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Communication through Hypersonic or Re-Entry Plasmas

Christopher N. Davis[1] and Peter Y. Peterson[2]
ElectroDynamic Applications, Inc., Ann Arbor, MI 48105

Sven G. Bilén[3]
The Pennsylvania State University, University Park, PA 16802

Plasma generated around a vehicle traveling at hypersonic velocities can be a significant impediment to fixed-frequency communications, particularly for GPS navigation signal reception. Under two complementary U.S. Air Force Phase II SBIR programs, we have been developing technology for improving communication through plasmas. ReComm (ReEntry and Hypersonic Vehicle Plasma Communication System) creates a physical communication window utilizing plasma density reduction and HyPASS (Hypersonic Plasma Adaptive Sensor System) improves the communication channel through that window by implementing an antenna matching system. The HyPASS system uses two diagnostic probes attached to frequency-adaptive vector network analyzer hardware to measure plasma parameters, and can use these parameters to adjust a matchbox, reducing the reflection at the signal antenna due to the plasma mismatch. The system also provides real-time information about local plasma parameters. When used in concert, ReComm and HyPASS are expected to provide a 25 dB or more increase in signal reception, thus enabling more bandwidth and broader communication envelopes for hypersonic vehicles.

I. Introduction

When a vehicle travels at hypersonic velocity through the atmosphere, the kinetic energy of the molecules striking the surface creates a thermal and inertial shockwave that envelopes the craft. If the thermal shock layer becomes sufficiently energetic, the impinging atmosphere will ionize and dissociate, which creates a plasma sheath at the surface of craft as illustrated in Figure 1. In this condition, communication below a certain electron-density-dependant frequency will be impossible due to the ability of the sheath electrons to move quickly enough to dissipate any incident radiation, regardless as to whether this radiation is incoming or outgoing. This is the aptly named the “blackout condition”. Plasma communication technology would be critical for the DoD hypersonic cruise missile program X-51 and follow-on systems [5]. This weapon system will depend on GPS navigation for accurate targeting over long ranges. The successful development of this platform will provide a significant improvement to national security by providing a prompt global strike capability. Additionally, our technology could dramatically improve the radio blackout issue during re-entry of space vehicles. Communication loss during re-entry introduces significant problems related to the vehicle’s safety including the possibility of catastrophe analysis, mission success, vehicle tracking, and electronic countermeasures. While our focus currently is at GPS frequencies, this technology could be applied to other frequencies of interest as well.

[1] Senior Engineer, davis@edapplications.com
[2] Director of Research, peterson@edapplications.com
[3] Associate Professor, sbilen@psu.edu, also affiliated with ElectroDynamic Applications, Inc.

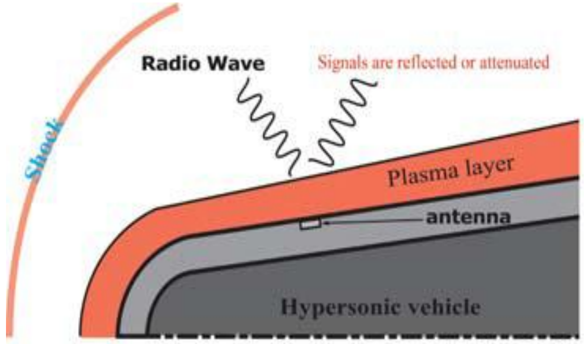

Figure 1. Illustration of the plasma sheath

This paper describes the progress to date of two technologies being developed to improve communications through hypersonic plasmas. The following is brief description of each technology.

A. Opening a Communications Window with ReComm (ReEntry and Hypersonic Vehicle Plasma Communication System)

ReComm uses electric and magnetic fields to locally reduce the plasma density around the receive antenna, thereby increasing the strength of signal that is transmitted or received through the communication blackout [1, 2]. This is illustrated in Figure 2. In its most simple configuration, the plasma manipulation system consists of crossed magnetic and electric fields. The method provides two means for lowering the plasma density: (1) the E×B drift and (2) the formation of an electrostatic sheath that is stabilized by the magnetic field.

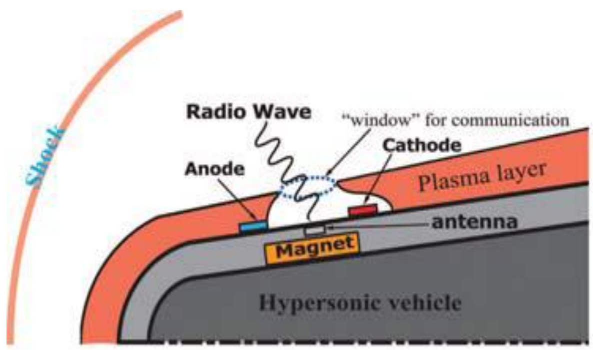

Figure 2. Illustration of the ReComm concept

The E×B drift causes an acceleration of both electrons and ions in a direction normal to the plane of the fields. Thus, if an antenna were placed within the crossed electric and magnetic fields, the general motion of the particles would experience acceleration away from the antenna. This would result in a region of lower density due to conservation of current.

