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ECHO CHARACTERISTIC ANALYSIS OF THE NONEQULIBRIUM WAKES OF REENTRY VEHICLE

by

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TITLE: ECHO CHARACTERISTIC ANALYSIS OF THE NONEQUILIBRIUM WAKES OF REENTRY VEHICLES

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SUMMARY This article makes use of Reference [1]'s method to calculate the flow fields of pure air nonequilibrium reentry vehicle wakes. It analyzes the effects of wake plasma body fields on radar wave frequencies. In conjunction with this, it takes a step further calculations of radar scattering cross sections under several types of elevation conditions. It explains several important factors influencing cross section size and distribution. Analyses and calculations clearly show that, after taking the Reynolds number, which is verified with the diameter of the bottom section or base of the object and environmental parameters, and arriving at turning point or transition values, in fully developed trubulent flow wakes, it is possible to show the appearance of the phenomenon of abrupt increase in scattering cross sections.

KEY TERMS Plasma, Echo Behavior, Radar Scattering Cross Section, Nonequilibrium Flow

I. INTRODUCTION

The plasma fields which are formed in the wakes of reentry vehicles are necessary conditions for capturing targets and providing control. In order to understand the echo behavior or characteristics of ionization wakes on ground radar, it is necessary to analyze the flow field characteristics of reentry vehicle wakes and the various types of factors which they have on the sounding frequency patterns of radar waves as well as on the echo behavior or charactertistics of responses.

This article makes use of the methods in Reference [1] to calculate pure air nonequilbrium reentry vehicle wake flow fields. It analyzes the frequency response effects of wake plasma fields on radar waves, and, in conjunction with that, carries a step further calculations of radar scattering cross sections under a number of elevation conditions, explaining several important factors influencing the size and distribution of cross sections. Going through analyses and calculations, one reaches the conclusion that, after taking Reynolds numbers verified from object base diameter and environmental parameters and arriving at turning point or transition values, in complete or fully developed turbulent flow wakes, it is possible to show the appearance of an abrupt increase in echo phenomena. As far as the factors influencing the size of echo cross sections and their changes are concerned, they include the shape of objects, dimensions, enthalpy or heat content values for neck sections, combustion corrosion constituents, and the related lengths of turbulent flow pulses. Because of this, in order to improve echo behavior or characteristics, it is necessary to do a complete and comprehensive analysis of the factors influencing them.

II. PLASMA WAKE FREQUENCY RESPONSE EFFECTS ON RADAR WAVES

1. FREQUENCY RESPONSE EFFECTS

When reentry vehicles fly back into the layers of the atmosphere due to the fact that the strength of the friction forces between the object and the atmosphere cause the peripheral gases of the environment to abruptly heat up, this creates, as a result, dissociation and ionization reactions. After the materials of the reentry vehicle have been corroded by the high temperature combustion of this, there will still be combustion corrosion products mixed into the environmental gases, participating, in conjunction with this, in reactions. This layer of reacting gases around the periphery of the reentry vehicle forms a plasma sheath and follows along in the direction of the flow to the rear portion of the object where it then forms a plasma wake (of course, in the vicinity of the neck portion, because of the recompression which gives rise to an increase in temperature in the laminar wake, gas ionization also makes a definite contribution). This type of ionization wake will, with the electromagnetic wave signals sent out by the ground radars, create mutual effects. 287

