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Report from the Workshop on Communications Through Plasma During Hypersonic Flight

Sponsored by

Air Force Office of Scientific Research
Office of the Air Force Chief Scientist
Air Force Flight Test Center

Held 29 August 2006
Boston, MA

By

Charles H. Jones, PhD
812TSS/ENTI
Air Force Flight Test Center
Edwards AFB, California
Technical Chair

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14. ABSTRACT

This workshop concentrated on a specific problem: how to communicate through the plasma sheath generated around an air vehicle at high Mach numbers. This plasma sheath is generated at about Mach number 10 and higher and introduces a high attenuation factor – often leading to full blackout – for standard radio frequencies used in telemetry and other communications. The attendees were either experts in this field or people actively involved in applications that require communications under these conditions. The workshop consisted of nine presentations followed by a two-hour directed discussion. The primary focus of this report is to present the conclusions reached during the directed discussion. The author hopes that these conclusions will aid in directing future research.

The first order of business in the discussion was to establish standard applications, standard communication requirements, and priorities for both. Reception of GPS is the top priority as well as the most difficult problem. The second order of business was to discuss what research needs to be conducted. The overriding conclusion was: *Experimental data is needed to validate computational and mathematical models.* The remaining discussion was on developing a list of potential solutions and the pros and cons of these solutions. At the end of the workshop, the attendees were asked to vote on what solutions show the most promise. The vote shows that the expert opinion of this group strongly supports certain solutions and dismisses others as not worth pursuing.

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Executive Summary

This workshop concentrated on a specific problem: how to communicate through the plasma sheath generated around an air vehicle at high Mach numbers. This plasma sheath is generated at about Mach number 10 and higher and introduces a high attenuation factor – often leading to full blackout – for standard radio frequencies used in telemetry and other communications. The attendees were either experts in this field or people actively involved in applications that require communications under these conditions. The workshop consisted of nine presentations followed by a two-hour directed discussion. The primary focus of this report is to present the conclusions reached during the directed discussion. The author hopes that these conclusions will aid in directing future research.

The first order of business in the discussion was to establish standard applications, standard communication requirements, and priorities for both. Reception of GPS is the top priority as well as the most difficult problem.

The second order of business was to discuss what research needs to be conducted. The overriding conclusion was:

Experimental data is needed to validate computational and mathematical models.

As such, a list of physical properties needing experimental data was developed along with an overview of what types of experiments might be performed and what type of equipment could be used.

The remaining discussion was on developing a list of potential solutions and the pros and cons of these solutions. At the end of the workshop, the attendees were asked to vote on what solutions show the most promise. The vote shows that the expert opinion of this group strongly supports certain solutions and dismisses others as not worth pursuing.

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1 Introduction

This workshop concentrated on a specific problem: how to communicate through the plasma sheath generated around an air vehicle at high mach numbers. This plasma sheath is generated at about Mach number 10 and higher and introduces a high attenuation factor – often leading to full blackout – for standard radio frequencies used in telemetry and other communications. The 37 attendees were either experts in this field or people actively involved in applications that require communications under these conditions.

The driving justification for this workshop is that telemetry is a requirement for test and evaluation (T&E) and there is currently no proven practical solution. Due to the velocities, pressures, and temperatures, modification of a hypersonic vehicle in the form of protrusions or destructive intrusion through the outer surface may cause significant changes to the aerodynamics and structural integrity of the vehicle. Therefore, it is likely that the solution can not be added on to the vehicle during developmental testing as is currently the practice. Solutions to communicating through plasma will have to be designed into hypersonic vehicles. The difficulty of the problem and the current theoretical state of potential solutions indicate a long lead time to finding a solution. This workshop was an initial step towards finding a solution by bringing experts together to present current and past research and to actively discuss how to obtain a solution.

The structure of the workshop was a series of presentations followed by a two-hour directed discussion. The opening presentation was by Dr. Mark Lewis, the Air Force Chief Scientist. This along with the next two presentations provided general background and requirements. Another six presentations provided technical overviews of current and past research. The agenda and abstracts of the presentations are included in the appendices. The last two hours of the workshop were a discussion directed by myself, Dr. Jones.

The primary purpose of this report is to present the conclusions reached during the directed discussion. These conclusions are intended to assist in directing future research.

2 Standard Hypersonic Applications

As indicated in table 1, three basic applications were identified. These serve two purposes. First, they capture the range of applications. Second, they provide a method of comparing research results.

1. *Low altitude, short duration armaments*. These were ranked first priority for several reasons. These provide the quick strike that is one of the main arguments for hypersonic vehicles. They are also, in some sense, the easiest to implement because of the short duration. (There are already some Mach 6 and 7 efforts underway.) The altitude is listed at 1,000 feet although some discussion suggested this should be higher. In the other direction, these armaments may target the ground and, from a test and evaluation point of view, the seconds before impact are the most critical for data collection. Since plasma

does not normally form until about Mach 10, the chosen Mach number of 8 may mean plasma communications are not an issue. However, plasma formation is partially dependent on atmospheric pressure, which increases as altitude decreases. This standard scenario might need to be split into two cases. The condition trying to be identified is an instantaneous, worst-case condition for either a penetrator or an interceptor. However, Mach 8 is probably too high for a penetrator impact, while an altitude of 1,000 feet is probably too low for an interceptor. An evaluation of when plasma forms at low altitudes needs to be performed and this standard application needs to be clarified further.

