift from 6.5 GHz to 12 GHz band, for the various power levels, at 0.5 m from the exit plane. Although the attenuation effects are very small, it can be seen that the trend is decreasing attenuation with increasing frequency. In addition, attenuation increases as the operating power increases. The amount of phase shift decreases with increasing frequency for a given power level. As a function of power, the phase shift increases with increasing power. This is the anticipated behavior since it is known that the electron number density of the plume increases with thruster power. Figure 3 and Figure 4 show the measured results for the 1.0 m and 1.5 m position. Here it can be noticed that at further distances the same effects are observed, but to a lesser extent. Again, this is the anticipated result because the electron number density decreases as a function of distance from the origin of the plume.

Figures 5, 6, and 7 show the results for the 12 GHz to 18 GHz band. Here it appears that the attenuation is so small that it cannot be measured accurately. Equipment limitations, including a 12 m length of semi-rigid cable between the synthesizer and the transmit horn, were probably a factor at these frequencies. The phase shift shows the same trends seen at the lower band with the phase shift continuing to decrease with increasing frequency, at a given power level.

A preliminary set of similar measurements [6], [7], found the same behavior for propagation through the plume. This indicates that the measurement system is repeatable since the tests being reported here were taken 15 months after the earlier ones. In conclusion, these attenuation and phase shift characteristics can be considered typical for the plume of an ion thruster.

SLANT PATH MEASUREMENT

The slant path measurement was designed to obtain a longer path length through the volume of the plume. This was achieved by configuring the antennas as shown in Figure 8. The transmit antennas were placed near the exit plane of the plume but in a position so as not to interfere with the plume. The angle of the receive antennas was modified so that the boresights were directed at the transmit horns. The distance between the exit plane and the point were the propagation path intersects the plume axis was established to be 1.5 m. The measurement procedure was the same as that described for the direct path measurement.

The results of these measurements are shown in Figure 9. Comparing this data to the 1.5 m data of the direct path measurement show that at the lower band, slightly more attenuation is experienced. The higher band data was noisy, as in the direct path measurement, but it can be concluded that the attenuation was not significant. The phase shift curves show the same shape as seen in the direct path measurements, however the magnitude is noticeably higher. Thus, this measurement verifies that the effects of the plume depend on path length through the plume as well as the density of the plume.

LINEAR PROBE MEASUREMENT

The previous measurements had demonstrated two important characteristics. The first was, for a given frequency and operating power, the major effect was a shift in phase of the signal. The second was that the magnitude of the phase shift was dependent on the portion of the plume through which the signal traveled. Thus, a large antenna, which has the plume in the near field, would experience a non-constant phase shift across the aperture due to the plume. This near field phase distortion could be detrimental to the far field performance of the antenna. For example, if the plume produced a linear phase shift across the aperture, there would be a pointing error in the far field of the antenna. This effect was demonstrated analytically by Ling [1] for an arcjet thruster by using a cold plasma model and ray tracing. Therefore, the goal of the linear probe measurement was to see if this effect could be measured using the ion thruster. To accomplish this objective, a near field measurement of an electrically larger antenna needed to be performed in the vacuum chamber.

For these measurements, the configuration of Figure 1 was used. The transmit antenna was an offset fed parabolic reflector with a nominal 55 cm diameter. It was fed by a 4 x 4 microstrip patch array antenna having a center frequency of 9.67 GHz. The receive antenna was a wide beam, broadband horn which was mounted to a linear translator. This horn was used because it was smaller and lighter than the narrow beam, broad band horns used previously and thus could be accommodated easily by the translator. The translator was oriented to be parallel with the axis of the plume and the height was set to measure along the horizontal centerline of the reflector. The center of the reflector antenna aperture and the center of the translator were set to be 1.0 m from the exit plane of the plume. The axis of the plume was 1.8 m from the transmit antenna and 1.7 m from the probe antenna thus making this a near field measurement. The antennas were oriented for vertical polarization.

After the thruster was operating at a set power level, the horizontal centerline of the reflector was probed. The total scan distance was 30 inches with 15 inches being the center of the aperture. Measurements were taken at 0.5 inch increments. At the center frequency of 9.67 GHz, 64 measurements were taken at each point and averaged.

