March 30, 1965 R. L. PHILLIPS ETAL 3,176,228

SPACE VEHICLE REENTRY COMMUNICATION APPARATUS

Filed Dec. 12, 1960

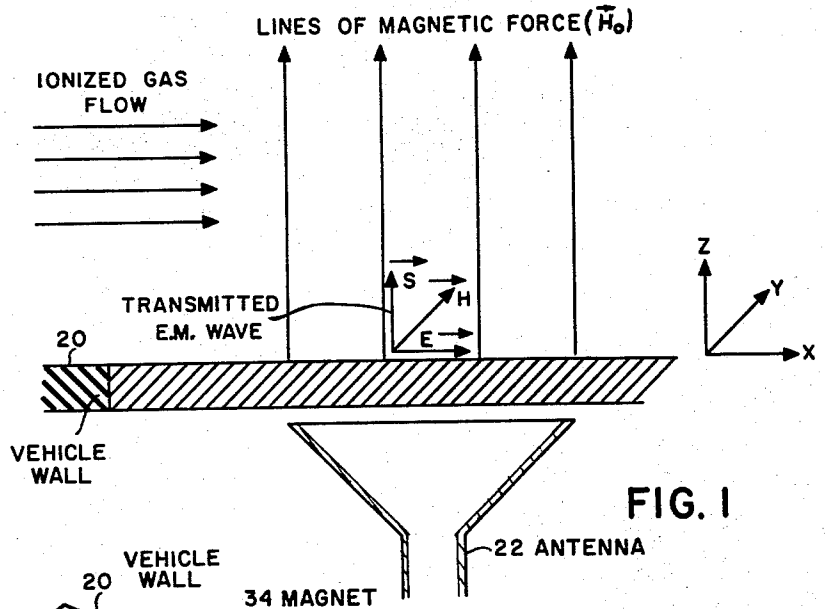


FIG. 1

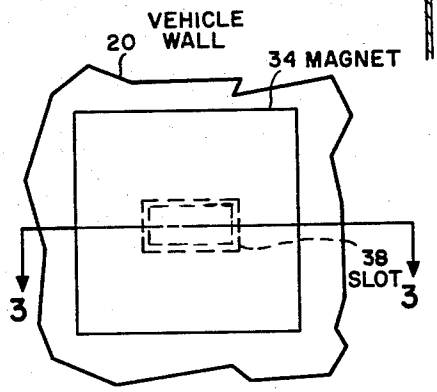


FIG. 2

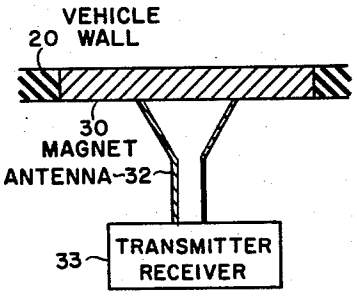


FIG. 3

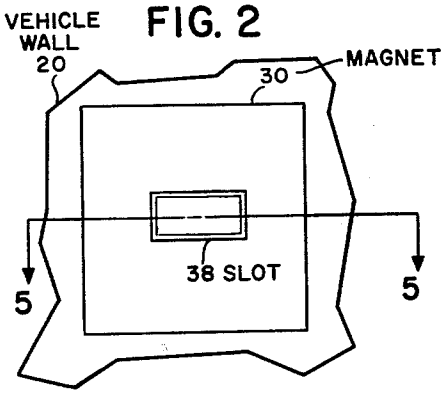


FIG. 4

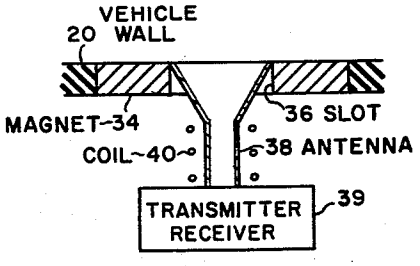


FIG. 5

INVENTORS
RICHARD L. PHILLIPS
ROBERT G. DeLOSH

BY

Richard J. Sager
ATTORNEY

United States Patent Office 3,176,228 Patented Mar. 30, 1965

3,176,228

SPACE VEHICLE REENTRY COMMUNICATION APPARATUS

Richard L. Phillips and Robert De Losh, Ann Arbor, Mich., assignors to The Bendix Corporation, Southfield, Mich., a corporation of Delaware

Filed Dec. 12, 1960, Ser. No. 75,293
3 Claims. (Cl. 325—65)

This invention pertains to a device for applying a magnetic field through the plasma sheath which is formed about a space vehicle entering the earth's atmosphere to provide a "window" for electromagnetic waves to pass. This provides a passage for communication signals between the space vehicle and a transmitting and receiving station.