2. *Orbital reentry vehicles*. A distinction is made between braking and nonbraking reentry. The space shuttle executes one large braking maneuver when re-entering. This, in essence, causes the entire bottom of the shuttle to become a leading edge and, conversely, the back side of the shuttle provides an opening in the plasma that allows communication via satellite. There are other scenarios that may not implement such a braking maneuver such as vehicles that enter and exit orbit.

3. *Sustained flight*. During Dr. Lewis' presentation, he made the point that hypersonics probably does not mean Mach 10 passenger planes. However, there are existing studies for human transportation at these Mach numbers and there are other scenarios that make use of being able to get anywhere in the world in about two hours. If communications can be accomplished in this application, then it can probably be accomplished in the other two applications as well. This is given the lowest priority since it will probably be the last scenario realized.

Although it may seem contradictory that the altitude for reentry is less than for sustained flight, reentry is fundamentally executing a long descent and thus 80,000 feet is representative of the regime it traverses. In contrast, sustained flight is likely to stay at a high altitude.

The two columns for vehicle shape and the properties of material of which the vehicle is made were added as significant factors in the scenarios. However, these do not lend themselves to easy description and there was not enough time during the discussion to clarify these. A primary next step in future research is to fill in these columns.

Table 1 Standard Hypersonic Applications

Property / Application	Mach	Altitude (ft)	Vehicle Shape	Material Properties	Priority
Low altitude armament	8	1,000			1
Orbital Reentry	20	80,000			2
Sustained flight **Powered** **Boost and glide**	10	10,0000			3

3 Main Types of Communication

Table 2 lists communication types and their priorities. There was virtually no disagreement with this prioritization. This again establishes the breadth of applications involved.

It is difficult to imagine any air vehicle not utilizing GPS in this day and age. GPS also represents the most difficult problem in terms of communicating through plasma since GPS signals are at such a low power that they are normally below the noise floor. Since initial hypersonic vehicles are most likely going to be unmanned, standard safety issues force the need for flight termination. However, for standard T&E, obtaining telemetered data is still a requirement.

Table 2 Communication Types

Communication	Priority
GPS	1
Flight Termination	2
Telemetry (data)	3

4 Future Research

The highest priority for future research is to validate existing models. At one point in the afternoon presentations, a speaker made a comment about his "favorite model." This serves to illustrate that there are quite a few computational and mathematical models describing plasma sheaths. Unfortunately, there are little experimental data to support the truthfulness of these models or, at the very least, little data are currently available to the community. There was some work done in previous decades, especially in relation to design of the space shuttle. However, much of these data are either lost or buried somewhere.[1] A suggestion was made, and fully supported, that it would be worthwhile to try to find and evaluate such data. Similarly, it was suggested that a foreign technology assessment would be of value.

So what data are needed to validate the models? Roughly speaking we need experimental data about:

1. The physical properties of the plasma and
2. The relations between communication properties and plasma properties.

A full characterization requires a matrix of these properties at different distances from the vehicle, at different Mach numbers, and at different altitudes. At some level, Mach number and altitude translate to temperature and pressure since these are the phenomena that create and affect the plasma. The shape of the vehicle, angle of attack, and material ablation also significantly affects these characteristics. Indeed, these are perhaps the first characterizations to validate. That is:

[1] Some known data and points of contact have been identified since the workshop.

1. What is the relation between temperature, pressure and plasma density?
2. What is the homogeneity of plasma distribution around the vehicle?

In order to compare results as research progresses some form of normalization will have to be established.

4.1 Physical properties

Plasma is an electrified gas with some fraction of its atoms dissociated into positive ions and negative electrons. In the hypersonic boundary layer this is a weakly ionized plasma, in which the density of ionized constituents is much lower than the neutral gas density. The following properties were identified as needing validation.[2]

1. *Plasma frequency* – the characteristic frequency of electrons oscillating around their equilibrium positions. When electrons in plasma are displaced from a uniform background of ions, electric fields build up in such a direction as to restore the neutrality of the plasma by pulling the electrons back to their original positions. Because of their inertia, the electrons overshoot and oscillate around their equilibrium positions.
2. *Plasma density* – density of charged particles in the plasma sheath.
3. *Electron distribution* – how the density of electrons change throughout the plasma sheath. This is related to plasma density in that, for quasi-neutral plasma, electron density is the same as plasma density. May also define the *electron distribution function* – the density of electrons in 6-dimensional physical space and velocity space as a function of location in the sheath
4. *Electron collision frequency* – the frequency of collisions between electrons and other particles. For communications blackout, electron-neutral collisions are usually of most interest, but electron-ion and electron-electron collisions may need to be considered.
5. *Electron gyro-frequency* – the angular frequency of the circular motion of an electron in the plane perpendicular to the magnetic field.
6. *Recombination rate* – the rate at which free electrons are captured to form new neutral atoms.

In addition to these plasma properties, the radio frequency communication properties of frequency and power need to be validated. The following ratios were of interest.

[2] Some of these definitions are paraphrased from Wikipedia [1]. This site also provides a reasonably good overview of plasma physics.