Figure 10 is the baseline data for the measurements. These plots were produced by taking two measurements with the thruster off and comparing one to the other. They give an indication of the type of accuracy and repeatability that can be expected of the subsequent measurements. Ideally, these plots would show a flat line at zero. However, since the receive antenna is now moving and thus pulling a cable, some error exists. This error is in addition to the stability over time of the measuring equipment.

Figure 11 through Figure 16 show the results for the following power levels: 0.54 kW, 1.0 kW, 1.37 kW, 1.7 kW, 2.08 kW and 2.3 kW. In general, no tapering in the phase shift can be seen at any power level. Although the attenuation and phase shift fluctuate, both effects appear to be insignificant. Therefore, one can conclude that the ion plume would not introduce any distortion in the far field of the reflector.
Only one set of measurements could be taken for this configuration. After measurements presented above were taken, the linear translator failed. This was apparently due to an inability of the translator to operate in a vacuum through many cycles. Therefore, the repeatability of the measurement could not be verified.

CONCLUSION

The measurements summarized in this report show that the plume of an ion thruster does have an effect on microwave propagation. The primary effect is a change in the phase of the signal that passes through it. Even in the worst cases tested, this change of phase is very small and most likely will not have a detrimental effect on communications with a spacecraft that utilizes ion thrusters. The plume also causes attenuation of the signal but the levels are such that it is insignificant. The near field scan of the reflector antenna indicates that the plume would not distort the far field pattern of the antenna under the conditions tested.

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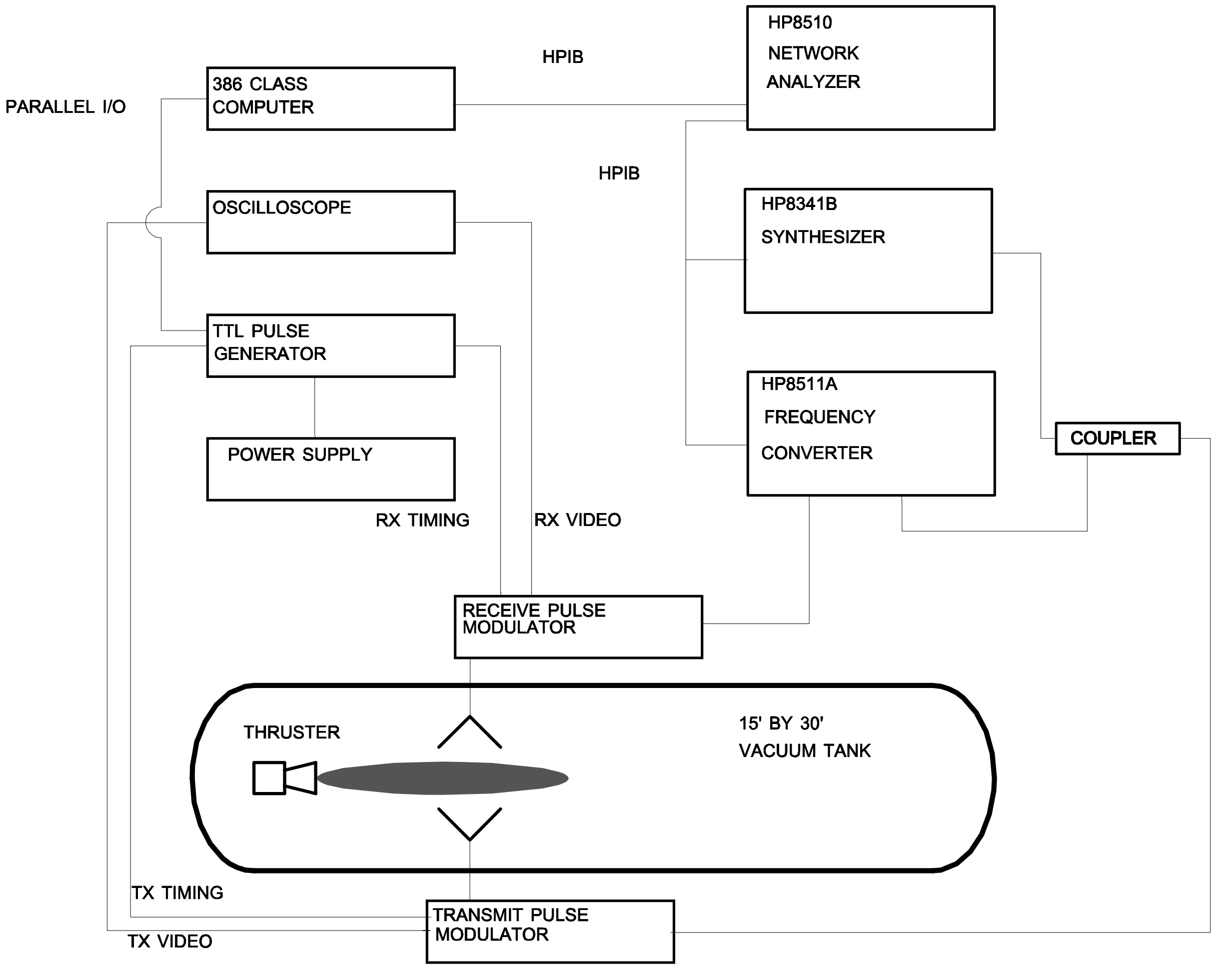

