URSI - RCRS 2022, IIT (Indore), India, 1 - 4 December, 2022

Detection of Hypersonic Missiles in presence of Plasma Stealth

Vangipurapu Lakshmi Harshitha, James A Baskaradas
SASTRA Deemed University, Tamil Nadu, India, 613401, https://www.sastra.edu/

1. Abstract

The hypersonic missiles are the type of missiles which can travel above Mach 5 that is 5 times the speed of sound. The hypersonic missiles with nuclear or non-nuclear warheads causes threat not only nationally but also globally. Due to their high speed, heat is produced which breaks down the molecules in the atmosphere causing formation of ionized gas layer called as Plasma stealth. So, it is very challenging to detect hypersonic missiles but few vulnerabilities of hypersonic missiles make it possible for its detection. The Plasma Stealth itself can be used to detect the hypersonic missiles. By detecting the Plasma footprint which will last for few milliseconds, the hypersonic missiles can be detected.

2. Introduction

The Missiles which travel above Mach 5 will create a shock wave. Shock waves are created when missile travels faster than the speed of sound. The shock wave connects the supersonic and the subsonic flows. The shock waves increase the pressure and temperature where ionization of the surrounding air takes place there by creating plasma which is a non-linear phenomenon. The shock waves also exist in plasmas when there will be no collisions among the particles. This created plasma blocks the radar signals and therefore detection of the hypersonic missiles becomes difficult as this plasma stealth will decrease the RCS. The blockage of RF signal depends on the electron density of the formed plasma. The created plasma can be detected the way we detect meteor trails thus detecting the hypersonic missiles.

The hypersonic missile can be compared with a meteor whose speed is much greater than the till date possible speed of hypersonic missiles. Many meteors will enter the earth atmosphere and interacts with it to form meteor trails. When a meteor hits the atmosphere, the air surrounding will be highly compressed to increase the temperature and form Plasma. The meteors produce large amount of energy and low frequency radio signals. These meteor trails mostly will last up to few milliseconds but sometimes it can even last for few minutes. The plasma produced by meteors is not only detected but also used for long range communications known as Meteor burst communications whose operating frequencies ranges from 40-150MHz. HF or VHF radars with high power and large aperture are used to trace the plasma trails created by the meteor.

3. Hypersonic missiles

The wars have a huge demand on the nations resources which affects the social and economic fabric of nations. But wars also contribute to technological development to design and invent armaments. Recently hypersonic missiles are trending and are being developed and manufactured by many developed and developing countries. The hypersonic missiles travel at a lower altitude than the ballistic missiles and they are highly maneuverable which can also change the trajectory during the flight because of which it's very difficult to detect them.

The maximum speed of above Mach 25 as of 2020 is achieved below the thermosphere which ranges from 500-1000kms.The Hypersonic gliders initially will be boosted by the rockets to higher altitudes and then they glide to their targets. The Aero-Ballistic hypersonic missile will be launched in hypersonic speed with the help of a rocket and then it follows its trajectory without any supply of power during its trajectory. A hypersonic Cruise missile is boosted with a rocket and then uses a Scramjet to sustain its speed. The hypersonic glide vehicles are faster than the ballistic missiles only in the higher altitudes whereas in the lower altitudes ballistic missiles can deliver warheads at faster speeds.

The drag forces increase with the square of the velocity of the hypersonic vehicle and the energy loss will be proportional to cube of its velocity. So, usage of re-entry hypersonic missiles which travels in the upper atmosphere is not very efficient way to reach the target. The altitude range of hypersonic missiles varies from 30-90kms which lies approximately in the mesosphere. The hypersonic missiles interact with the mesosphere to form the plasma stealth. The main reason for the Plasma stealth is friction between the missile and the air which heats and ionizes the surrounding air to form high energy plasma. This created plasma stealth will attenuates the radar signals which prevents the detection of hypersonic missiles. [1][2].