The crossed electric and magnetic fields also create a region of lower number density via the creation of a high-voltage sheath. This sheath depletes electrons from a region surrounding an antenna. The concept relies on the fact that, since ions are much more massive than electrons, magnetic fields have more of an effect on electrons than ions. So, in this case, the electric field accelerates the ions past an antenna, while the magnetic field traps electrons preventing arcs between the electrodes. The acceleration of the ions again results in the lowering of the plasma density due conservation of current.

B. Improving the Communications Window with HyPASS (Hypersonic Plasma Adaptive Sensor System)

While ReComm can effectively decrease the ambient plasma density, the remaining plasma constitutes a significant and varying departure from the free-space impedance environment of typical communication. This impedance mismatch at the antenna causes additional signal degradation. HyPASS uses a combination of plasma sensing and continuously varying antenna matching technology to match as best as possible the antenna impedance to the ambient plasma impedance to maximize signal reception (Figure 3). While HyPASS is designed to optimize reception of low strength incoming signals, the impedance matching simultaneously optimizes the antenna for transmission as well. HyPASS is expected to decrease antenna mismatch losses up to 10 dB of received signal.

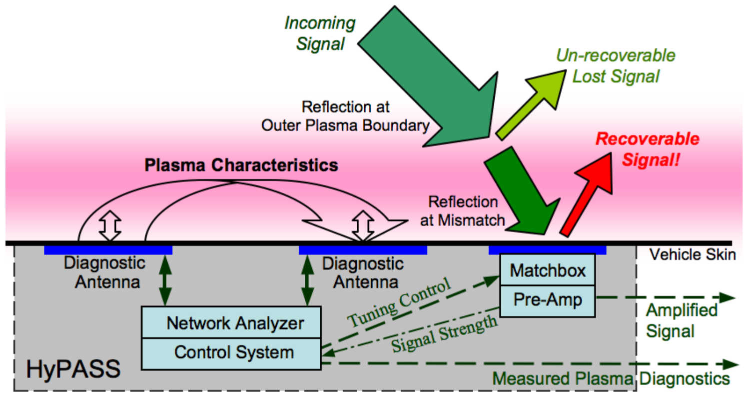

Figure 3. Notional Sketch of HyPASS

The sensors feed data on plasma parameters such as density to a system controlling the antenna's matching circuit, allowing the system to adapt in real-time to local plasma conditions. In addition, real-time density measurements can be used to improve the performance of any other mitigation technique operating simultaneously by allowing that system to tune itself to the changing local conditions throughout the mission profile. When used in concert, ReComm and HyPASS are expected to deliver a 25-dB-or-more improvement in signal losses incurred when communicating through plasma layers generated by hypersonic and re-entry vehicles.

II. ReComm Results Summary

ReComm uses electric and magnetic fields to reduce the plasma density locally around the receive antenna. Figure 4 shows an illustration of the ReComm experimental system layout. As shown in the figure, the far electrode from the plasma source is biased negative and the near electrode is grounded. The electrodes are embedded into a mica sheet mounted on top of the ReComm magnet, which is an electromagnet cable of generating a vertical (*z*-directed) field of 2000 G at the negative electrode.

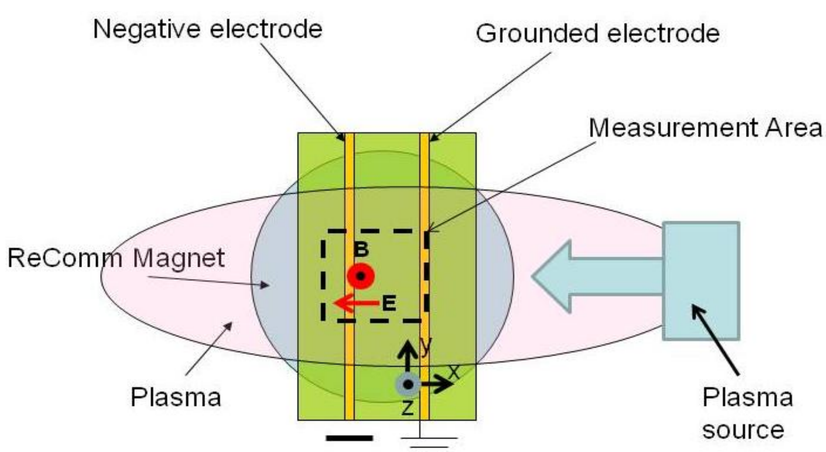

Figure 4. Schematic of ReComm experimental setup

A. Plasma Enviroment

For testing of ReComm, the plasma source used was a 3-kW, 13.56-MHz helicon source capable of creating a ~10^{16} m^{-3} plasma over the electrodes. A helicon source was chosen for its ability to efficiently create a large volume of high density plasma with an electron temperature similar to what is found in hypersonic plasmas [3]. Figure 5 below shows pictures of the helicon source and a view from the top of the ReComm experiment mounted on the vacuum chamber.