FIGURE 1. EQUIPMENT CONFIGURATION FOR THE MEASUREMENTS

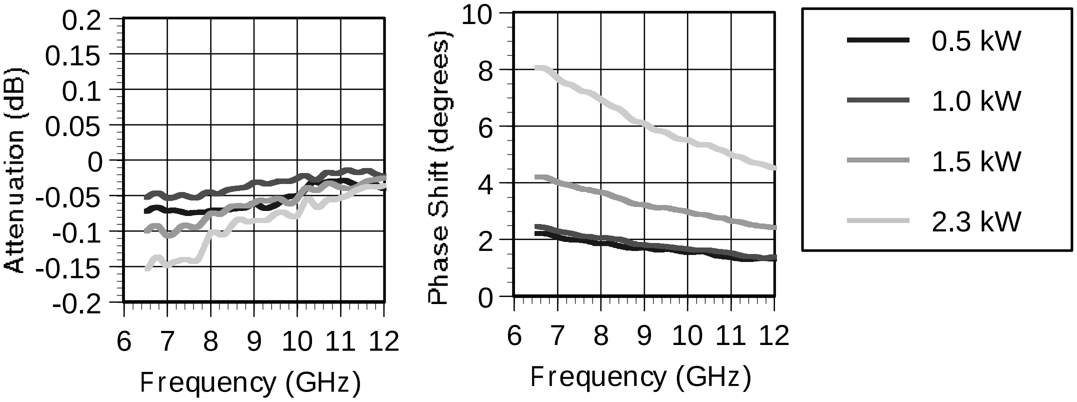

Figure 2. Signal attenuation and phase shift at 0.5 meter from the exit plane.

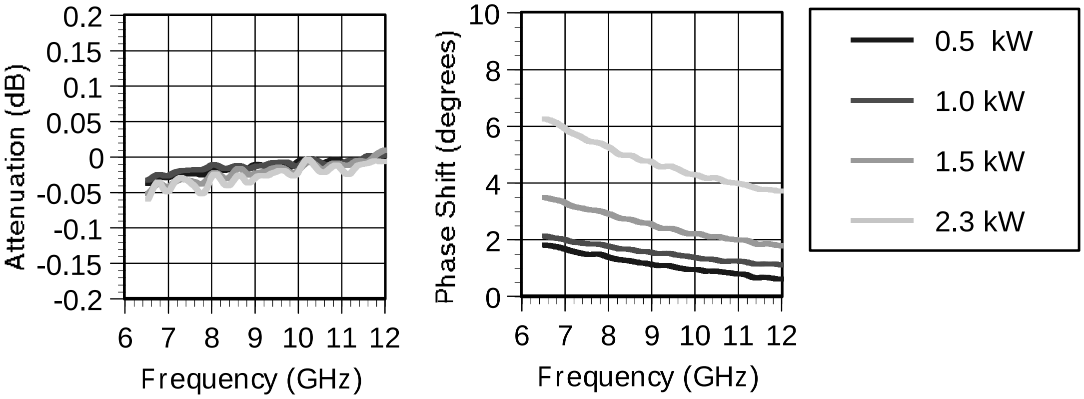

Figure 3. Signal attenuation and phase shift at 1.0 meter from the exit plane.