1. Electron collision frequency to plasma frequency.
2. Communication frequency to plasma frequency.
3. Communication frequency to electron gyro frequency.
4. Communication power in to power out (for a given communication technique.)

Most of these properties involve electrons rather than ions or neutral particles. This is because electromagnetic waves interact mostly with electrons.

4.2 Sensor Development

The topic of whether or not adequate sensors exist for measuring plasma properties was briefly discussed. A plasma density probe is under development by AFRL at Hanscom AFB, Massachusetts. This issue needs to be addressed more thoroughly.

4.3 Experiments

Plasma communications experiments fall into three categories: flight test, wind tunnels, and other laboratory facilities. The most promising version of flight test is through sounding rockets as represented by the Fresh-FX program, although piggy-backing on space re-entry flights is always a possibility. There are actually quite a few wind tunnels that could perform some level of plasma experiments but wind tunnels do not reproduce flight conditions. Appropriate gas mixtures and insertion of ablated materials are always an issue and there was also concern expressed about achieving realistic plasma densities. The main other laboratory technique mentioned was a vacuum chamber currently under development. Other types of facilities probably exist.

The following notes were made during the discussion.

1. Rocket sounding techniques could analyze high power, high frequency techniques, antenna mutual coupling, and is the best technique for model validation. Because the shape of a sounding rocket does not vary much, this technique only captures plasma properties as a consequence of Mach number and altitude.
2. Wind tunnels would be appropriate for measuring recombination rates, although this is dependent on ablation materials and rates.
3. Other laboratory techniques could be used for wave mixing experiments regarding three-wave interactions, up modulation techniques, and acoustic modes.

4.4 R&D Cost

The question of cost was discussed briefly. The order of magnitude of cost to solve this problem was estimated at $100M. (That is, $10M is not enough and $1B is probably more than enough.) Both wind tunnel tests and flight tests tend to be expensive. Realistically, in addition to continued model development, hundreds of wind tunnel tests and dozens of flight tests are probably called for to provide a complete answer. Such tests would include not only the model

validation prior to developing a solution, but also the testing of any potential solution. Further, it is likely that we need more than one technique to solve the problem for all applications.

5 Potential Solutions

Over the years leading up to this workshop I have been forming a list of techniques that could provide potential solutions. This list was handed out to the attendees including initial comments on pros and cons for each technique. During the discussion, several additional techniques were identified. The pros and cons were discussed and some additional comments were added. At the end of the workshop the attendees were asked to vote on the techniques either Yes, No, or No opinion. In most cases, a "No opinion" vote indicated lack of knowledge of the technique. The form of the question was: "Where do we put the money?"

5.1 The List

The following is the list of techniques and brief descriptions of each.

1. *Low Communication Frequencies* – Using very low frequencies avoids the plasma induced attenuation. Specifically how low has not been fully established.
2. *High Communication Frequencies* – Using very high frequencies avoids the plasma induced attenuation. Specifically how high has not been clearly established and is dependent on various properties.
3. *Optical (Laser)* – Optical communications is maturing. However, there was no one present that was an expert in this area.
4. *High Power* – Plasma adds one more attenuation factor. It would be possible to just communicate through it by transmitting with enough power.
5. *Relay Ejection* – Periodically eject a relay that is close enough to the vehicle to pick up and re-transmit the signal.
6. *Three Wave Interaction* – Use the inherent properties of the plasma. The three waves involved are a stimulus signal, the plasma oscillation, and the communications signal itself. The interactions of these three signals generate another signal that can be transmitted or received.
7. *Electrophilic Injection* – Inject a substance (fluid) into the plasma sheath that de-ionizes the plasma therefore reducing (or eliminating) the attenuation factor.
8. *Electrophilic Heat Shield Additive (Ablation*) – Add a substance to the vehicle skin that ablates into the plasma sheath and de-ionizes the plasma therefore reducing (or eliminating) the attenuation factor.
9. *Magnetic Control for Attenuation Reduction* – Using permanent magnets (or other magnetostatic, electrostatic, or electromagnetic techniques), de-ionize the plasma to reduce the attenuation around the antenna. This is, in essence, punching a hole into the plasma.
10. *Magnetic Control for Plasma Shaping* – Using permanent magnets (or other magnetostatic, electrostatic, or electromagnetic techniques), shape the plasma to deflect the sheath around the antenna. This is, in essence, punching a hole into the plasma.
11. *Aerodynamic Shaping* – Control the shape of the plasma sheath by controlling the shape of the vehicle. This will have an effect on any solution.

12. *Air Spike* – Control the shape of the plasma sheath by inserting a leading sharp point in front of the main vehicle. Suggested approaches include either a physical spike or a laser spike.
13. *Trajectory Shaping* – Control the shape of the plasma sheath by controlling angle of attack and position relative to receivers.
14. *Control Surfaces* – A form of aerodynamic shaping, but recognizing that moving the control surfaces of the vehicle will change the shape of the plasma sheath.
15. *Plasma Modulation* – (Introduced during the discussion but not elucidated on.)
16. *Electron Beams* – (Introduced during the discussion but not elucidated on.)
17. *Cooling Techniques* – Since the plasma is fundamentally caused by heat, cooling the area around the antenna would reduce (or eliminate) the attenuation.
18. *Antenna Location and Type* – Certainly, these will play a factor in a successful solution.
19. *Whistler Mode Antenna* – a transmitter designed to launch radio waves to propagate in the form of whistler waves through a plasma with an imposed magnetic field. Whistler waves can have a broad range of frequencies to open up a wide radio window for radio communications in the plasma environment during hypersonic flights.