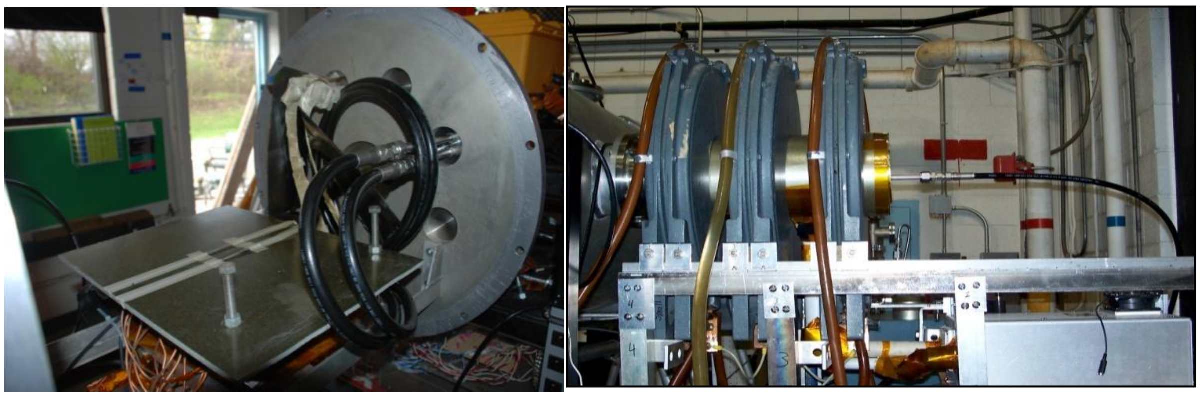

Figure 5. ReComm experimental setup (left) and helicon plasma source (right)

B. Plasma Reduction Measurements

Figure 6 shows a representative measurement of the plasma mitigation area of ReComm taken 50 mm above the electrodes using an RF-compensated Langmuir probe system. The plot is presented in terms of density ratios. The density ratio is defined as $n_r = n_{v,B}/n_0$, where $n_{v,B}$ is the density with ReComm turned on and n_0 is the density with ReComm turned off. The axial position of the plot is referenced to the distance from the exit plane of the helicon source with 0 mm being at the exit plane. The negative electrode is at axial position 390 mm and the grounded electrode is at 350 mm. As can be seen from the plot, the density is reduced by more than 80% from its initial value near the negative electrode in an approximately 10×10 mm area. This corresponds to a reduction in plasma cutoff frequency from 1.3 GHz to 570 MHz.

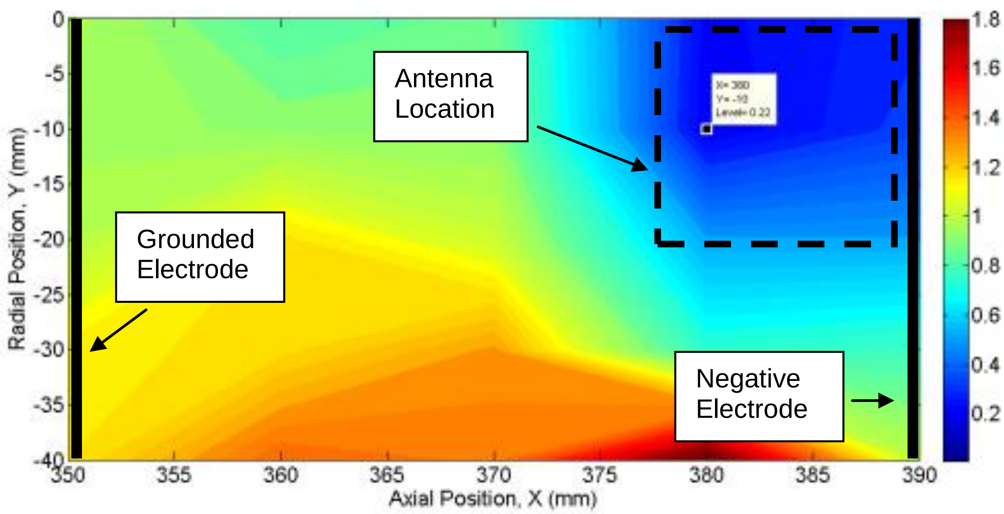

Figure 6. Density ratio at 50mm above the electrodes.

As a confirmation of the Langmuir probe measurements above, hairpin resonance probe measurements were also taken. Figure 7 below shows plasma density measurements taken with a hairpin resonance probe in the plasma mitigation region. A hairpin resonance probe can measure the plasma frequency directly using the relationship [6]

$$f_p^2 = f_{rp}^2 - f_r^2 \, , \tag{1}$$

where f_p is the plasma cutoff frequency, f_{rp} is the resonance frequency of the hairpin probe in the plasma, and f_r is the free-space resonance frequency of the hairpin probe. The probe was scanned between the electrodes (i.e., in the x direction) with the point x = 390 mm on the plot corresponding to the position of the negative electrode.