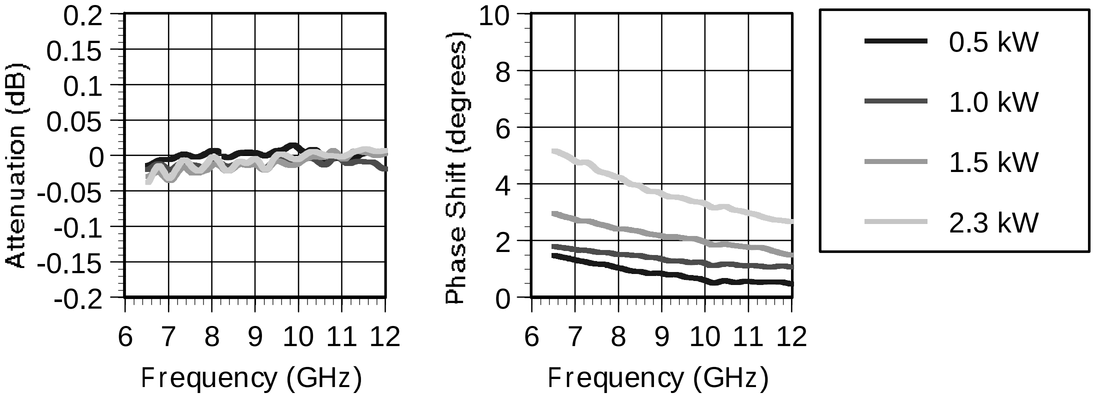

Figure 4. Signal attenuation and phase shift at 1.5 meter from the exit plane.

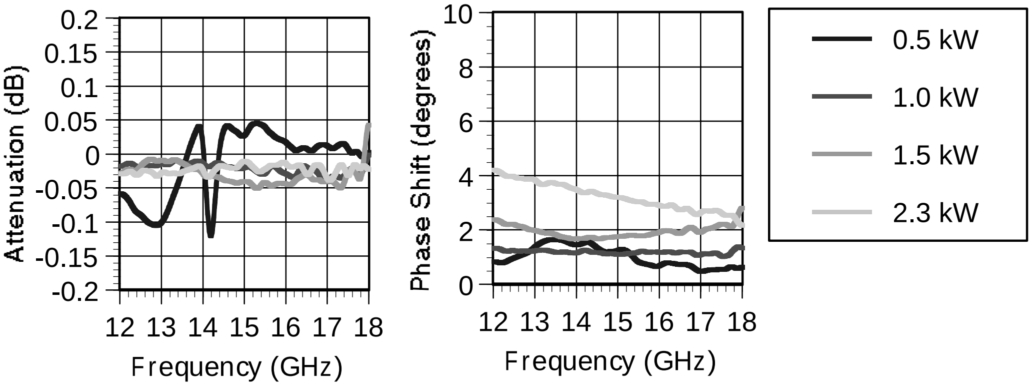

Figure 5. Signal attenuation and phase shift at 0.5 meter from the exit plane.

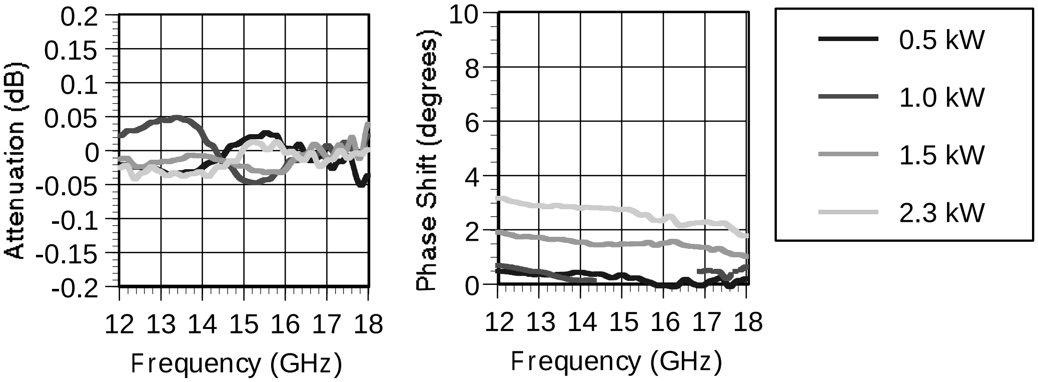

Figure 6. Signal attenuation and phase shift at 1.0 meter from the exit plane.