Techniques 13-19 were introduced during the workshop. Additionally, the distinction between 7 and 8, electrophilic injection vs. electrophilic ablation was introduced at the workshop. The other techniques were on the original list distributed to the group.

5.2 Pros and Cons

In order to evaluate potential solutions let us discuss some general aspects of potential solutions and what properties a desired solution would have. In particular, consider these questions.

1. Is the solution active or passive?
2. Does the solution allow reception of GPS?
3. How well does the solution meet general engineering and practical concerns?

A passive solution, such as aerodynamic shaping, is something that is designed into the vehicle, does not require special equipment, and introduces little or no additional maintenance. An active solution, such as electrophilic injection, introduces extra equipment and maintenance. An example of a passive solution that may introduce some maintenance is a particular shape for a leading edge. If the shape is deformed through ablation, then the leading edge may need to be maintained between flights. Of course, not all techniques fit nicely into active or passive categories. In some sense trajectory shaping is a passive technique in that you don't have to modify the vehicle. However, it may introduce a lot of maintenance if you have to calculate special trajectories for each type of test or operation. From an engineering perspective, passive solutions are certainly desirable since they are a "do once" activity and have less chance of failure.

GPS is of special concern since it is of highest priority and also because GPS reception is the most difficult problem to solve. GPS signals are very weak and are usually well below the noise floor. Reception of GPS is only possible because the characteristics of the signals are so well defined. The attenuation of GPS through a plasma sheath very likely destroys the signal entirely.

Just because a theoretical solution is found, does not mean it can be implemented. The following list identifies some practical considerations.

1. Size and Weight
2. Low Maintenance
3. Low Energy Requirements
4. Minimal Changes to Infrastructure
5. Ease of Implementation
6. High Bit Rates
7. Low Bit Error Rates
8. Flexible Wave Form Generation
9. Long Distance Transmission
10. Use Already Allocated Spectrum

Many of these are simply standard concerns for anything that is put on an air vehicle, such as size and energy use. Some of these are standard for radio frequency (RF) communications, such as bit error rates. But some are more specific to the needs of Test and Evaluation (T&E), such as flexible wave forms. There is an ongoing problem of a decrease in available spectrum and an increase in telemetry requirements. One way of reducing this problem is to change modulation techniques. A solution that restricts the wave form will not allow advances in this area.

The last item, allocated spectrum, deserves some comment. It is not a technical issue, but a political one. Only certain frequency bands are allocated for telemetry. It has been argued that in a time of war, we will use what ever frequency we need. There are at least two rebuttals to this in terms of finding a usable solution. First, just because you might use a frequency in an operational scenario during a time of war does not mean that that frequency can be used during T&E in a time of peace. Second, just because we are at war with one country does not mean that the adjacent countries will allow us to interfere with their spectrum usage.

Something else to consider when deciding whether to fund a certain technique or not is that some solutions will have an effect whether they are a complete solution or not. Aerodynamic shaping seems to be a leader in this category. No matter what, the shape of the vehicle is going to affect the solution but it currently appears that changing the shape of the vehicle will probably not solve the problem completely for all applications.

A final consideration, especially from a T&E point of view, is whether or not the designers (and manufacturers) will actually incorporate a solution into a vehicle. For example, can we truly expect to insist that a particular material be added to the vehicle skin to support ablation based de-ionization? It may very likely be the case that testers will, as is often the case, figure out how to test these vehicles without any real input into the design. Thus, we need to pursue multiple solutions to allow flexibility when the time comes.

Table 3 shows the list of pros and cons as it stood at the end of the workshop. The last seven techniques have the fewest comments since they were introduced at the workshop.

Table 3 Technique Pros and Cons

Approach	Pros	Cons	Comments
Low Frequency	Works.	Low bit rates. Not a GPS solution.	Below 100 MHz?
High Frequency	Works. High bit rates.	Spectrum not allocated. High energy cost. No infrastructure. Limited distance. Atmospheric attenuation. Not a GPS solution.	Above 30GHz?
Optical (laser)	High bit rates. Spectrum currently not regulated. Self focusing.	No infrastructure. Safety issues. Not a GPS solution. Energy use?	
High Power	Use existing spectrum and infrastructure.	Very high energy cost. Not a GPS solution.	Do we know what level of power?
Relay Ejection	Low transmission distance required.	What happens to the relays? Ejection control problems. Not a GPS solution.	
3 Wave Interaction	Uses existing ground infrastructure. GPS solution?	Spectrum not allocated. High energy cost? Increased engineering complexity. Weight?	Requires stimulus above plasma frequency.
Liquid or Electrophilic Injection	GPS solution? Works. Good materials exist.	High mass cost. Some materials not environmentally friendly. Injection complexity.	
Electrophilic heat shield additive (ablation)	GPS solution? Works. Good materials exist.	Some materials not environmentally friendly.	
Magnetic Control Attenuation Reduction	Use existing spectrum and infrastructure. Minimum mod to vehicle. GPS solution?	Probably won't eliminate all attenuation.	
Magnetic Control Plasma Shaping	May aid solution.	Not a complete solution. Probably not a GPS solution.	
Aerodynamic Shaping	May aid solution.	Not a complete solution. Probably not a GPS solution.	Will effect solution.
Air Spike		Physical spike – aerodynamic and maintenance concerns. Laser spike – tenuous results. Probably not a GPS solution.	
Trajectory Shaping	May help.		
Control Surfaces	May help.		
Plasma Modulation			
Electron Beams	GPS solution?		