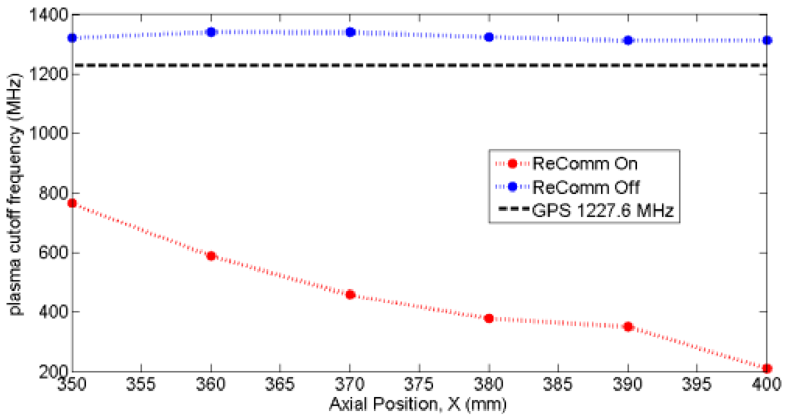

Figure 7. Plasma cutoff-frequency measurements with ReComm

The cutoff frequency is reduced from 1.3 GHz to 200 MHz near the negative electrode. The 1227.6-MHz GPS frequency is provided for reference to demonstrate how the plasma cutoff frequency is lowered below the GPS frequency with ReComm turned on, which means, roughly speaking, the signal would not pass through the plasma without ReComm enabled. The improvement to signal level at the GPS frequency as the plasma density is reduced may be quantified by the expression [7]

$$K = 1.8 \times 10^{-7} \sqrt{80.26 n_e - f_0} \;\; \text{(dB/m)}, \tag{2}$$

which provides the signal attenuation per meter for a given plasma density, n_e, at communication frequency, f_0. Using the plasma density profile for a re-entry vehicle traveling at 7.5 km/s at an altitude of 60 km (n_e = ~5×10^{17} m^{-3} and plasma width ~2.5 cm) [1], Figure 8 shows a plot of Equation (2) as a relationship between density ratio defined earlier (n_r) and signal attenuation at 1.227 GHz. As can be seen in the plot, reducing the density ratio to 0.2 (i.e., an 80% reduction in plasma density) gives an improvement in attenuation of ~15 dB.

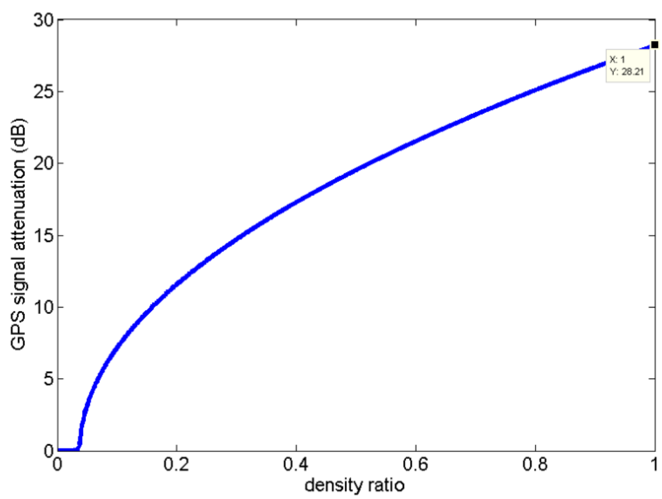

Figure 8. Calculated GPS signal attenuation versus plasma density ratio.

III. Summary of HyPASS Results

The HyPASS program consists of three efforts: (1) development of a prototype "stripped down" vector network analyzer that can be flown on a hypersonic/re-entry mission; (2) hypersonic plasma diagnostic development based on *S*-parameter measurements from a vector network analyzer; and (3) developing and demonstrating an antenna matching network in plasma to improve GPS signal reception. In support of these efforts, we have worked to improve our hypersonic testing capabilities from those used during the ReComm effort, and we discuss this first below.

A. Plasma Environment

Significant work was performed during the HyPASS program to improve our hypersonic testing capabilities. Specifically, a plasma torch was installed in EDA's vacuum facility and a mechanism built to allow it to be aimed at a test article positioned at varying angles relative to the torch. Figure 9 shows a picture of the setup. The impact of the plasma stream from the torch creates a plasma layer on the surface of the test article as can be seen in the figure. Air is fed into the torch to produce the plasma, and the background pressure of the chamber is around 20 Torr when the torch is in operation. The purpose of this improved capability is to provide a more accurate testing environment for the final development of the diagnostic probes and matching network both in terms of the plasma characteristics and thermal environment. The development of the hypersonic and re-entry plasma simulator for the HyPASS program has provided EDA with a great tool for future work in plasma communications experimentation.

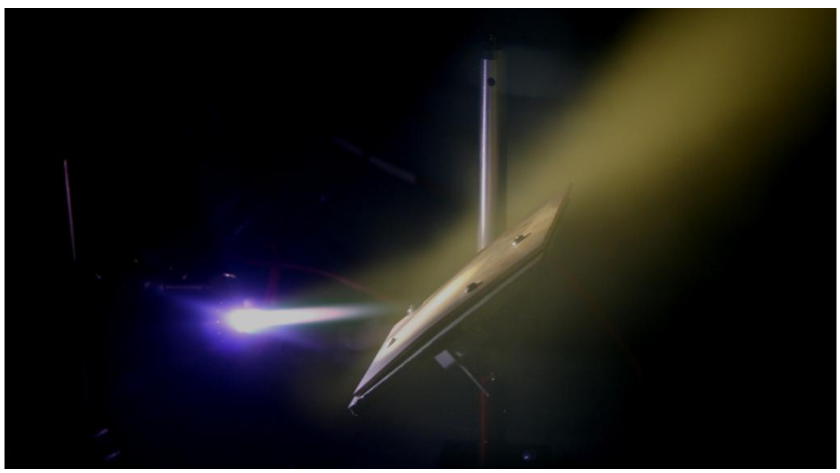

Figure 9. Plasma torch impacting GPS patch antenna. Antenna is covered with 0.0625″ boron nitride and 0.024″ mica.