It is known that when a space vehicle traveling at very high speeds enters the earth's atmosphere, a plasma of very hot ionized gases surrounds the surface of the vehicle. The electrons and ions in the plasma seriously interfere with and attenuate any communication signals to or from the vehicle. This invention overcomes this problem by providing a magnetic field from within the vehicle which has lines of force emanating from the fuselage or surface of the space vehicle, which causes the plasma electrons to describe the circular paths about the lines of force. However, since there are many heavy and neutral particles in the plasma, the electrons are not able to travel in a full circle due to collisions with these more massive particles and instead travel in a cycloidal path. The signals transmitted from the space vehicle are preferably circularly polarized in a direction the same as the direction of the cycling plasma electrons, in order for the signal to pass through the plasma sheath with a minimum of attenuation.

This invention also proposes the use of a lightweight magnetic material which has extremely small ferromagnetic particles, each particle containing only a single magnetic domain, which are suspended in a base material to provide a very strong magnetic field extending through the plasma sheath.

It is, therefore, an object of this invention to provide a magnetic field through the plasma sheath surrounding a re-entering space vehicle to thereby form a "window" for electromagnetic communication signals to pass through.

An object of this invention is to provide means for establishing a magnetic field in a space vehicle with the field being of sufficient strength to cause cycling of the electrons in the ionized plasma sheath surrounding the space vehicle at a frequency which is greater than the frequency of a transmitted communication signal from the space vehicle.

It is another object of this invention to provide in addition to the device of the previous object, means for circularly polarizing the entire transmitted communication signal in a direction the same as the cycloiding plasma electrons.

It is a further object of this invention to use a lightweight magnetic material having very small magnetic particles, each particle consisting of a single magnetic domain, suspended in a base material to provide the magnetic field of the device of the first object.

These and other objects will become more apparent when preferred embodiments are discussed in connection with the drawings in which:

FIGURE 1 is a diagrammatic view of an ionized plasma gas flowing over a small section of space vehicle wall surface;

FIGURE 2 is a diagrammatic plan view of a first embodiment for providing the magnetic field having lines of force which extend through the ionized plasma sheet;

FIGURE 3 is a side view of the embodiment of FIGURE 2 showing the antenna for transmitting electromagnetic communication signals beneath the magnet material;

FIGURE 4 is a plan view of a device similar to FIGURES 2 and 3 wherein the antenna extends through the magnet material; and

FIGURE 5 is a side view of the embodiment of FIGURE 4.

Before the particular embodiments of FIGURES 2–5 are discussed, a mathematical explanation of the theory used in this invention will be undertaken.

Referring to FIGURE 1 of the drawing there is seen a small segment of a space vehicle wall **20** of dielectric material which may be considered to be moving in a direction from right to left. In the XYZ vector representation shown, the XY plane is the plane of the vehicle surface and the Z vector is in a direction perpendicular to the vehicle surface. The EHS vector diagram represents the electric (E) and magnetic (H) vector components of the transmitted E.M., or electromagnetic, wave. The S vector is the product of the E and H components and is in the Z direction and represents the direction of wave propagation. The ionized gas flow is shown moving from left to right over the surface.

FIGURE 1 indicates that a steady, uniform magnetic field, H_0, has been imposed upon the plasma in the z direction only. The gas flows from left to right along the vehicle wall **20**. An antenna is located below the wall (or inside the vehicle) and the radiation issued propagates in the direction of the magnetic field. For this analysis, the electromagnetic wave from antenna **22** is plane polarized and monochromatic. Furthermore, the wave propagates from a free-space environment into a plasma with the vehicle wall being a sharply-defined boundary between the two regions. It is assumed that the plasma properties do not vary along the propagation path and that the plasma occupies a semi-infinite region which is the space above the x-y plane. Under these conditions it is possible to calculate the phase shift and attenuation constants as well as the reflection coefficient of the wave in the presence of the plasma. The method in which the radiation interacts with the plasma is by E-vector excitation of the free electrons which are present. Since these electrons are at least 1840 times less massive than any other charged particle in the plasma, the effect of the radiation on positive and negative ions is generally neglected; only the equations of motion of the electrons require consideration. Finally it can be shown that the exciting force on the electrons because of the H vector of the wave is insignificant in comparison to the electrostatic force arising from the E vector. With the foregoing assumptions and simplifications in mind, it is possible to proceed by writing the equations of motion of a free electron being acted upon by the combined forces of electric and magnetic fields as well as a force resulting from collisions with other particles in the plasma (positive and negative ions and neutrals). This equation assumes the form (MKQS units are used throughout):