Table 4 Technique Pros and Cons (Concluded)

Approach	Pros	Cons	Comments
Cooling Techniques	May help.		
Antenna Location and Type	Will make a difference.		
Whistler Mode Antenna			

5.3 The Vote

This section provides the tally of the votes from the attendees. They were asked to vote Yes, No, or No opinion on each of the potential solution techniques. In most cases, a "No opinion" vote indicated lack of knowledge of the technique. The form of the question was: "Where do we put the money?"

There were 21 people that voted. The highest number of votes for a single technique was 15; some techniques had as few as 4 votes. The raw vote counts are provided in appendix C.

Table 4 sorts the techniques based on the number of Yes votes minus the number of No votes. It is not difficult to break the results into three general groups: 1) those techniques that the group sees as highly worth pursuing, 2) techniques that are clearly viewed as not worth pursuing and 3) techniques that do not have a clear consensus.

Table 6 sorts the tally by the number of Yes votes divided by the total number of votes. I label this "confidence" since a value of 1.0 indicates that every one that had an opinion felt it was worth pursuing. Several techniques rise much higher on the list with this sorting. A prime example is whistler mode antenna. During the presentation, it was clear that this was an idea many in attendance hadn't heard about before. Those that understood it apparently felt it was an interesting idea to pursue.

Optical communications seems to be the most controversial. There were 8 Yes votes indicating fairly strong support. However, the 4 No votes caused it to rank in the middle in both tables. I believe this is partly due to the fact that there were no optical communications experts in the room.

Note on possible bias. Due to human nature, people are more likely to vote positive for ideas with which they are personally familiar or are working on. One potential for bias in the vote tally is that, due to the workshop's proximity, there were a contingent of attendees that are involved with electrophilic ablation. Thus, this technique may have a slight bias in the tally. Otherwise, I believe the results are reasonably objective.

Table 5 Vote Tally of Techniques Sorted by "Yes Minus No"

Technique	Yes	No	Total Votes	Yes - No
Electrophilic Injection or Ablation	14	1	15	13
Magnetic Control - Attenuation Reduction	12	1	13	11
Trajectory Shaping	11	0	11	11
Aerodynamic Shaping	12	2	14	10
Three Wave Interaction	10	2	12	8
Whistler Mode Antenna	7	0	7	7
Optical (Laser)	8	4	12	4
Control Surfaces	5	1	6	4
Plasma Modulation	4	0	4	4
Antenna Location and Type	4	0	4	4
Electron Beams	3	1	4	2
Cooling Techniques	3	2	5	1
Magnetic Control - Plasma Shaping	5	5	10	0
High Frequency	6	7	13	-1
High Power	5	8	13	-3
Air Spike	2	6	8	-4
Low Frequency	1	12	13	-11
Relay Ejection	1	12	13	-11

Table 6 Vote Tally of Techniques Sorted by Confidence

Technique	Yes	No	Total Votes	Confidence Yes / Total Votes
Trajectory Shaping	11	0	11	1.00
Whistler Mode Antenna	7	0	7	1.00
Plasma Modulation	4	0	4	1.00
Antenna Location and Type	4	0	4	1.00
Electrophilic Injection or Ablation	14	1	15	0.93
Magnetic Control - Attenuation Reduction	12	1	13	0.92
Aerodynamic Shaping	12	2	14	0.86
Three Wave Interaction	10	2	12	0.83
Control Surfaces	5	1	6	0.83
Electron Beams	3	1	4	0.75
Optical (Laser)	8	4	12	0.67
Cooling Techniques	3	2	5	0.60
Magnetic Control - Plasma Shaping	5	5	10	0.50
High Frequency	6	7	13	0.46
High Power	5	8	13	0.38
Air Spike	2	6	8	0.25
Low Frequency	1	12	13	0.08
Relay Ejection	1	12	13	0.08

6 Conclusions

The single most overriding conclusion of this workshop is:

Experimental data is needed to validate computational and mathematical models!

This translates somewhat directly into a need for funding of experiments. Additional experimental data can probably be found if an extensive effort is made to search and retrieve historical data.

A secondary conclusion is that reception of GPS is the most critical capability for which we need to find a solution. This is because of its overarching importance to flight. GPS is also the most difficult problem due to its innately weak signal.

A fairly exhaustive list of potential solution techniques has been compiled (although there is always the potential for a new idea to surface). The vote by this community of experts provides strong guidance as to what techniques are most promising and also identifies several techniques that should be relegated to the "of historical interest" category.

In order to evaluate the value of different techniques some form of normalization needs to be developed; most likely in the form of a standard set of applications and configurations.