B. Vector Network Analyzer

Recent developments in high frequency circuit technology have led to the availability of vector network analyzers (VNAs) that are small and light enough to consider flying on hypersonic vehicles, which opened up the possibility of this new type of plasma sensor based on the VNA. A trade study determined that designing and building a VNA from scratch was not cost-effective; hence, the path taken was to modify a commercial-off-the-shelf VNA. This work is being done by Penn State under the HyPASS Phase II SBIR program. A picture of the prototype network analyzer hardware is shown below in Figure 10.

Figure 10. Prototype Network Analyzer Hardware

C. Antenna Matching

A matching circuit is used to tune the GPS receive antenna to minimize the loss of signal due to impedance mismatches. The matching network can be tuned by varying the voltages on two varactor diodes. Changing the voltage changes the capacitance of the circuit and allows the matching network to tune an antenna over a particular frequency range. The match of the antenna is measured using a network analyzer to measure the reflected power, or S_{11} response, of the antenna. The signal power loss due to antenna mismatch is calculated as shown below in Equation (3) [8].

$$P_{loss}(dB) = 10log(1 - |S_{11}|^2) \quad (3)$$

where $|S_{11}|$ is the magnitude of the measured reflection coefficient.

Figure 11 below shows an example of tuning the antenna in the plasma. The matching network was tested by connecting it in series with a GPS patch antenna with center frequency of 1.575 GHz and was placed next to the plasma torch. The dashed black line represents the initial S_{11} free-space response of the antenna and the red line is the S_{11} response with the plasma turned on. The minimum of the dip in the S_{11} response represents the resonant frequency of the patch antenna. As can be seen from the plot, the plasma de-tunes the antenna away from the original center frequency by about 40 MHz. The green line shows the S_{11} response with the antenna tuned back to the center frequency of the patch antenna in the plasma.

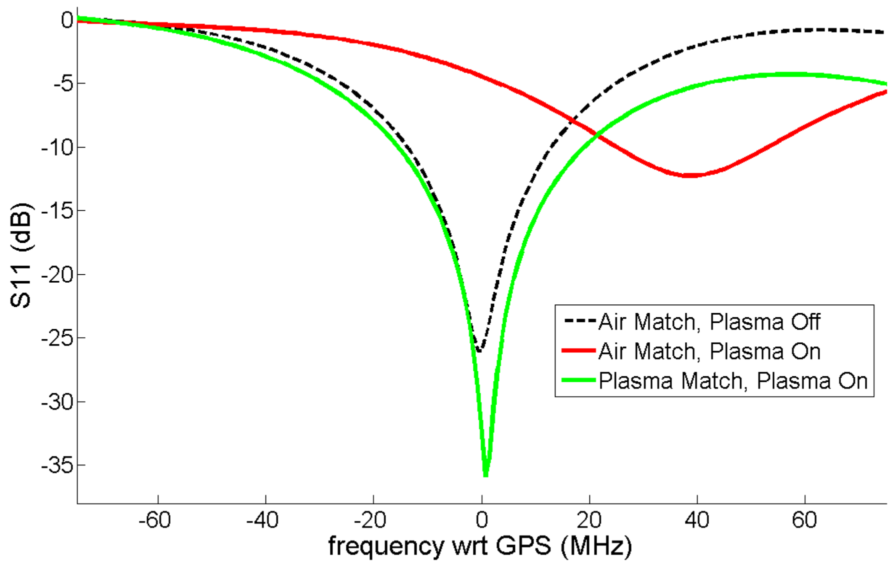

Figure 11. Tuning example of GPS patch antenna with plasma

Signal strength measurements were made using the network analyzer to quantify the improvement in signal reception with an external matching network on a GPS antenna in plasma. An infinitesimal dipole was used as the transmitter and was placed 30 cm above the GPS antenna out of the plasma sheath. The time-gating feature of the network analyzer was used to minimize the effect of reflections. Comparisons were made by first measuring the signal strength with the GPS antenna tuned to the GPS frequency 1575 MHz in free space with the plasma torch turned on and then measuring the signal strength with the antenna tuned in the plasma. Figure 11 shows an example measurement. The signal strength was normalized to the signal strength at 1575 MHz in air. As can be seen from the figure, with the plasma turned on the received signal at 1575 MHz drops by about 15 dB. With the antenna matched to the plasma there is an improvement of ~4 dB in received signal strength.