$$m\frac{\vec{dv}}{dt}+\vec{mvv}=e\left(\vec{E}+\vec{vx}\mu_0\vec{H}\right) \qquad (1)$$

where v is the velocity vector of the particle, m and e the electronic mass and charge respectively, E is the electronic field vector, and H the magnetic field vector. Finally, ν is the frequency of elastic collisions suffered by the electrons with all other particles present in the plasma.

In component form, Equation 1 becomes:

$$\frac{dv_x}{dt}+\nu v_x+e/m[E_x+\mu_0(v_yH_z-v_zH_y)]$$

$$\frac{dv_y}{dt}+\nu v_x=e/m[E_y+\mu_0(v_zH_x-v_xH_z)]$$

$$\frac{dv_z}{dt}+\nu v_z=e/m[E_z+\mu_0(v_xH_y-v_yH_x)]$$

The constraints on the problem dictate that H_x and H_y are products only of the E.M. wave and are therefore neglected in determining the motion of the electrons. Also it is required that E_z be zero. Making the proper simplifications, produces

$$\frac{dv_x}{dt}+\nu v_x=e/m(E_x+\mu_0 v_y H_0)$$

$$\frac{dv_y}{dt}+\nu v_y=e/m(E_y-\mu_0 v_y H_0) \qquad (2)$$

$$\frac{dv_z}{dt}+\nu v_z=0$$

where $H_z=H_0$.

The solution to the third equation of the above set is seen to be:

$$v_z=v_{z_i}e^{-\nu t} \qquad (3)$$

From this expression it is seen that the particle velocity in the z direction (which initially is v_{z_i}) has a relaxation time of ν^{-1} seconds. For the plasmas under consideration ν is typically 10^8–10^{10} sec.$^{-1}$ and therefore the z velocity component need not be further considered. All particle motion, then, takes place in the x-y plane and the following symbols may be introduced:

$$u=x+iy,\ E=E_x+iE_y,\ H=H_x+iH_y$$

where i is the imaginary number, $\sqrt{-1}$. With the aid of the above identities, the equations of motion of an electron may be expressed by the single complex equation:

$$\frac{d^2u}{dt^2}+\left(\nu+i\frac{e\mu_0H_0}{m}\right)\frac{du}{dt}=e/mE \qquad (4)$$

the Maxwell field equations

$$\nabla x\vec{E}+\frac{\partial\vec{B}}{\partial t}=O,\ \nabla x\vec{H}-\frac{\partial\vec{D}}{\partial t}=\vec{J} \qquad (5)$$

may be written as

$$\frac{\partial E}{\partial z}-i\mu_0\frac{\partial H}{\partial t}=0$$

$$\frac{\partial H}{\partial z}+i\epsilon_0\frac{\partial E}{\partial t}=-iN_e e\frac{du}{dt} \qquad (6)$$

in which the electron density, N_e, times the average velocity has been introduced for the current density, J. The permeability and permittivity of free space are denoted respectively by μ_0 and ϵ_0. Since the incident E.M. wave is characterized by a sinusoidal variation of the electric vector, it is natural to assume that solutions to Equations 4 and 6 will have the form:

$$E=a'e^{\pm i(kz-\omega t)},\ H=b'e^{\pm i(kz-\omega t)},\ u=c'e^{\pm i(kz-\omega t)}$$

where ω is 2π times the transmission frequency, f. Solving the determinant formed by the coefficients of a', b', and c' by the technique followed in Reference 1, an equation for the propagation constant, k is obtained

$$\frac{c^2k^2}{\omega^2}=1-\frac{\frac{N_e e^2}{m\epsilon_0}}{\omega^2\mp\frac{e\mu_0H_0\omega}{m}+i\nu} \qquad (7)$$

where c is the speed of light in vacuo.

Physically, the double sign in Equation 7 means that a linearly polarized wave entering the plasma is resolved into a right-handed and a left-handed circularly-polarized component, one having a propagation k_+ and the other k_-.