A good amount of analyses and calculations point out that, when reentry flight craft come back into the layers of the atmosphere initially, they possess a weak ionization plasma wake. The status of the flow movements presents a laminar flow or, within a relatively large distance, from the neck section toward the rear, laminar flow states in all cases. The macro motions of laminar flow plasma are regular. Their response to radar signals approximates the form presented by mirror surface reflections. Single station ground radars, at often used non-normal azimuth angles of incoming radiation, are capable of receiving extraordinarily small relected powers. Moreover, under the conditions of this initial return to the ground of weak ionizations, it is possible that the reflected powers are also extremely small. After the Reynolds number $Re_{\infty D}$ of incoming flows reach as high as a certain fixed value (for a long thin flat cone with a base diameter of 1 meter, it is approximately $Re_{\infty D}=5x10^5$ with a corresponding elevation of 45-50 km), the wake as a whole is, in all cases, turbulent flow movements. In turbulent flow wakes, despite the fact that plasma macro motions are random and chaotic movements, and their scattering of radar waves is almost chaotic, on the basis of differences in plasma density levels, however, (it is possible to reflect the magnitude of the inherent or proper frequency f_p), the scattering effects are capable of dividing to form two areas of consideration. The area where the plasma's inherent or proper frequency is higher than the radar signal frequency (and the various components of the interior of the wake have plasma frequencies corresponding to electron collision frequency v which are also not too high, that is, when damping is small) is where the area or section is called overdense. In this area, although the effects produced with the incoming waves are turbulent flow pulse plasma, it still, however, belongs to a type of surface scattering effect, mainly producing coherent scattering[2]. In order to calculate the size of scattering cross sections, from Reference [3], one takes this section and sees it, in approximate terms, as forming a uniform diffuse reflection associated with a Lambert suface type. Because of this, the size of the scattering cross section is only related with the size of the plasma cross section and the azimuth angle of the waves sent out. However, on site measurements[4,2] point out that radar systems are certainly not capable of clearly receiving this section's scattering signals. When plasma frequencies are lower than radar signal frequencies, it is called a sub-dense area or underdense. In these areas, plasma frequency responses to radar waves are capable of including the three protions of transmission, absorption, and and reflection. This is a type of volume or capacity effect (noncoherent scattering). In the reflective part, this is particularly the case with the reflected energies in non lens or mirror surface directions, determined by the totally random pulses of plasma. Reference [2], from measurements and analyses, explains the echo signals received by radars as primarily originating from this reflective portion.

From the above analysis, it is possible to know that, in laminar wakes, regardless of the magnitude of the frequency of the plasma, (overdense or underdense), in all cases, use is made of mirror or lens surface reflections in order to make approximations. Within areas of mirror or lens surface reflections, due to the fact that the waves sent out by the ground radars generally will not form incoming radiation in a normal direction, as a result, they are able to receive very few echos. In overdense areas of turbulent flow wakes, pulse surfaces form diffusion and reflection states in incoming radiation. As a result of this, the reflected power and the echo energies which the radars are capable of receiving are very small. However, in underdense areas of turbulent flows, by contrast, the echo energies are much, much larger. Because this is the case, it is possible to recognize that, at often used azimuth angles (this article selected 45°), radar scattering cross sections are, primarily, the results of scattering associated with turbulent flow underdense sections. As a result of this, accurate predictions of reflective cross sections of underdense plasma have the greatest practical significance.

Distinguishing the overdense and underdense critical characteristic quantities is the frequency f_r of the transmitted electromagnetic waves. When the plasma frequency f_p is higher than the radar signal frequency, this portion of the plasma is placed in the overdense area. On the other hand, when $f_p < f_r$, the plasma is placed in an underdense area or zone. At this time, one should consider volume or capacity scattering effects. With precisely determined radar transmitting signal frequencies, estimates of reflective cross sections must be related to the electron density pulse strength in the plasma and the correlated turbulent flow pulse length.