It seems probable there is not one solution for all situations. Different solutions may be better for different applications. Even further, it is likely that a combination of techniques will be required even if it is simply taking into account the effects of the shape of the vehicle. From a T&E perspective, multiple solutions are desirable since designers may or may not design a complete solution into the vehicle and testers may have to modify the vehicle for telemetry.

7 Summary of Recommendations

This section recaps recommendations stated in the body of the report.

1. Collect experimental data to validate mathematical and computational plasma models.
2. Complete Standard Hypersonic Applications (Table 1) by filling in vehicle shape and material properties columns.
3. Perform an evaluation of attenuation effects at different altitudes and Mach numbers. This should cover the full range from re-entry to sea level and a full range of Mach numbers from 3 to 26. This evaluation is dependent on validation of models.
4. Research and obtain related data from historic activities – most notably evaluation of plasma effects on the space shuttle.
5. Perform a foreign technology assessment.
6. Evaluate sensor technology for measuring plasma characteristics.
7. Pursue research, development, and testing of top voted solutions. (Tables 4 and 5)

These recommendations are not prioritized per se. However, it would seem prudent to start by collecting experimental data to validate existing models. This would aid most of the other recommendations and would help guide research before spending too much effort on specific theoretical solutions.

8 References

[1] Wikipedia – Plasma (physics), http://en.wikipedia.org/wiki/Plasma_%28physics%29

Appendix A Agenda

The final agenda.

TIME	EVENT
0730 – 0815	Registration
0815 – 0830	Opening and Administrative Remarks Dr. Charles Jones, AFFTC, Edwards AFB, CA Dr. John Schmisseur, AFOSR, Arlington, VA
0830 – 0900	The Challenges and Opportunities in Plasma Dynamics for Future Air Force Capabilities Dr. Mark Lewis, USAF Chief Scientist
0900 – 0930	Need for Hypersonic Communications During Test and Evaluation Dr. Charles Jones, AFFTC, Edwards AFB, CA
0930 – 1000	Mitigating The Attenuation Effects on RF Signals Due To Plasma: The Past, Present & Future. Ashley Sharma, AFFTC, Edwards AFB, CA
1000 – 1015	BREAK
1015 – 1045	Radio Frequency (RF) Blackout During Hypersonic Reentry Lt. Eric M. Brighton, AFRL, Hanscom AFB, MA
1045 – 1115	Re-entry and Hypersonic Vehicle Plasma Communication System Dave Morris, ElectroDynamic Applications, Inc., Ann Arbor MI
1115 – 1145	Parametric Antenna in the Ionospheric Plasma Dr. Vladimir Sotnikov University of Nevada at Reno, NV
1145 – 1300	LUNCH
1300 – 1330	Plasma Sheathing Control Using Boundary Layer Stabilization And Additives Dr. Hartmut Legner, Physical Sciences Inc., Andover, MA
1330 – 1400	Communicating Subplasma Frequency Signals Through Plasma Both To And From Supersonic Speed Vehicles Dr. Alan Newell, U. of Arizona, Tuscon, AZ
1400 – 1430	Aerodynamic Shaping Effects on Hypersonic Plasma Telemetry Dr. Ryan Starky, U. of Maryland, College Park, MD
1430 – 1445	BREAK
1445 – 1700	Directed Discussion

Appendix B Abstracts

These are the abstracts of the presentations.

B1 Abstract for Presentation 1

Title: The Challenges and Opportunities in Plasma Dynamics for Future Air Force Capabilities

Presenter: Dr. Mark Lewis, USAF Chief Scientist

Abstract:

The use of hypersonic vehicles during military activities is very attractive. Speed has always been, and continues to be, an important issue. But maintaining a balance of range and accuracy with hypersonic speeds is a challenge. Hypersonics allows the use of impact energy rather than explosive energy but this advantage diminishes if the vehicle must slow down to maintain guidance and control capabilities. The physics of flight and propulsion indicate we are reaching the limits of rockets and airbreathers hold the promise for hypersonic velocities and improved access to space. It took 46 years to fly the first scramjet. There is a need to reinvigorate fundamental research into hypersonic technologies.

The presentation overviews the military opportunities of hypersonics and the challenges involved in getting there. This includes reviewing the basic equations involved and the foundations for future research that are being put into place. In particular, the Fundamental Resarch in Hypersonics (FResH) program and the X-51 are discussed. Looking to the past we see that the X-15 program was a phenomenal success in implementing fundamental research. It should be our gold standard for current research programs. Thus, FResH emphasizes test over demonstration as a return to asking fundamental questions and the X-51 is being developed as a testbed to answer these questions.

B2 Abstract for Presentation 2

Title: Need for Hypersonic Communications During Test and Evaluation

Presenter: Dr. Charles Jones, AFFTC, Edwards AFB, CA

Abstract: The standard paradigm for test and evaluation (T&E) of military vehicles includes real time telemetry throughout the test. Further, the standard paradigm includes modifying the vehicle to add sensors, telemetry transmitters and other instrumentation. This modification process is often intrusive, sometimes including drilling holes and adding instrumentation to the exterior of the vehicle. Plasma forming around the vehicle at about Mach number 10 and above causes telemetry blackout. Such vehicles very likely will not tolerate the intrusive nature of current modifications.