These two components may be designated as the "extraordinary" and "ordinary" waves. For the extraordinary wave, the electric vector rotates in the same sense as the electrons gyrate about the magnetic line of flux. The minus sign in Equation 7 applies in this case; hence the propagation constant k_+ denotes the extraordinary wave. Converse remarks apply for the ordinary wave. These two propagation constants are seen to be:

$$k_+^2=\frac{\omega^2}{c^2}\left[1-\frac{p^2/\omega^2}{1-\frac{\omega_e}{\omega}+i\nu/\omega}\right]$$

$$k_-^2=\frac{\omega^2}{c^2}\left[1-\frac{p^2/\omega^2}{1+\frac{\omega_e}{\omega}+i\nu/\omega}\right] \qquad (8)$$

where the following notation has been introduced: p is the so-called plasma frequency and is given by

$$p^2=N_e e^2/m\epsilon_0;\omega_e$$

is the electron cyclotron frequency, $e\mu_0H_0/m$. Assuming that k is a complex number of the form

$$k_\pm=\beta_\pm+i\alpha_\pm$$

it is possible to obtain

$$2\alpha_\pm^2=\frac{\omega^2}{c^2}[(A_\pm-1)+\sqrt{(A_\pm-1)^2+A_\pm^2B_\pm^2}]$$

$$2\beta_\pm^2=\frac{\omega^2}{c^2}[-(A_\pm-1)+\sqrt{(A_\pm-1)^2+A_\pm^2B_\pm^2}] \qquad (9)$$

where A and B have been introduced for simplicity and are defined as

$$A_\pm=\frac{p^2/\omega^2\left(1\mp\frac{\omega_e}{\omega}\right)}{\left(1\mp\frac{\omega_e}{\omega}\right)^2+\frac{\nu^2}{\omega^2}},\ B_\pm=\frac{\nu/\omega}{1\mp\frac{\omega_e}{\omega}} \qquad (10)$$

Equation 9 represents, respectively, the attenuation and phase shift constant of the E.M. wave. To obtain the attenuation in units of decibels per meter of plasma thickness, multiply the value of α from Equation 9 by 20 $\log_{10}e$ where in this case e is the base of the natural logarithm. The reflectivity coefficient or the fraction of power in the E.M. wave which is reflected at the free space-plasma interface is given by:

$$R_\pm=\frac{(1-c/\omega\beta_\pm)^2+\frac{c^2}{\omega^2}\alpha_\pm^2}{(1+c/\omega\beta_\pm)+\frac{c^2}{\omega^2}\alpha_\pm^2} \qquad (11)$$

All of the above relations reduce to those describing propagation through a plasma with no magnetic field present present when ω_e is set equal to zero.

With the aid of the expressions derived from Equations 9 and 11, it is possible to obtain quantitative information about the passage of an actual E.M. wave through a plasma. A typical set of plasma properties encountered by a boost-glide vehicle would be: At velocity of 23,000 ft./sec. and altitude of 250,000 ft.

$$N_e=1.3\times10^{12}\ \text{cm.}^{-3}$$

and

$$\nu=3.8\times10^8\ \text{sec.}^{-1}$$

from which

$$p^2=4.13\times10^{21}\left(\frac{\text{rad.}}{\text{sec.}}\right)^2$$

is obtained. Selecting a transmission frequency, f, of 240 mc./sec. and a magnetic field strength, μ_0H_0, of 1000 gauss it is possible to obtain through a tedious but straightforward calculation:

$$\alpha_+=9.75\ \text{db/meter}$$

$$\alpha_-=520\ \text{db/meter}$$

For comparison, the attenuation of an E.M. wave for $H_0=0$ would be 1815 db/meter. Since plasma sheath thicknesses as great as 0.50 meter can be encountered, transmission with no magnetic field present is not even faintly feasible. Even with a magnetic field, however, the ordinary wave (α_-) will not be successfully transmitted to an outside receiver. On the other hand, the extraordinary component of the E.M. wave suffers only slight attenuation and therefore implies an ostensibly feasible propagation scheme. The success of the extraordinary wave is not established until reflective losses are first calculated. For $H_0=0$, the reflectivity coefficient is (for all practical purposes) 1.00. That is, almost all of the energy is reflected back into the free-space region. Upon application of the 1000 gauss field, only 74% of the incident energy is reflected, which again is a contribution to the feasibility of this scheme of communication.