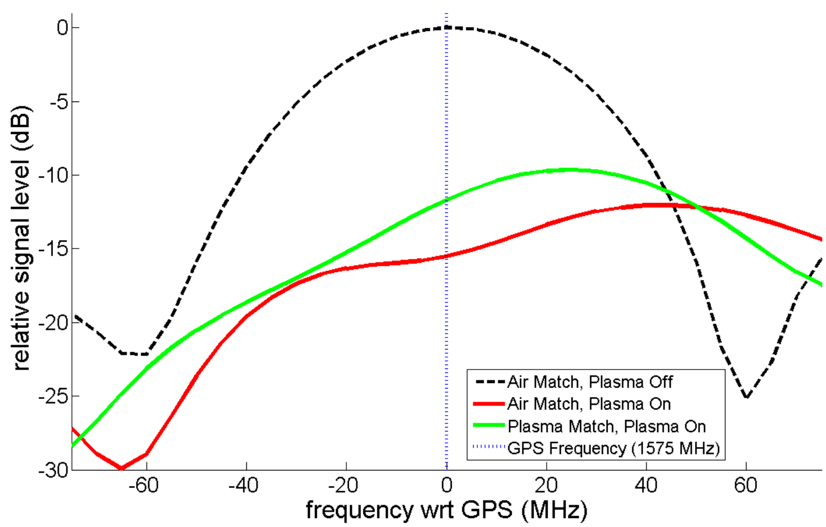

Figure 12. Relative signal strength change

Figure 13 shows an example measurement using an automated matching system to tune the antenna to the plasma based on the reflected power (S_{11}) measurement at the antenna input for a frequency of 1575 MHz. From the figure, the antenna is initially mismatched (i.e. $S_{11} \approx 0$ dB) and then is matched to freespace when the matching system is turned on. At ~10 seconds the plasma is turned on and the antenna again becomes mismatched (i.e. S_{11} increases significantly) with the presence of the plasma layer. The antenna is then automatically matched to the plasma as is illustrated in Figure 13.

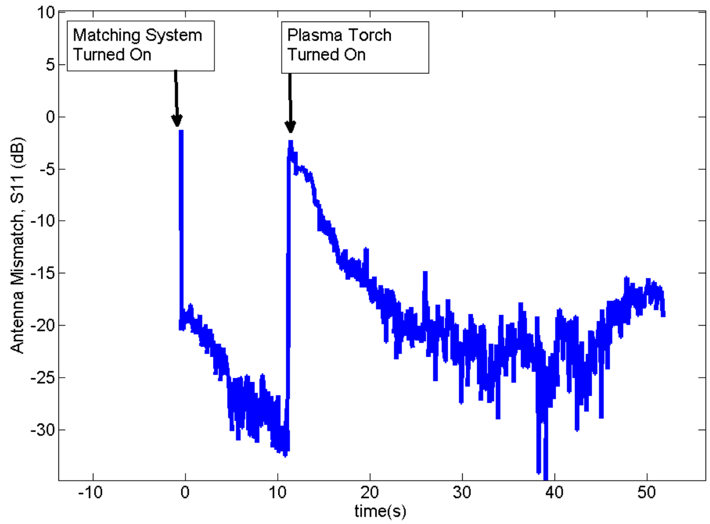

Figure 13. Example tuning by automated matching network

Using Equation (3) with the measured reflection coefficient data gives a calculation of the mismatch loss of the antenna due to the plasma versus time. This is shown below in Figure 14.

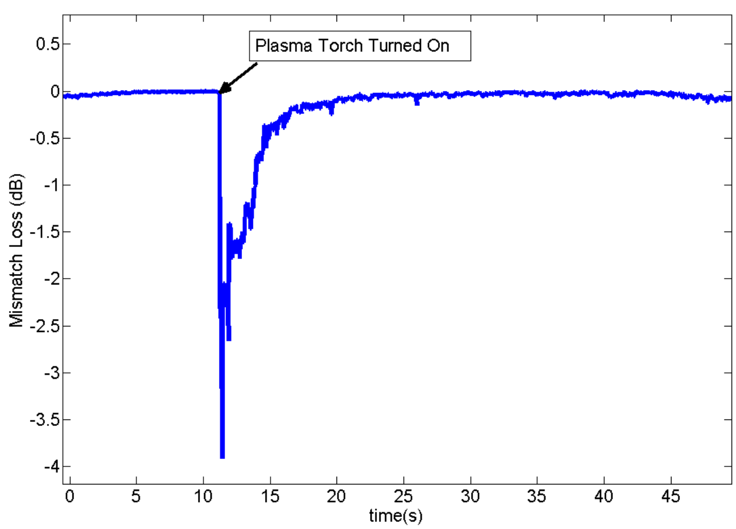

Figure 14. Calculated Mismatch Loss

As can be seen from the figure, there is initially a 4 dB mismatch loss at the antenna due to the plasma and then is decreased to close to 0 dB loss over a time period of about 5 seconds. The initial 4 dB mismatch loss is consistent with signal strength measurements shown in Figure 12 taken with the same plasma torch operating conditions.