The presentation overviews the T&E process and emphasizes the need for a telemetry solution to be designed into hypersonic vehicles in order to avoid these modifications. A list of practical requirements is provided including a discussion of the political restriction of spectrum allocation. The presentation also sets the stage for the directed discussion at the end of the workshop. This includes a list of potential solutions and an outline of what questions will be addressed during the discussion.

B3 Abstract for Presentation 3

Title: Mitigating The Attenuation Effects on RF Signals Due To Plasma: The Past, Present & Future.

Presenter: Ashley Sharma, AFFTC, Edwards AFB, CA

Abstract: A historical look at past solutions devised by the European Space Agency and the National Aeronautical Space Agency to limit the telemetry blackout period of re-entry vehicles. A cursory overview of some current research efforts to mitigate these effects in both Endo and Exo-atmospheric vehicles. And finally one perspective on the technology focus areas necessary to charter the course of neutralizing plasma fields with a synopsis of the accompanying levels of Developmental Test and Evaluation.

B4 Abstract for Presentation 4

Title: Radio Frequency (RF) Blackout During Hypersonic Reentry

Presenter: Lt. Eric M. Brighton, AFRL, Hanscom AFB, MA

Abstract: Air ionization and heat shield ablation generate a plasma sheath around reentering hypersonic vehicles. This ionized plasma layer reflects and attenuates propagating electromagnetic waves to a point where total RF blackout can and does occur. RF blackout is of special concern for hypersonic vehicles because continuous contact with ground stations and GPS satellites is required for communication and navigation. The degree of plasma formation and signal attenuation varies considerably depending on many factors. Some factors that impact RF attenuation are reentry velocity, vehicle design, heat shield impurity levels, and antenna placement. The U.S. Air Force Research Laboratory (AFRL), in conjunction with Xontech has developed the HYpersonic GPS SIMulation (HYGPSIM) code. This suite of models includes a hypersonic flowfield solver called the Reentry Aerothermal CHemistry code (REACH) and an electromagnetic propagation solver called EMRUN. The REACH code predicts the on-body plasma formation during hypersonic reentry for multiconic and lifting body vehicle geometries that fly ballistic and maneuvering trajectories. The EMRUN code then predicts the antenna performance during flight, accounting for the reentry plasma effects on the electromagnetic signal. This paper demonstrates AFRL's efforts in plasma modeling and provides a tradespace analysis for a generic conic body. The analysis investigates how changes to the flight trajectory, vehicle design, and antenna placement affect the degree of plasma formation and RF attenuation.

B5 Abstract for Presentation 5

Title: Re-entry and Hypersonic Vehicle Plasma Communication System

Presenter: Dave Morris, ElectroDynamic Applications, Inc., Ann Arbor MI

Abstract: ElectroDynamic Applications, Inc. is working in partnership with The University of Michigan to develop a solution to radio blackout. This solution, dubbed ReComm, uses the application of electric and magnetic fields to control the properties of the plasma layer surrounding a hypersonic vehicle. An embedded magnet integrated beneath the spacecraft antenna magnetizes the plasma electrons, reducing their mobility. Biased electrodes are placed on each side of the antenna. Under the considered conditions, the E×B layer configuration leads to an electron drift in the E×B direction and provides plasma quasi-neutrality across the layer. As a result, a significant electric field can be maintained across the magnetic field. This causes ion acceleration leading to a plasma density decrease. A reduction in plasma density by a factor of 10 is predicted in the case of a 0.2 T magnetic field and a voltage drop across the ExB layer of 150 V.

Our study suggested that two limited cases are possible, the plasma-optic regime and the magneto-hydro-dynamic (MHD) regime. In the preliminary study we concentrated on the plasma-optic regime, i.e. a partially magnetized plasma (ions are unmagnetized). In the high-density case (below 61 km altitude) ion-neutral coupling becomes extremely important and the ions should be considered magnetized. This is the so-called MHD regime, which is considered at low altitude. We can still expect ion acceleration but a higher magnetic field is required and we need to consider a smaller interelectrode distance.

Using flat plate electrodes and internal permanent magnets, this system will have minimal impact on the vehicle's aerodynamic characteristics. This effort, initially funded by a phase-I SBIR, began with the development of hydrodynamic codes to calculate the density and position of the plasma surrounding a vehicle based on it's geometry and velocity, so that the characteristics of the plasma which must be mitigated are known. Then the ReComm technique was demonstrated analytically and in simulations. The project has now entered SBIR phase-II and an experimental demonstration is under construction. An experimental facility is being configured with a helicon plasma source to generate a reasonable simulation of high altitude hypersonic plasmas. The ReComm system will be tested in this environment, with various plasma diagnostics and, as a primary indicator, communication between an embedded antenna and a remote antenna measured across a range of frequencies as the plasma environment and ReComm electric and magnetic field configurations are varied. This setup will allow verification of the effect, characterization and optimization, and will also be useful for testing other mitigation techniques. Additional goals of phase-II include extending the neutral flow and plasma simulations and modeling to improved capabilities including lower altitudes. This presentation will cover the ReComm effect, analytical and simulation work, and experimental results to date.