As an aid to understanding the above development, reference is made to J. A. Ratcliffe's "Magneto Ionic Theory and Its Applications to the Ionosphere," Cambridge Press, and J. A. Stratton's "Electromagnetic Theory," McGraw-Hill.

In the embodiments shown in the drawing, the first preferred embodiment is shown in FIGURES 2 and 3 wherein a magnet material **30** is placed in the vehicle surface **20** and flush with the exterior thereof. This magnet material has very small ferromagnetic particles which contain a single magnetic domain which exhibits very unusual magnetic properties in that enormous coercive forces and remanences are theoretically achievable. These particles, which may be iron, are suspended in a nonferromagnetic matrix, which may be any plastic material and the agglomerate is pressed into magnet form.

The ferromagnetic particles are aligned in the matrices of magnet **30** to provide a magnetic field having lines of force preferably perpendicular to the surface of the vehicle. The magnetic field from magnet **30** causes the electrons in any adjacent ionized plasma to tend to circle about the magnetic lines of force. The electrons are prevented from completing a circle since they collide with the heavier positive ions and the result is that the electrons follow a cycloidal path.

Placed below and adjacent to magnet **30** is an antenna **32** which is connected to a transmitter-receiver **33** and radiates an electromagnetic signal through magnet **30** and the plasma thereabove. Preferably, the entire electromagnetic signal from antenna **30** is circularly polarized in the same direction as the cycling direction of the plasma electrons and is necessarily of a frequency less than the frequency of the cycling electrons to minimize losses.

The embodiment shown in FIGURES 4 and 5 has a magnet **34** of similar composition to magnet **30** but magnet **34** has a slot **36** formed centrally therein. An antenna **38** is connected to a transmitter-receiver **39** and extends through this slot and is flush with the vehicle surface. Also, a coil **40** is wound around the antenna **38** and is connected to voltage source (not shown) to aid in providing the magnetic field.

The embodiment shown in FIGURES 2 and 3 has the advantage that since the antenna is displaced by at least the thickness of the magnet **30** from the plasma surrounding the vehicle surface, voltage breakdown of the plasma due to the high induction fields near the sharp edges of the antenna will be less likely. Also, if magnet **30** is a permanent magnet, the magnetic field will be much stronger if a slot or opening is not formed therein and, therefore, this provides a further advantage.

As mentioned, an electromagnet can be used in conjunction with a suitable magnet constructed like magnet **30**. Other magnet materials can be used with this invention but a magnet **30** provides a very desirable weight to magnetic field strength ratio.

Having thus described our invention, we claim:

1. A device for aiding the transmission of electromagnetic waves through ionic plasma comprising means for establishing a magnetic field having lines of force penetrating said plasma, to clear a path for transmission of electromagnetic energy, means for transmitting electromagnetic waves through the region of plasma penetrated by said lines of force, said last means transmitting electromagnetic waves along said lines of force of said magnetic field, said last means polarizing substantially the entirety of said transmitted waves in the same direction as the direction of the cycling of electrons about the magnetic field lines.

2. A device for aiding the transmission of electromagnetic waves through ionic plasma comprising meanss for establishing a magnetic field having lines of force penetrating said plasma, to clear a path for transmission of electromagnetic energy, means for transmitting electromagnetic waves through the region of plasma penetrated by said lines of force, said lines of magnetic force causing the free electrons in said plasma to travel in cycloids, the frequency of the cycloids being greater than the frequency of the electromagnetic wave.

3. The device of claim 2 where the frequency of the cycloids (ω_e) the transmitted frequency (ω), the plasma frequency (p) and the frequency of elastic collisions suffered by the electrons with all the other particles present in the plasma (ν) are related to the propagation constant (k) in the following manner:

$$k^2=\frac{\omega^2}{c^2}\left[1-\frac{p^2/\omega^2}{1-\frac{\omega_e}{\omega}+i\frac{\nu}{\omega}}\right].$$

where c=velocity of light and $i=\sqrt{-1}$ (MKSQ units).

References Cited by the Examiner

McIlroy article, S.A.E. Journal, vol. 66, No. 4, April 1958, pp. 90–93.

Resler et al.: Article, Journal of the Aeronautical Sciences, April 1958, pp. 235–245.

Kantrowitz article, Astronautics, October 1958, pp. 18–20 and 74–77.

DAVID G. REDINBAUGH, *Primary Examiner.*

HERMAN K. SAALBACH, *Examiner.*