4. Properties of Plasma formed

Plasma is a Quasi-neutral gas of both charged and neutral particles that exhibits the collective behavior. The plasma will exhibit non-linear properties when intense radio waves are incident upon them [3]. The organized motion of ions in the plasma is called plasma oscillations. The frequency at which electrons in the plasma start to oscillate naturally is known as the plasma frequency. The created plasma both absorbs and also reflect back the radio signals.

The relation between the cutoff frequency of the plasma and the electron density is described in the equation (1) where N_{max} is the electron density.

$$f_c = 9 * (N_{max})^{1/2} \qquad (1).$$

.

The relation between plasma collision frequency and altitude of the hypersonic missile is given in equation (2) where T is the temperature and the (ρ/ρ_0) is the gas density ratio.

$$f_c = 3 \times 10^8 \, (\rho/\rho_0) \, T \qquad (2).$$

.

Any signal with higher frequency than the critical frequency of the plasma will propagate through the plasma and any frequencies less that the critical frequency will gets reflected. The operating frequency of the radar should be inversely proportional to the altitude at which hypersonic missile flies. [4]

Finding the electron density of the plasma stealth is the primary step to find the critical frequency of the plasma to fix the operating frequency of the radar below that. The electron density of the plasma will be varying because of the complex thermochemical reactions and the flight dynamics. The space-time varying density of plasma leads to attenuation of the radio signals. If some part of the radio signal is reflected and some part is absorbed by this created plasma stealth, this creates a resonating electric field in the plasma itself.

5. Characteristics of Meteors

Meteoroids enter the earth atmosphere at high speeds above 11.2km/s creating shock waves and burnup to form the meteors. This shock waves generates very high sound energy which can exceed 200 decibels. The air in the mesosphere is very dense that it burns up the fast-moving meteor and creates a lot of heat. This heat creates plasma trails which can be detected by the radar. The plasma is caused due to the ambipolar diffusion and also the drifts with the surrounding air. A meteor shower can be observed when a lot of meteors appear in a short time. Meteors also produces sonic booms which can be heard after few seconds of visibility of the meteor. Generally, high power and large aperture radars operating at HF or VHF bands are used to trace the plasma trails of the meteors. [5]

The main radio echo will be observed only when the beam is directed at right angle to the meteor. The relation between the electron density α in cm and ε which is the power scattered back by the receiver when aerial beam is perpendicular is described in terms of the radar parameters in the equation (3) where $\left(\frac{mc^2}{e^2}\right)$ is the inverse of the classical electron radius, G is the power gain of the transmitter and the receiver, P is the peak transmitter power, λ is the operating wavelength of the radar and R is meteor trail distance from the radar.

$$\alpha = (24)^{1/2} \, \pi \left(\frac{mc^2}{e^2}\right)\left(\frac{1}{G}\right)(\, \varepsilon R^3/P\lambda^3)^{\frac{1}{2}} \qquad (3)[6].$$

.

The minimum speed of a meteor to enter the earth's atmosphere is equal to the escape velocity of the earth which is 11.2km/s. Any meteor observed will have higher speed that this. The maximum speed of the meteors observed is 72km/s which is approximately twelve times higher than Mach 20 which is equal to 6.86km/s. These fast-moving meteors are not only detected but also traced by HF and VHF radars. The meteor trail will enable the transmitted signal to be reflected back at some point which can be detected. [7].

6. Comparison table between Hypersonic missile and Meteor

Parameter	Hypersonic Missile	Meteor
Speed	Minimum speed is Mach 5 (1.715km/s). Maximum possible which is found aerodynamically stable is Mach 20 (6.86km/s).	Minimum speed to enter the earth's atmosphere is 11.6km/s. Maximum detected meteor speed is 72km/s.
Atmospheric temperature	183K is the temperature of top layer of Mesosphere. Temperature decreases as we move higher in the Mesosphere.	150K- 750K is the temperature range where meteors are found.
Surface temperature	Approximately 2473K	Approximately 1922K
Mass	The average mass of the missile is found to be 3000kg	The largest meteor found to have 4000kgs where surviving fragment is 1170kgs
Altitude	30-90kms	80-120kms
Maximum possible RCS	-40dbsm	-42dbsm

[8][9][10][11].

