POTENTIAL SOLUTIONS TO COMMUNICATIONS DURING PLASMASONIC FLIGHT

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ABSTRACT

At about Mach number 10 and above, a high energy plasma field forms around a vehicle. This plasma sheath has a high attenuation factor that can cause communications black out. No practical solutions to communicating through a plasma sheath are known. In addition to standard real time data needs for test, a driving requirement to solve this problem is that most solutions will have to be designed into the vehicle. Modifications of vehicles designed to travel at these Mach numbers, especially any exterior modifications, will be extremely difficult due to effects on aerodynamics, thermal protection, and the materials used.

A list of possible solutions to communications through hypersonically induced plasma has been collected over several years. This list was added to and verified during the *Workshop on Communications through Plasma during Hypersonic Flight*. Pros and cons of these potential solutions have been discussed and documented as well. The workshop also included a vote by the attending experts on what solutions are most promising. This paper reviews these solutions, their pros and cons, and a recommended way forward to solving this problem.

KEYWORDS

Plasma, Hypersonic Flight, Telemetry, High Energy Physics, Radio Communications

INTRODUCTION

A standard Test and Evaluation (T&E) paradigm is to obtain real time telemetry during testing. Within the flight test community, this communications requirement exists for at least three reasons: safety of flight, catastrophe analysis, and test point clearance (is it safe to go onto the next test point without landing.) There are also communications that must be received by test vehicles. For example, there is a growing dependence on GPS during test and there are flight termination requirements for unpiloted air vehicles.

Many readers will be familiar with the compression of air that causes a sonic boom to form as a vehicle crosses the supersonic barrier. As the Mach number increases and a vehicle traverses the hypersonic regime, a somewhat analogous, electromagnetic, barrier is crossed at roughly Mach

10.   That is, the pressure and temperature cause the atoms in the air to start to dissociate into positive ions and negative electrons forming a plasma field around the vehicle. Thus we might talk about a “plasmasonic” regime just as we talk about a supersonic regime. A key aspect of plasmasonic flight is a high attenuation factor that causes telemetry and GPS blackout.

Although there are plenty of ideas on how to communicate through plasma, there are no proven, practical solutions. Lacking such a solution to a fundamental communications requirement, a *Workshop on Communications through Plasma during Hypersonic Flight* [1,2] was instigated. This workshop was sponsored by the Air Force Office of Scientific Research (AFOSR), the Air Force Flight Test Center (AFFTC), and the Office of the Air Force Chief Scientist. During the workshop, several theoretical approaches were reviewed and discussions were held regarding how to make progress in solving this problem. One of the main objectives of the workshop and this discussion was to develop a list of potential solutions and try to determine which of these solutions showed the most promise. The following sections discuss these potential solutions along with the pros and cons of each.

CRITERIA

Before presenting the potential solutions and discussing the pros and cons of each, let us consider what the criteria for a solution are. 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 in that extra material must be carried and some form of nozzle must be added to inject the material into the airstream. 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, partly because the workshop participants voted this the highest priority, but 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 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 waveform 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 whatever 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 must, 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.

POTENTIAL SOLUTIONS

Over the years the author has been forming a list of techniques that could provide potential solutions. There were seven new techniques added during the workshop and one added after the workshop. This section discusses the pros and cons of these techniques.

Low Communication Frequencies – Using very low frequencies avoids the plasma induced attenuation. Specifically how low has not been fully established although below 100MHz has been suggested. Although this method will work and can propagate long distances, it provides very low bit rates and is not a GPS solution. Further, the infrastructure is not in place and the spectrum is not allocated for telemetry use.

High Communication Frequencies – Using very high frequencies, specifically above the plasma frequency, avoids the plasma induced attenuation. How high a frequency has not been clearly established and is dependent on various properties. A positive aspect of this solution is that it provides high bit rates. However, it has been suggested that this needs to be above 30GHz which introduces several difficulties: the spectrum is not allocated for telemetry use and consequently there is no infrastructure, there is a high energy cost, atmospheric attenuation causes limited distance, and it is not a GPS solution.