2. SEVERAL HYPOTHESES

Observations of actual flow movements clearly demonstrate that plasma wakes are not uniform fields (within wake cross sections, electron density distributions are not uniform. Wake widths are also undergoing changes, and so on.) There is a process to the transition from laminar flow to turbulent flow and it does not suddenly occur at one location. The plasma boundary is not an optical boundary surface. Moreover, in the process of coming back to earth, the azimuth angles of objects show variations. Furthermore, because turbulent flow pulses act, in plasma boundaries, so that incoming radar waves are also capable of giving rise to phase changes, polarization, and so on. Actual original or primitive flow fields of this type are complicated. There is no way, theoretically speaking, to strictly calculate out their flow fields and echo behavior or characteritics. In order to be able to take the analyses of the section above and use them to figure the wake flow fields of flight craft returning to earth as well as to calculate the echo behavior or characteristics, it is necessary to make simplified hypotheses with reference to flow fields and several related quantities. In this article, the long thin blunt cone shaped objects which are considered returning to earth are under flight conditions of 70-50 km. We make the simplified hypotheses below.

(1) Calculations of wake flow fields make use of the quasi one dimensional model of Reference [1] to solve for distribution values for electron density along the direction of flow on axses. Because of 288 the fact that, within wake cross sections, electron densities on axses reach peak values, it follows as a result that, using them in order to substitute for the distribution values within cross sections, one is capable of reflecting actual flow movements. This is an option. In this, we hypothesize that the transition from laminar flow to turbulent flow occurs suddenly at a certain single location along the axis. Moreover, consideration is not given to the transition process. Turbulent flow average electron density is figured out from the average value for temperature within the flow field. The influences of all pulse quantities on average values, for all cases, actualize themselves through turbulent flow transmission or shipping coefficients which are made use of in equations.

(2) The electron density pulse strengths which are used to calculate turbulent flow underdense radar scattering cross sections make use of local averages of electron densities in order to display them, that is, they assume $\overline{\Delta n_e^2} = n_e^2(T)$. This is often used in the engineering calculations of electron density pulse strengths. Here, it is convenient to point out that, from a theoretical point of view, relatively strictly analyzing the influences of turbulent flow pulses, now and in the future, still should have carried a step further detailed research on it.

(3) The magnitude of turbulent flow correlation length is determined by the selection of the turbulent flow correlation model. Besides this, assuming that, in situations in which one selects an index type correlation model, one makes use of the approximations of Reference [2], one arrives at the correlation length being only related to the atmospheric density, that is, under certain specified elevation conditions, the correlation length is a constant value.

(4) Divisions between overdense and underdense regions, in turbulent wakes, are assumed to occur suddenly, that is, taking the electron densities along axial directions, in their distribution, that location which corresponds to critical *frequency* values is defined as a critical point.

III. FLOW FIELD AND SCATTERING CROSS SECTION CALCULATIONS

1. FLOW FIELD CALCULATION RESULTS

This article makes use of the quasi one dimensional methods of **Reference** [1]. For a small blunt-nosed cone with a base diameter of 1.852 m, it approximates, for an invariable speed (approximately 7.65 km/s), under three elevation conditions of 70, 59, and 48 km, calculations for the distributions of various quantities of wake flow fields along the wake axis. Winding flow media are only considered for nonequilibrium thermodynamic situations with pure air. Fig.1 shows the distribution, along the direction of flow, of wake axis electron density. From the results of calculations, one learns that:

(1) Under the 70 km condition, at the location of the transition point from laminar flow to turbulent flow, the inherent frequency of the corresponding plasma f_p is far smaller than the three types of radar wave frequencies which are used in this article (UHF frequency

band uses f_1 waves. S frequency band uses f_2 and $f_{s(illegible)}$ waves). As a result, when at 70 km, turbulent flow wakes, relative to these three types of waves, in all cases, belong to the underdense category and are, moreover, weak plasma regions.

Fig.1 Electron Density Changes On Nonequilibrium Wake Axses

(2) When at 59 km, the turning or transition point corresponding to f_p is still smaller than the frequency values for the waves $f_{1(illegible)}$, f_2, and f_3. Because this is the case, the whole turbulent flow wake also belongs, in every case, to the underdense region.