7. Differentiating Hypersonic missile from Meteor

The Meteors travels ten to twelve times faster than the hypersonic missiles. The speed can be used as a constraint to differentiate the meteors and the hypersonic missiles. As the speed differs, the time difference between the first echo and second echo will also be different. Meteors occurs in groups. The launching of Hypersonic vehicles with speeds above Mach 20 in a group is highly challenging. Thus, meteors can be easily differentiated from hypersonic missiles.

A Pulse Doppler Radar with high Pulse Reception Frequency can be used to detect the Plasma footprints. This Radar can also be used to track the Plasma footprints.

8. Working of Pulse Doppler Radar

The Pulse Doppler Radar (PDR) is the combination of both Pulse radar and Continuous wave (CW) radar which can be used to get accurate velocity and ranges. Pulse Repetition Frequency (PRF) is number of pulses per unit time. A high PRF PDR is used to get high range accuracy and low PRF is used to get velocity of the target accurately. The limitation of the PDR is blind speeds which occurs when the speed of Hypersonic missile is equal to PRF can be avoided by using the Staggered Pulses.

Pulse generator generates a rectangular pulse waveform and the output is given to the transmitter block. The transmitter block amplifies and then transmits the signal with the help of antenna. The receiver receives the backscattered signals and amplifies the incoming signal. An FIR filter is used whose coefficients are the time reversal of the transmitted signal. Before the detection this filter is used to improve the SNR. Time varying gain is applied to each signal to compensate the range loss in range gate. The pulse integrate is used to integrate the successive pulses. Then the echo will be displayed. A Duplexer can be used to transmit and receive the signals using same antenna. The main advantage of this same local oscillator and be used in both transmission and reception end thus preserving the coherence.

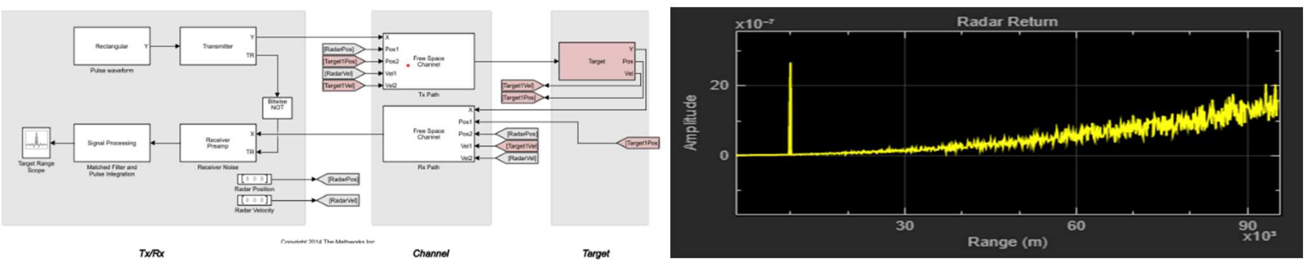

Figure 1. Blockdiagram of PDR, Return Echo observed from a missile

The PDR is simulated in the MATLAB whose operating frequency is fixed at 30MHz and maximum range of 100kms. The echo can be observed at the desired range by changing the target position. High power is used to capture these echoes.

9. Considerations

The operating frequency will be inversely proportional to the altitude of the hypersonic missile. The operating frequency should be less than the cutoff frequency of the plasma stealth formed so that it can be reflected back and be detected. But due to the HF and VHF bands there will be many challenges while designing the radar. [12].

At low frequencies, the antenna height becomes large. These ranges have lower bandwidths and less reliability when compared to other higher frequency ranges. Operating at VHF induces cosmic background radiation due to the strong diurnal oscillations. This can be used to calibrate the radar. Flicker noise will increase with decrease in the frequency. Power transmitted can be high as the Hypersonic missile itself faces communication blackouts. So, it cannot have counter measure system as even that system gets blocked by the plasma created.

10. Limitations

The electron density found in the plasma varies with the speed, temperature and the altitudes. So, fixing an operating frequency is very challenging as the critical frequency of plasma which is dependent on the electron density. If operating frequency is above this cutoff frequency, then attenuation of the signal happens and no echo will be detected. Hence, we should ensure that operating frequency should be less than the cutoff frequency of the highly dynamic plasma formed.