Figure 15 shows an estimate of the mismatch loss for the antenna as the antenna's S_{11} response is shifted in frequency. The calculations were made by numerically shifting the antenna response away from the center frequency of the antenna and using Equation (3) to calculate the signal power reception improvement that could be made by matching the antenna. As can be seen from the plot, a 4 dB improvement in signal strength for a 40 MHz offset in resonance frequency is consistent with the measured data.

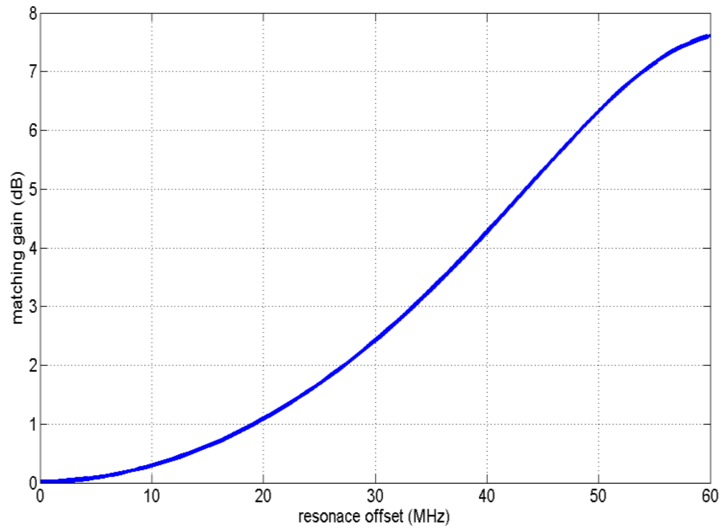

Figure 15. Estimated Signal Reception Improvement versus Patch Antenna Resonance Offset

D. Hypersonic Plasma Diagnostics

Another aspect of the HyPASS project is to provide diagnostics both for potentially aiding in matching the antenna to the plasma environment and for general hypersonic plasma characterization. The HyPASS system uses two diagnostic probes attached to frequency-adaptive network analyzer hardware to measure plasma parameters, providing real-time information about local plasma parameters.

Two planar diagnostic probes are used to measure plasma parameters. By measuring the magnitude and phase of the reflected and transmitted power (S_{11} and S_{21}) using a network analyzer, the plasma parameters of electron density, sheath size, and collision frequency can be derived. Typical probes and the flight prototype of the network analyzer are shown in Figure 16. The probes are 5 cm x 5 cm, though may be reduced in size somewhat depending on space constraints. The probes can be covered by a protective dielectric layer or integrated beneath a hypersonic vehicle's skin and still give accurate results.

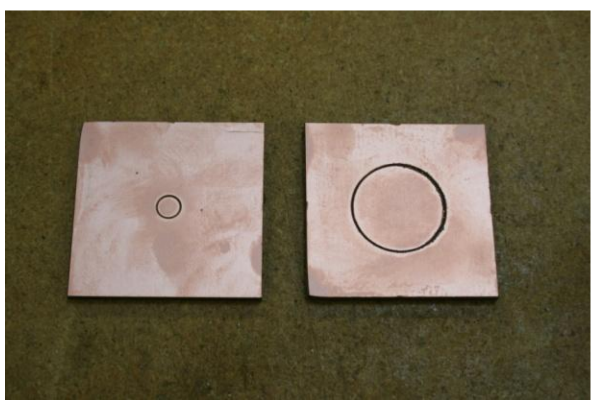

Figure 16. Picture of typical hypersonic plasma probes

The location and width of the resonance of the reflected power (S_{11}) can be used to determine the plasma density and collision frequency of the plasma. A circuit model of the probe and plasma was developed based on experimental measurements. In this model, the plasma impedance was modeled as a capacitor with a relative permittivity, ε_p, that depends on plasma density and collision frequency given by Equation (4) below [4].

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega(\omega - j\nu_m)} \ , \tag{4}$$

where ω is the RF frequency, ν_m is the electron collision frequency, and ω_p is the plasma frequency. Figure 17 below shows the measured reflected power (S_{11}) for a single diagnostic probe in the plasma torch fit to the circuit model. The probe was covered by a 0.0625″ layer of boron nitride and a 0.024″ layer of mica. The measurement yields a plasma density of 4.5×10^{16} m^{-3} and a collision frequency of 1.3 GHz. This would correspond to the plasma density at ~70 km for a re-entry vehicle traveling at 7.5 km/s.

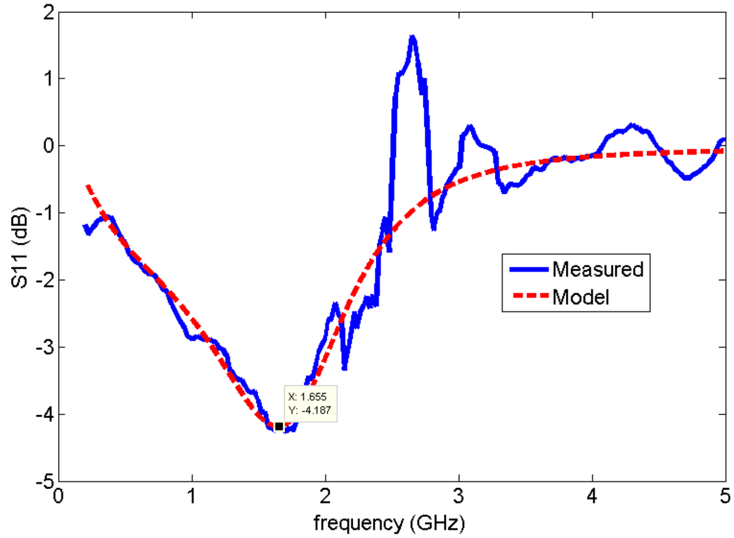

Figure 17. S_{11} response in plasma with planar diagnostic probe compared to model