(3) When at 48 km, f_p corresponding to the turning or transition point from laminar flow to turbulent flow belongs to underdense reflection relative to f_2 and f_3. Moreover, with regard to f_1 waves, the wake includes the two overdense and underdense regions. (It should be explained that, due to the approximate nature of the precise determination of the location of turning or transition points as well as $n_{c\ trans}$ calculations, the result of it is that the locations of the critical points determined below are a type of estimated result).

These results and the estimates and experimental measurement results of References [2] and [4], for long thin objects with blunt heads in proximate orbits, are qualitatively in line with each other.

2. RADAR WAVE REFLECTIVE CROSS SECTION CALCULATIONS

From the analysis in the first and second sections, it is possible to know that ground radar stations are capable of receiving echos which, basically, in all cases, come from the reflections of underdense regions of plasma. Here, one does not do overdense region calculations, but only considers the reflective cross sections of underdense regions after critical points. Making reference to the scattering equation supplied by Reference [3], one obtains 289

$$\sigma_{u,D}=8\pi\times10^{-16}\int\frac{\overline{\Delta n_e^2}\cdot l^3}{\left[1+\left(\frac{4\pi l}{\lambda}\right)^2\right]^2}dV$$

σ u(illegible),D indicates the underdense radar scattering cross section after being nondimensionalized by the object base diameter. In the equation, $\overline{\Delta n_{e(\text{illegible})}^2}$ is the electron density pulse strength, that is, the mean square value of the electron density pulse quantity $\Delta n_{e(\text{illegible})}$. According to assumption (2), one has $\overline{\Delta n_e^2} = n_{e(\text{illegible})}^2(\overline{T})$. $\overline{T}$ is the average quantity for temperature in turbulent flow wakes. V is the volume of underdense plasma regions. l is turbulent flow correlation length. It reflects turbulent flow pulse effects. This article quotes the relationship which is precisely determined in Reference [2] (see Fig.2). After selecting index model correlation functions, it makes use of actual measurements of the radar reflection cross section relationships for S frequency bands and UHF frequency bands. It solves the relationship of correlation length and flight orbit or track passage altitude, drawing up the relational formula between l and the atmospheric density to be

$$l=\left(\frac{1.5\times10^{-4}\rho_0}{\rho_\infty}\right)^{\text{[illegible]}}(M)$$

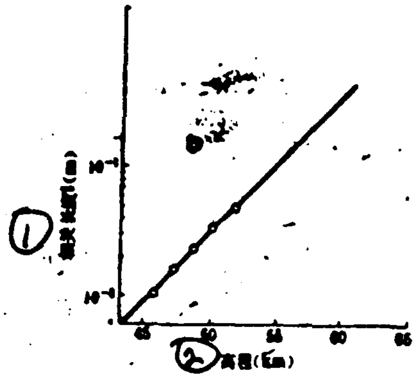

Fig.2 The Relationship Between Correlation Length and Elevation[2]
(1) Correlation Length (2) Elevation (km)

In this, p_o is the atmospheric density at sea level. p is the atmospheric density corresponding to the elevation. Reference [2] confirms that the selection of the correlation function--kolmogorov 2/3 degree power rule or index form of correlation function--does not have any great influence on 1.

The conditions under which the reflective cross section estimating formula which is selected by this article is appropriate for use require, within wakes, the satisfying of two dimensional scale similarity rules. A good deal of analysis which already exists makes clear that, in the wakes of vehicles reentering at hypersonic speeds, before reactions capturing electrons associated with the production of oxygen molecules, two dimensional scale similarity rules are capable of being set up in an approximate way. This article's calculations point out that the location of the occurence of capturing reactions is far after 100-200 times the base diameter. Moreover, at this time, it already belongs to the category of weak plasma. Energies reflected toward electron waves are already very small. As a result of this, the selection of the equation above is desirable.

IV. RESULTS AND ANALYSES

The situation for the calculations in this article is a base diameter of 1.852m, a small blunt nosed cone with a semiangle of 11°, and a flight speed of 7.6 km/s, figured at three elevations.