High Power – Plasma adds one more attenuation factor. It would be possible to just communicate through it by transmitting with enough power – a lot of power. This increases the energy requirement on the vehicle. There is also an interference problem. It has been suggested that plasma formation and deformation happens as fast as flipping a light switch. Control of this powerful transmission would thus have to react to deformation as quickly or there is a potential to interfere with other spectrum users. This is not a GPS solution.

Aerodynamic Shaping – Control the shape of the plasma sheath by controlling the shape of the vehicle. The shape of the vehicle has a tremendous affect on the shape of the plasma. For example, during re-entry, the leading edge of the space shuttle is effectively the entire bottom of the shuttle. This huge leading edge allows for an opening in the plasma on top of the shuttle that allows for nearly continuous transmission (via satellite). In contrast, a sustained flight vehicle will have a very sharp leading edge probably causing a plasma sheath to form around the entire vehicle. There is some small hope that the shape of the vehicle would allow diversion of the plasma from around the antenna. However, it is more realistic to think that this could be used to minimize or stabilize the plasma over the antenna. If nothing else, the shape of the vehicle will have an effect on any other solution.

Antenna Location and Type – At the simplest level, if the plasma sheath does not encompass the entire vehicle (most likely towards the rear) then an antenna could be placed where the plasma does not form. There are also ideas regarding types of antennas that might aid in penetrating the plasma. However, in the context of a complete plasma sheath, this is not a complete solution. But it seems certain that location and antenna type will play a factor in any successful solution.

Electrophilic Injection – Inject a substance (fluid) into the plasma sheath that de-ionizes the plasma therefore reducing (or eliminating) the attenuation factor. This was demonstrated during a Gemini reentry using water. However, the amount of water is large (on the order of pounds per second depending on various factors.) There are better materials than water, but weight and environmental factors come into play. There is also the question of the complexity of the injection mechanism. On the plus side, this is potentially a GPS solution.

Electrophilic Heat Shield Additive (Ablation) – This is a more passive version of electrophilic injection and has similar benefits and issues. However, this adds a design factor into developing the material structure of the vehicle. There is also a potential maintenance issue in that, for re-usable vehicles, ablative material might need to be replaced. This is also a potential GPS solution.

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 essentially creates a hole in the plasma. Initial studies show promise for use at high altitudes (i.e., low atmospheric pressures) but there are very real concerns about size and weight at lower altitudes. This is because electron density in a plasma is related to pressure; the higher the pressure the higher the density and thus the higher energy requirements for the magnetic field. Permanent magnets get larger and heavier as their power increases. This technique would allow use of existing infrastructure and requires relatively minor modifications to the vehicle. This is potentially a GPS solution although the de-ionization may not be complete and thus there may still be attenuation.

Magnetic Control for Plasma Shaping – Instead of magnetically de-ionizing the plasma, it is possible to magnetically control the shape of the plasma. That is, it may be possible to divert the plasma around an antenna. The same benefits and issues apply as for magnetic control for attenuation reduction although there is more skepticism regarding GPS reception since complete diversion of the plasma is questionable. This seems to lend itself to being a supplemental technique that could possibly aid other techniques.

Three Wave Interaction – This uses 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. This technique could use the existing infrastructure since the generated signal could be in the existing telemetry bands. There is theoretic potential for this being a GPS solution. However, this requires adding another transmitter to provide the stimulus signal which, if nothing else, increases the engineering complexity. However, the stimulus frequency must be high powered and above the plasma frequency (initial estimates are a MW of power at over 30 GHz) which increases the energy costs and stretches current technology for onboard transmitters. Further, the question has to be asked, if there is a transmission unaffected by the plasma, why not use it for the data transmission? Even if you are not using the stimulus signal for data transmission, you still need the frequency allocated for this use, which it is not.