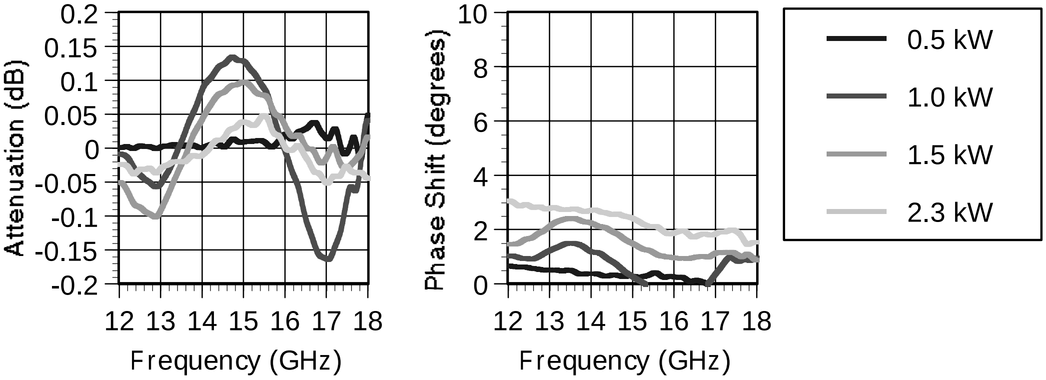

Figure 7. Signal attenuation and phase shift at1.5 meter from the exit plane.

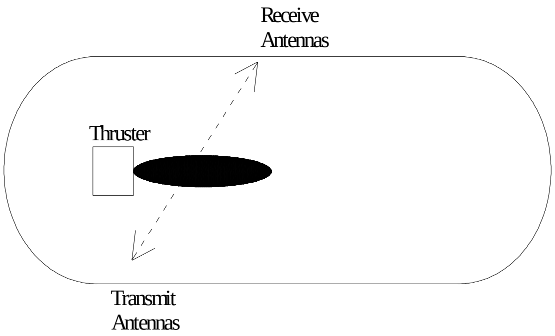

Figure 8. Chamber configuration for the slant path measurements.