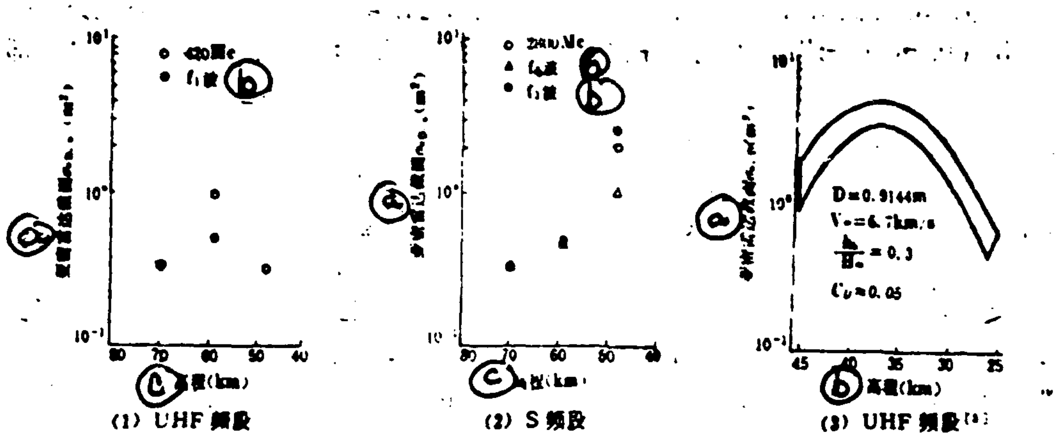

Fig.3 Underdense Radar Cross Section Relationships With Changes in Elevation (1) UHF Frequency Band (a) Underdense Radar Cross Section (b) Wave (c) Elevation (2) S Frequency Band (a) Underdense Radar Cross Section (b) Wave (c) Elevation (3) UHF Frequency Band[3] (a) Underdense Radar Cross Section (b) Elevation

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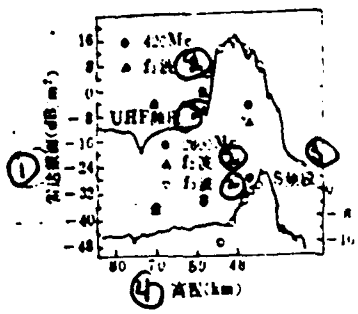

Fig.4 A Comparison of Calculations and Measurements for the U.S. Trailblazer Ik Model Radar Signal (1) Radar Cross Section (2) Wave (3) Frequency Band (4) Elevation O Calculated Value --- Measured Value[2] ● △▽ This article's calculated value

Consideration is given to nonequilibrium mixed air wakes associated with 8 types of components and 14 chemical reactions. The neck section enthalpy value is assumed to be the empirical value which is selected for conventional cold objects, that is, h_{en}/(illegible) H_e = 0.3. The concentrations of the various constituents of the neck section originate from the calculation results for body section nonequilibrium flow fields. In the base section shear layer, the various constitutents are considered according to freezing or congealing. For the object in question, the reflective cross sections calculated out for turbulent flow underdense areas are as shown in Fig.3 and 4. This article also considers the influence of correlation length on reflective cross section. When assuming different correlation lengths, the changes for two frequency band reflective cross sections are seen in Fig.5.