Mutual coupling between the diagnostic probes as measured by the S_{21} parameter can provide a method for measuring the plasma sheath thickness. As the sheath "edge" moves closer to the surface, the coupling between antennas increases. S_{21} measurements were collected using two planar resonance probes for four different angles relative to the plasma torch (here, 0 degrees means the probes are parallel to the torch). Varying the incident angle of the torch changed the visual width of the plasma layer above the probes with 0 degrees corresponding to the thickest plasma layer and 75 degrees corresponding to the thinnest. Figure 18 below shows a summary of the results.

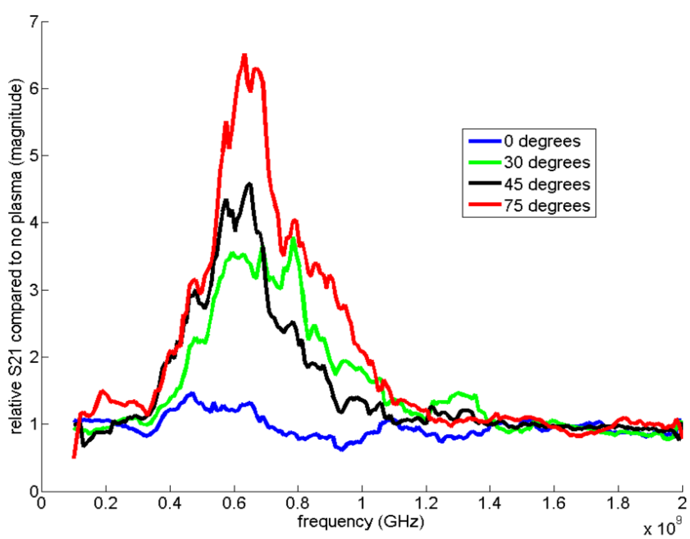

Figure 18. Coupling measurements for several plasma torch angles

As can be seen in the figure, there is a clear correlation between angle of the plasma torch and coupling between the probes with the largest coupling occurring with the largest angle and thinnest visual plasma layer. The coupling decreases as expected as the angle is reduced and the plasma layer becomes larger. These results show a similar trend to simulations using a metal plate to simulate the plasma, which is promising for using this diagnostic as a method to approximate plasma width.

IV. Conclusions

ElectroDynamic Applications has made significant progress in developing two technologies capable of improving communication through hypersonic or re-entry plasmas by an estimated 25 dB or more. Improved plasma communication is a critical technology for hypersonic cruise missiles such as the X-51 program and for staying in contact with manned re-entry vehicles. ReComm uses a combination of electric and magnetic fields to lower the plasma density over the antenna, effectively opening up a window for communication through the plasma. Experiments have shown a density reduction of 80% on a prototype ReComm. HyPASS provides antenna matching to further improve plasma signal reception by up to 10 dB as well as providing plasma diagnostics of the hypersonic plasma.

V. References

1. Keidar, M., M. Kim, and I. D. Boyd, "Electromagnetic reduction of plasma density during atmospheric reentry and hypersonic flight," *Journal of Spacecraft and Rockets*, vol. 45, no. 3, pp. 445–453, Jun. 2008.
2. Lemmer, K.M., A.D. Gallimore, T.B. Smith, C.N. Davis, and P. Peterson, "Experimental results for communications blackout amelioration using crossed electric and magnetic fields," *Journal of Spacecraft and Rockets*, vol. 46, no. 6, pp. 1100–1109, 2009.
3. Lemmer, K., *Use of a Helicon Source for Development of a Re-Entry Blackout Amelioration System*, Ph.D. Dissertation, Then University of Michigan, 2009
4. Liebermann, M.A. and A.J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, 2nd Ed., Wiley, New Jersey, pp. 168–175, 2005.
5. Norris, G., and G. Warwick, "Hyper Hopes," *Aviation Week & Space Technology*, 22 March 2010, p. 58.
6. Sands, B.L., N.S. Siefert, and B.N. Ganguly, "Design and measurement considerations of hairpin resonator probes for determining electron number density in collisional plasmas," *Plasma Sources Sci. Tech*., vol. 16, 2007.
7. Spencer, D.F., "An evaluation of the communication blackout problem for a blunt Mars-entry capsule and a potential method for the elimination of blackout," Technical Report 32-594, Jet Propulsion Laboratory, Pasadena, California, 15 April 1964.
8. Balanis, C.A., *Antenna Theory – Analysis and Design*, John Wiley & Sons, Inc., 1997