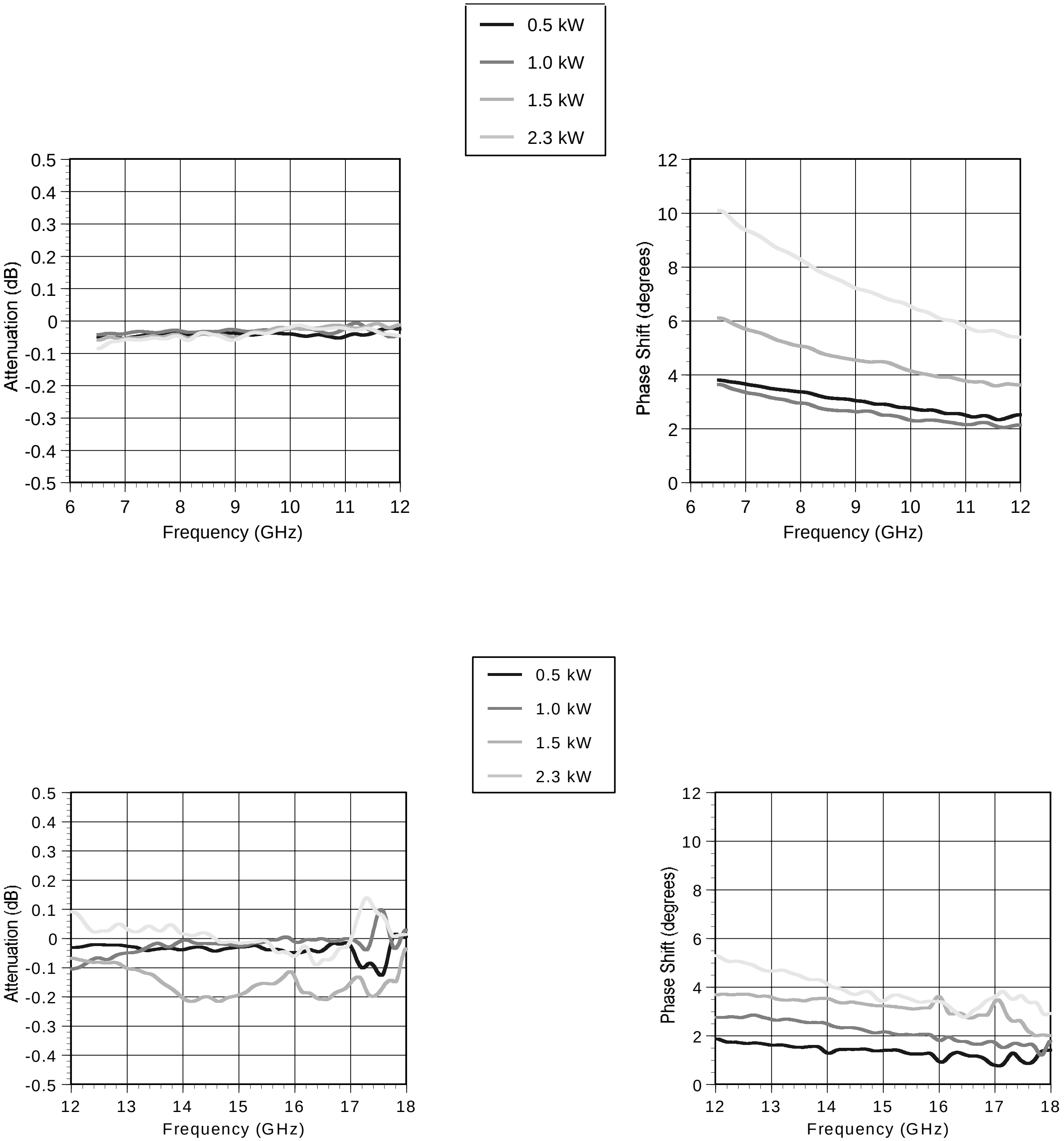

Figure 9. Attenuation and phase shift measurements taken with the direction of propagation along the slant path through the plume.

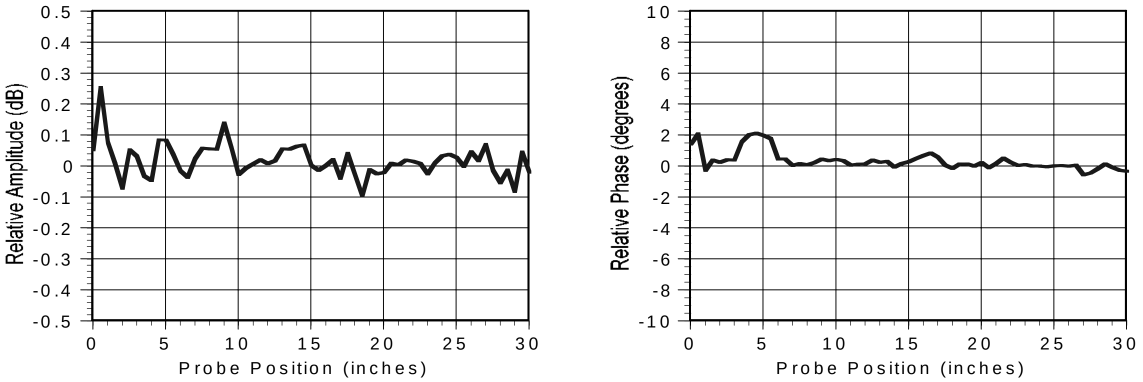

Figure 10. Attenuation and phase shift as a function of axial position for the thruster at 0kW.