Though we can transmit high powers, the existing equipment might get saturated when high powers are used. The entire radar system which can operate for high powers should be designed which is again cost effective. Detection alone will not be enough but also the destruction of hypersonic missile should also be done. The counter surface-to-air missiles should be at equal or at higher speeds than the incoming hypersonic missile.

11. Conclusions

The hypersonic missiles can be detected the way we detect the meteors and also can be tracked. The dynamically changing plasma which will lasts for some 10 milliseconds can be detected and traced. A Pulse doppler radar with high powers can be used which operates at HF bands for the detection. Though there are many challenges, those can be mitigated by fixing the operating frequency below the cutoff frequency thus enhancing the probability of detection of the hypersonic missiles by the radar.

The formation of plasma is inevitable at hypersonic speeds. There are ways to detect the plasmas formed in the mesosphere using MST radars. Thus, detecting the hypersonic missiles is easier this way by tracing the plasma formed and differentiating it from the naturally formed plasma in mesosphere and also due to the meteors rather than concentrating on how to bypass plasma stealth and detect the hypersonic missile.

12. Acknowledgements

Acknowledgements go in here.

13. References

1. David Wright, Cameron Tracy, "The Physics and Hype of Hypersonic Weapons", Scientific American-space and physics, 1 August 2021, doi: 10.1038/scientificamerican0821-64

2. "Vulnerability of a hypersonic missile to Surface-to-Air Defensive Missiles", National Research Council, 1998, pp. 54-58, doi: https://doi.org/10.17226/6195.

3. Francis F. Chen, "Introduction to Plasma Physics and controlled Fusion", Plasma Physics, 2nd ed, vol 1, 12 January 2010, pp. 297-308.

4.Mike Hapgood, "Linking Space Weather Science to Impacts—The View from the Earth", 2018, doi: https://doi.org/10.1016/B978-0-12-812700-1.00001-7

5. Masaki Tsutsumi, David Holdsworth, Takuji Nakamura, Iain Reid, "Meteor observations with an MF radar", 10 June 1999, doi: https://earth-planets-space.springeropen.com/articles/10.1186/BF03353227

6. J.B. Brown, K. Mendelssohn, "A New Technique for Studying the Helium Film", Nature 160, 15 November 1947, doi: https://doi.org/10.1038/160670a0

7. J.D. Mathews, "Radio science issues surrounding HF/VHF/UHF radar meteorstudies", 20 November 2003, doi: 10.1016/j.jastp.2003.11.001

8. G. Stober, Ch. Jacobi, "Electron line densities and meteor masses calculated from models and meteor radar measurements", Wiss. Mitteil. Inst. f. Meteorol. Univ. Leipzig, 2008, pp. 156-159.

9. Sigrid Close, Stephen M. Hunt, Michael J. Minardi, and Fred M. McKeen, "Meteor Shower Characterization at Kwajalein Missile Range", vol 12, 2000.

10. Lihao Song, Bowen Bai, Xiaoping Li, Gezhao Niu, Yanming Liu, Liang Zhao, "Space-Time Varying Plasma Sheath Effect on Hypersonic Vehicle-borne SAR Imaging", in IEEE Transactions on Aerospace and Electronic Systems, 21 April 2022, doi: 10.1109/TAES.2022.3166062.

11. Obenberger, K. S., Taylor, G. B., Hartman, J. M., Dowell, J., Ellingson, S. W., Helmboldt, J. F., Henning, P. A., Kavic, M., Schinzel, F. K., Simonetti, J. H., Stovall, K., Wilson T. L, "Detection of radio emission from fireballs- The Astrophysical Journal", 2014, https://doi.org/10.1088/2041-8205/788/2/l26

12. Dan Cheng, Li Ying Feng, "Electromagnetic Characteristics of Reentry Target in Plasma Sheath", 29 July 2019, IEEE International Conference on Computational Electromagnetics (ICCEM), pp. 1-3, doi: 10.1109/COMPEM.2019.8779126