B6 Abstract for Presentation 6

Title: Parametric Antenna in the Ionospheric Plasma

Presenter: Dr. Vladimir Sotnikov, University of Nevada at Reno, NV

Abstract: Results concerning the parametric excitation of electromagnetic waves in an ionospheric plasma are applicable to the problem of radio frequency communication through a hypersonic plasma sheath. It is well known that only a small percentage of the power radiated by a VLF loop antenna in an ionospheric plasma goes into the electromagnetic whistler mode, which can propagate large distances from the source. In order to increase the total power in the whistler mode, a nonlinear mechanism was proposed. This mechanism involves the transformation of lower oblique resonance oscillations on quasi-neutral density perturbations excited by a dipole antenna, giving rise to whistler waves on combination frequencies. The amplitude of the nonlinearly excited whistlers may be several times the amplitude of whistler waves excited linearly by the loop antenna itself.

Experimental results and a nonlinear model for excitation of VLF sideband emissions during the CHARGE 2B mission will be presented.

Finally, application of developed methods as well as possible future simulation and laboratory experiments related to the problem of communication through plasma sheaths will be discussed.

B7 Abstract for Presentation 7

Title: Plasma Sheathing Control Using Boundary Layer Stabilization And Additives

Presenter: Dr. Robert F. Weiss (authored by Dr. Hartmut Legner , John F. Cronin, and W. Terry Rawlins), Physical Sciences Inc., Andover, MA

Abstract: Three techniques to mitigate the deleterious effects of high electron density distributions in hypersonic boundary layers were evaluated and analyzed for enhancing communication through plasmas. The boundary flow stabilization technique employs a metallic hydride on the vehicle surface to maintain an extremely low surface temperature and laminar flow with benign plasma sheath conditions. The additive techniques involve two schemes: liquid (water, Freon) injection into the boundary layer and low-concentration electrophilic metallic oxides distributed in the heat shield material. Both additive methods yield orders of magnitude reduction in electron density as calculated using the Non-Equilibrium Boundary Layer (NEBL) code for trans-atmospheric hypersonic vehicle flight conditions. Initial designs for implementing the techniques have also been developed and all are feasible, however, distributing electrophilic species in the heat shield involves the least flight system impact. Laboratory demonstrations of the three methods are required prior to selecting candidates for hypersonic flight test applications.

B8 Abstract for Presentation 8

Title: Communicating Subplasma Frequency Signals Through Plasma Both To And From Supersonic Speed Vehicles

Presenter: Dr. Alan Newell, U. of Arizona, Tuscon, AZ

Abstract: We examine in detail the propagation of a signal wave from a distant source (land or Afwet based or GPS) through the plasma sheath surrounding a hypersonic speed vehicle. We show how to achieve 10^11 and better W/Msqd sensitivity levels by using a pump wave generated on the vehicle which reflects off the resonant layer behind which the incident signal is trapped. We also show how to generate a signal from the craft by using the wave scattered from two on vehicle sources one of which carries information.

B9 Abstract for Presentation 9

Title: Aerodynamic Shaping Effects on Hypersonic Plasma Telemetry

Presenter: Dr. Ryan Starkey, U. of Maryland, College Park, MD

Abstract: Intelligent aerodynamic shaping of hypersonic vehicles facilitates the use of secondary options for telemetry through hypersonic plasma layers which may otherwise be undesirable. An overview of the effects of aerodynamic shaping with a focus on minimizing plasma frequencies and plasma sheath thicknesses will be given. Secondary methods for transmitting through this sheath will then be detailed. A summary of methods which have undergone flight tests on both historical and modern vehicles (for which data has been made available) will be given.

Appendix C Raw Voting Data

Table C1 Raw Votes for Each Technique by Voter

Technique/Voter #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Trajectory Shaping		1	1				1	1			1	1		1	1	1	1		1		
Whistler Mode Antenna			1	1			1		1			1	1								1
Plasma Modulation		1			1							1		1							
Antenna Location and Type							1					1			1				1		
Liquid or Electrophilic Injection		-1	1		1	1	1	1	1		1	1			1	1	1		1	1	1
Electrophilic heat shield additive (ablation)		-1	1		1	1	1	1	1		1	1			1	1	1		1	1	1
Magnetic Control - Attenuation Reduction		-1	1	1		1	1			1		1	1	1		1	1	1			1
Aerodynamic Shaping		-1	1	1		1	1	1			1	1			1		-1	1	1	1	1
3 Wave Interaction	1	-1	1		1	1	1	-1	1		1	1					1	1			
Control Surfaces		1	1					1							1	-1	1				
Electron Beams	1	1					-1					1									
Optical (Laser)	1	1					-1	-1			-1	1			1	1	-1	1	1		1
Cooling Techniques		1					-1	-1						1		1					
Magnetic Control - Plasma Shaping		-1	-1		1		1					-1		1		-1	-1	1			1
High Frequency	1	1	1	-1			-1	-1			-1	1	-1	1			-1	1			-1
High Power	-1	1		-1		-1	-1	-1	-1		1	1		1		1	-1				-1
Air Spike	-1	1	-1			-1					-1			1			-1				-1
Low Frequency	-1	-1		1		-1	-1	-1	-1		-1	-1				-1	-1	-1			-1
Relay Ejection		-1	-1			-1	-1	-1	-1	1	-1	-1			-1		-1	-1			-1