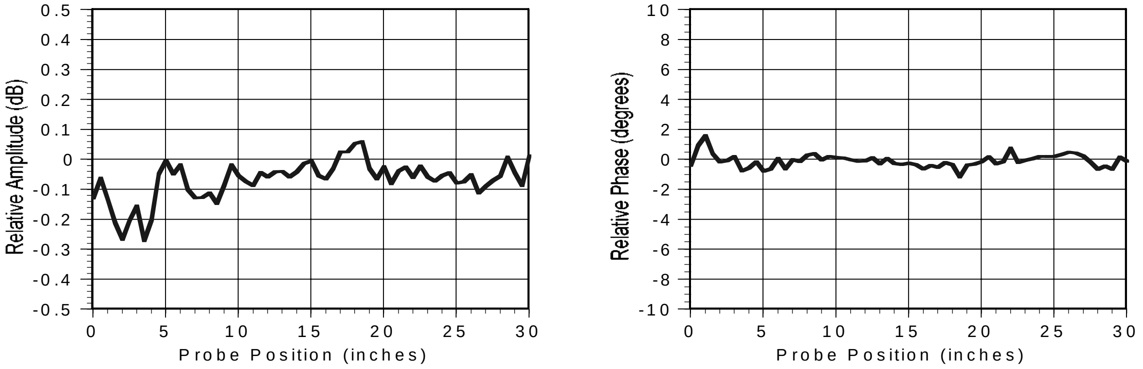

Figure 11. Attenuation and phase shift as a function of axial position for the thruster at 0.54 kW.

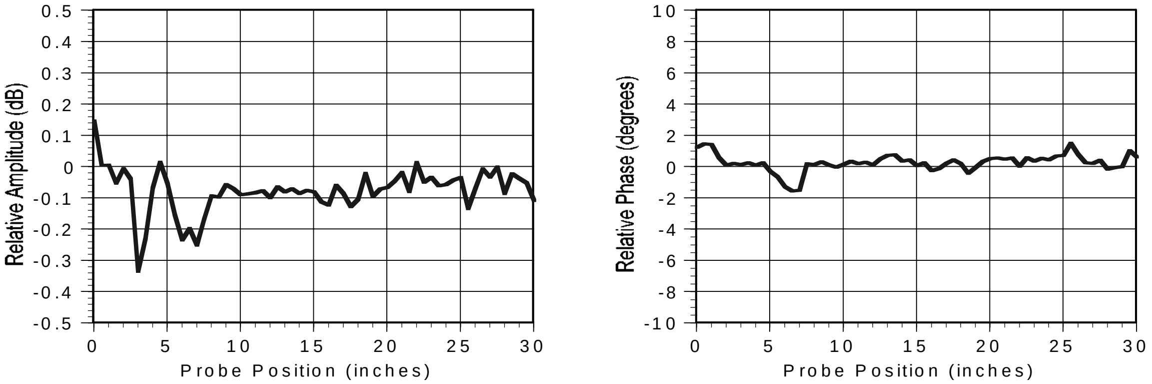

Figure 12. Attenuation and phase shift as a function of axial position for the thruster at 1.0 kW.

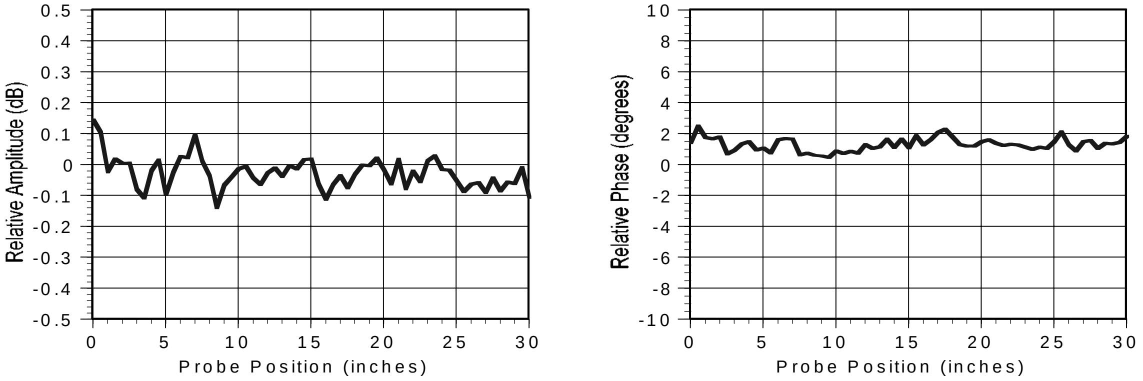

Figure 13. Attenuation and phase shift as a function of axial position for the thruster at 1.37 kW.