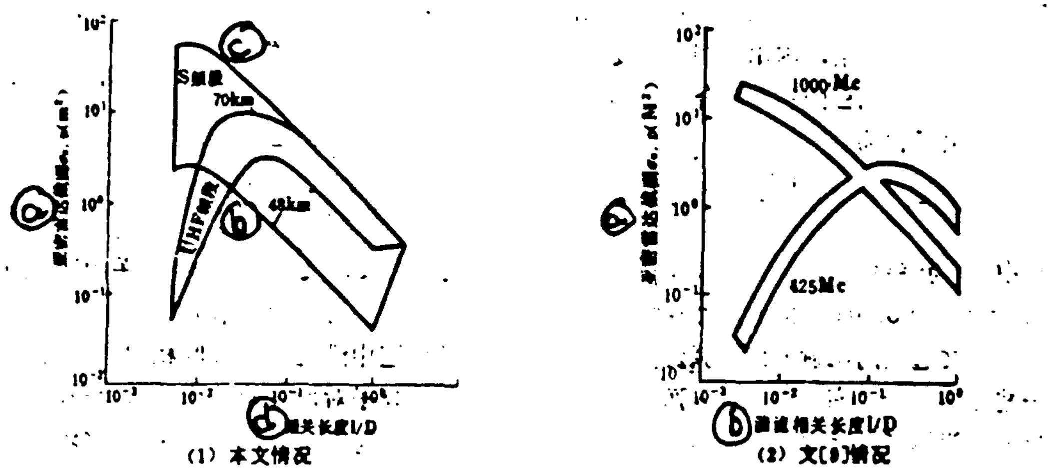

Fig.5 Influence of Correlation Length on Wake Radar Cross Sections
(1) This Article's Situation (a) Underdense Radar Cross Section
(b) Frequency Band (c) Frequency Band (2) Reference [3]'s
Situation (a) Underdense Radar Cross Section (b) Turbulent Flow
Correlation Length

From the results above, one comes up with several analytical opinions.

1. Within the orbital range which this article considers, ground radars are capable of recieving echo signals which originate primarily in the underdense region of turbulent flow wakes.

2. Within the range of three elevations that this article calculates, three wavelengths of echos show the appearance of sudden increase phenomena. Among these, the elevation of the sudden increase phenomena peak values associated with f_1 waves were a good deal higher than those for f_2 and f_3, that is, during the process of returning to earth, relatively long wavelength (f_1) echo peak values, compared to relatively short wavelength (f_2 and f_3) echo peak values show their appearance at a relatively early instant. This is completely in line with results from the reference. How does one explain this phenomenon? The author recognizes that, first of all, looking from the point of view of the elevation at which the sudden increases show their appearance, in all cases, they only show their appearance in situations in which the environmental Reynolds number exceeds the transition values and wakes are all turbulent flow movements from the neck sections onward. Furthermore, the mechanism for the appearance of the sudden increases is the occurence of resonance in situations in which incoming waves and plasma are at relatively close frequencies. As a result of this, it causes the reflected energies to suddenly increase, and that is the cause of it. Calculations clearly demonstrate that, when one is at 70 km, within one relatively long section of distance in the wake, in all cases, it belongs to laminar flow movements. However, from the turning or transition point onward, $n_{e\ trans}$ has a corresponding inherent frequency value which is then already lower than the f_1 value. Flowing downward, f_p is then even smaller. As a result of this, in this region, it is only possible to have echos, but it is not possible to give rise to resonance. Also, one will then, at this elevation, not see the appearance of sudden increases. When one is at 59 km and 48 km, the location of the turning or transition point is very close to the neck section. If one is positioned at the turning or transition point or within a short distance after it, one will arrive at the critical point. At this time, the plasma and the incoming waves have frequencies which are relatively close. It is possible to give rise to resonance. From Fig.6, it is possible to see that, under the conditions indicated in Reference [4], the sudden increase in UHF frequency band echos makes its appearance approximately around the 50

km vicinity. The sudden increase in S frequency band echos makes its appearance approximately around the 35 km vicinity. (This article, because of a shortage of initial data for even lower elevations, has not yet been able to accurately calculate out the locations for the appearance of sudden increases). Plasma wakes for this section of elevations (50-35 km), satisfy just perfectly two aspects of the 291
situation, that is, one aspect, when one arrives at this elevation, is that wakes have already completely turned into turbulent flow (There are already calculations explaining that, in the orbit track returning to earth of a long thin blunt nosed body with a base diameter of 1 m, the environmental Reynolds number reaches 5 x 10(illegible), and wakes then completely become turbulent flow movements.) The other aspect is that, in wakes, electron density peak values along orbital tracks generally show their appearance within this range of elevations. Lower than this elevation, electron density values fall, that is, they become weak plasma wakes. At that time, the reflections of incoming radiated waves are also capable of being reduced and will not show the appearance of sudden increases.