Evanescent Wave Propagation – At present this is a theoretical solution based on mathematical physics. Recall that the mathematical description of a radio signal has both real and complex components. It is normally the real component that is of interest when transmitting information and it is the real component that suffers from the attenuation of the plasma. However, it turns out that the complex component increases while the signal propagates through the plasma. The question becomes, how is this component of the signal captured? First off, there has to be at least some level of power left in the real component, which is questionable depending on various factors. Second, initial theoretical analysis suggests the best method of capturing the complex component is using metamaterials. That is, very recently produced, rare, and not well understood materials that have a negative index of refraction. There is some potential to this solution, but there appear to be significant engineering difficulties.

Optical (Laser) – Optical communications is a maturing technology. A major plus to this solution is the potential for very high bit rates. Also, this part of the spectrum is currently unregulated. Whether this will work through plasma seems to be an open question. There is some concern since many optical communications systems work in the infrared and the plasma sheath tends to be hot (as much as 9000 degrees Celsius at the leading edge of the plasma.) However, the plasma is not necessarily visually opaque. Energy use is a potential issue although some techniques put the majority of the energy requirement on the ground. Somewhat surprisingly, even at plasmasonic velocities, tracking is probably not a problem although there may be a cost factor. There is certainly no infrastructure and there are distinct safety concerns. This is not a GPS solution.

Trajectory Shaping – Control the shape of the plasma sheath by controlling angle of attack and position relative to receivers. This potentially allows utilizing any break in the plasma, most likely looking towards the rear of the vehicle. This may be useful for some specific test flights. However, every flight would require analysis – including for unintended trajectory deviations. This is certainly not a general solution and not practical for operations (vs. test).

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. Since the control surfaces will be moving, this probably does not lead to a continuous solution throughout the flight.

Cooling Techniques – Since the plasma is fundamentally caused by heat, cooling the area around the antenna would reduce (or eliminate) the attenuation. It is not clear how big or heavy or how complex such a cooling mechanism would be. Also, where do you transfer the heat too? This technique is probably not a complete solution, but considering heat effects may aid in determining where to place the antenna.

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 plasmasonic flights. This technique was introduced at the workshop but not elucidated on.

Plasma Modulation – This was introduced during the workshop but not elucidated on. This is probably a transmission only technique and thus probably not a GPS solution.

Electron Beams – This was introduced during the workshop but not elucidated on. Although a comment was made that this might be a GPS solution.

Air Spike – This is a form of aerodynamic shaping but specifically puts a sharp leading point (either physically or using a laser) in front of the vehicle. Other than moving the leading edge of the plasma forward and, perhaps, opening up the plasma towards the rear of the vehicle, it is not clear how this allows control of the shape of the plasma. Both physical and laser spikes add a new factor to the aerodynamics. A physical spike raises ablation and maintenance questions and a laser adds onboard energy requirements and engineering complexities.

Relay Ejection – Periodically eject a relay that is close enough to the vehicle to pick up and re-transmit the signal or provide burst transmissions. The big safety question is what happens to the relay after you eject it? This still requires transmission through the plasma, just shorter distances, although at greater than 8,000 miles per hour, the distances may not be so short or a lot of relays may need to be ejected. This is not a GPS solution.

THE WORKSHOP VOTE

During the workshop, a vote on the different techniques was taken. This section provides the tally of those votes. The attendees 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 most votes for a single technique were 15 and some techniques had as few as 4 votes. Evanescent wave propagation was identified after the workshop and thus not voted on.

Table 1 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 those techniques that the group sees as highly worth pursuing, techniques that are clearly viewed as not worth pursuing and techniques that do not have a clear consensus. The last column of Table 1 lists the vote "confidence" which is the number of yes votes divided by the total number of votes. The term "confidence" is used 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 worth pursuing.

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 Table 1 and when sorted by confidence. 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 they are personally familiar with 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 1 Vote Tally of Techniques Sorted by "Yes Minus No"

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

CONCLUSIONS

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 the workshop 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.

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.

In order to move forward towards a solution, continued research must take place. The single most overriding aspect of this research is:

Experimental data is needed to validate computational and mathematical models!

Most of the leading techniques identified have models that support their validity. However, there is very little experimental data to validate any of these. Although theoretical analysis can continue, determining which solutions work is not possible without more experimentation.

REFERENCES

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