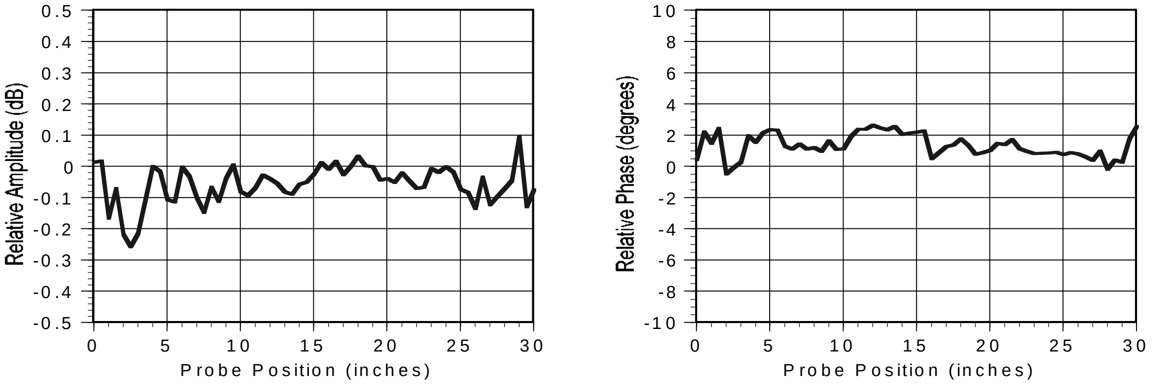

Figure 14. Attenuation and phase shift as a function of axial position for the thruster at 1.7 kW.

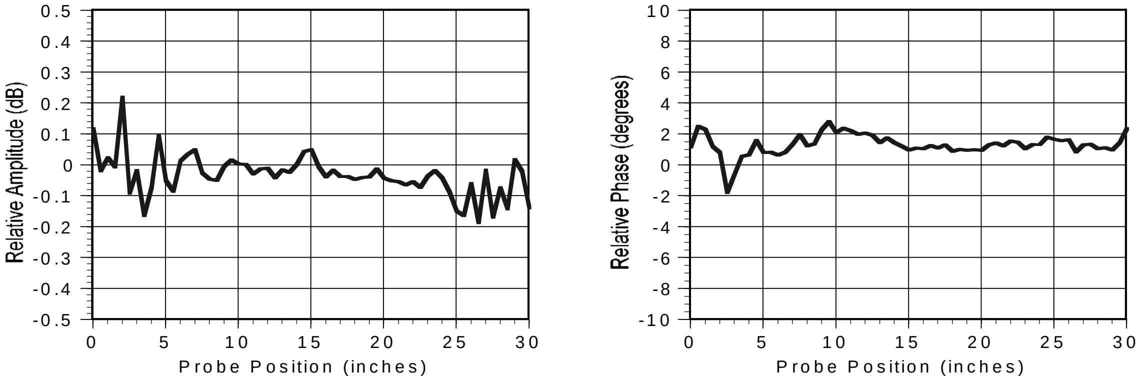

Figure 15. Attenuation and phase shift as a function of axial position for the thruster at 2.08 kW.

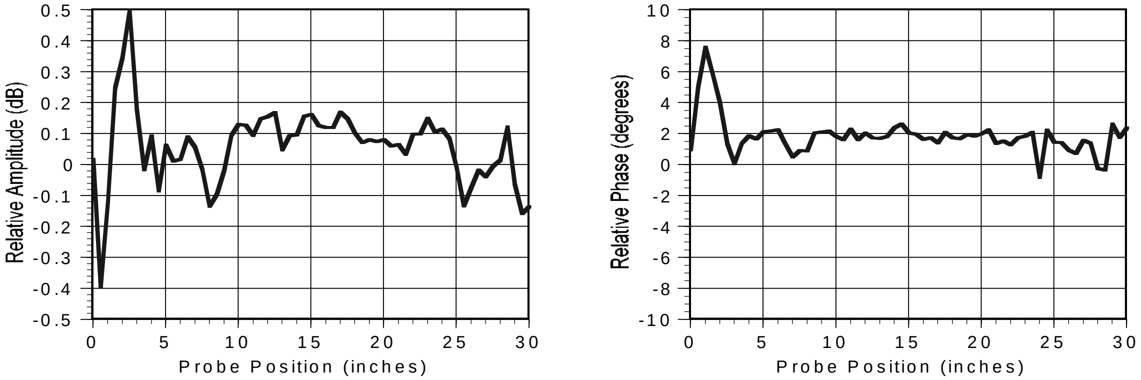

Figure 16. Attenuation and phase shift as a function of axial position for the thruster at 2.3 kW.

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