Fig.6(1) UHF Radar Cross Sections Following Changes in Elevation[4] (a) UHF Radar Cross Section (b) Elevation

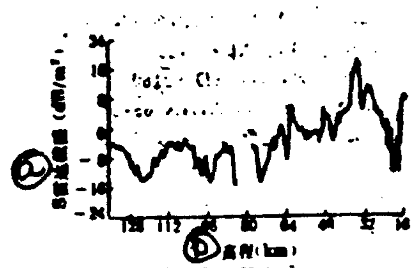

Fig.6(2) S Radar Cross Sections Following Changes in Elevation[4] (a) S Radar Cross Sections (b) Elevation

3. Turbulent flow pulse correlation length has clear influence on underdense scattering cross sections as is shown in Fig.5.

The analysis described above clearly shows that, along orbit tracks, advancing to the vicinity of the elevation at which wakes make complete transitions, under conditions with a certain turbulent flow pulse correlation length and positioned at a critical point associated with a strong plasma flow field, the resonance produced by the plasma and the incoming waves is just right for the production of maximum energy echos. Because of this, in receiving them on a screen, they are capable of showing the appearance of sudden echo signal increase phenomena.

4. Looking from the point of veiw of the preceding analysis, in wakes, the magnitudes of electron density peak values as well as the positions of critical points have influences on the special characteristics of underdense scattering cross sections. With object forms which are invariable and after precise determination of turbulent flow correlation length, the calculation of electron density values is important. This article calculates wake electron density for mixed or adulterated air media on the basis of pure air dissociation and after ionization. After the end has added to it thermal protective material, combustion corrosion products will have an influence [6] on the magnitude of electron densities in wakes. Moreover, along the direction of the flow, in wakes, the content of combustion corrosion products as well as their influence is not uniform. Because of this, the existence of combustion corrosion products is capable of altering, in wakes, the magnitude of electron densities and their distributions. In addition to this, it is also capable of altering the location of critical points. Because of this, analyses should consider a step further wake calculations which include combustion corrosion products in order to estimate the influences of combustion corrosion products on scattering cross sections.

From this article's calculations and analyses, it is possible to arrive at the conclusions below:

1. Under the conditions calculated for in this article, ground radars are capable of receiving echo signals which originate primarily from the underdense regions of turbulent flow wakes.

2. As far as the comparison of the three elevations which are dealt with in this article are concerned, echo cross section values associated with the three types of frequencies, respectively, at different elevations, show the appearance of sudden increases. f_1 waves show their appearance in the interval between 60 and 50 km. The sudden increases of f_2 and f_3 waves are located in the vicinity of 48 km.

3. Calculations from the related Reference [3] point out that the dimensional characteristics of objects as well as their neck section enthalpy values have obvious effects on echo cross sections. Relevent calculations have not yet been made for the limitations which come from the initial conditions that pertain in this article.

4. Echo cross sections are extremely sensitive to changes in turbulent flow correlation lengths.

5. Under given conditions for the shape of the object, dimensions, and enthalpy values for the neck section, when the environmental Reynolds number is higher than the transitional Reynolds number, and, when at a certain correlation length, critical plasma will produce resonance with incoming waves. As a result of this, sudden increases in reflective cross sections are formed.

6. Because of the fact that combustion corrosion products have an obvious influence on the location of the appearance of turbulent flow[6,7], and, at the same time, they also have an influence on the magnitude and distribution of electron densities in wakes, it is possible, as a result, for them to have influences on the reflective effects exerted on incoming waves.

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