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Changes in Electromagnetic Properties of the Upper Atmosphere due to Rocket Effluents

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Artificial reduction of the plasma concentrations in the ionosphere and magnetosphere can affect electromagnetic wave propagation. The molecular species found in rocket exhaust vapors promote recombination of electrons and ions (i.e., O^+, H^+, and He^+) in the upper atmosphere. This recombination produces localized regions with strong variations in radio refractive index. Regions of ionospheric plasma reduction produce focusing at high and very high frequencies and defocusing at very low frequencies. Subionospheric propagation in the vicinity of an artificial plasma hole can suffer the effects of multipath fading and defocusing by reflection at the sides of the hole. Should irregularities form because of the plasma gradients, amplitude scintillations will be introduced in waves passing through the region.

Introduction

THE Earth's plasma atmosphere can be divided into four regions with approximate boundaries given as follows: The D region is at altitudes between 70 and 90 km; the E region extends from 90 to 120 km altitude; the F region, lying between 120 and 800 km, contains the bulk of the ionospheric plasma, above the ionosphere is the magnetosphere which extends from 800 km altitude to over 10 Earth radii.

Rocket engine firings in the upper atmosphere release vapors which can temporarily neutralize some of the plasma in the F region and, to a lesser degree, in the magnetosphere. This process produces regions of localized plasma reduction called plasma "holes." Radio waves propagating through the disturbed regions can be strongly refracted and scattered.

The object of this paper is to survey the variety of effects that artificially produced plasma depletions can have on electromagnetic waves. For this study, numerical models of the upper atmosphere are used to predict the size and durations of the depletions. Two- and three-dimensional ray-tracing programs are employed to investigate the changes in the radio wave ray trajectories. This study is motivated by the need to evaluate the consequences of temporary alteration of the ionosphere. Such alteration might be produced by the launches required to construct large, orbiting space systems such as the solar power satellite (SPS).[1]

Molecular Species Present in Rocket Exhaust

Exhaust vapors from chemically powered rockets may react with the plasma in the upper atmosphere. This is not normally considered by the designer of rocket propulsion systems. The designer considers a rocket fuel in terms of its performance rather than in terms of its effect on the environment.

Figure 1 illustrates a comparison of propellants by specific impulse and bulk density. All of the propellants in this figure produce exhaust species which react chemically in the ionosphere, causing a reduction in plasma concentration. Designing a useful chemical propulsion system which does not eject reactive exhaust vapors may not be feasible.

Table 1 lists the exhaust species for two solid rocket propellants. The species designated by an asterisk are known to produce modification of the ionosphere. The exhaust from solid rocket motors may also contain chlorine compounds which can effect the stratospheric ozone concentration. Most solid rockets burn only in the lower atmosphere and do not affect the ionosphere.

Exhaust vapors from liquid rocket engines usually contain fewer species than are produced by solid rockets (Table 2). This exhaust is mainly composed of oxides, hydrogen, and carbon as well as unburned molecular hydrogen. Most of

Table 1 Typical solid rocket exhaust species and concentrations

Oxidizer	NH_4ClO_4, 66%		Double-base	
Binder	$(CH_2)_x$		–	
Fuel	Al, 22%		Al, 22%	
Theoretical I_s, s	266		275	
Combustion temperature, K	3644		4017	
Exhaust products, mole fraction	H	0.0283	H	0.1036
	Cl	0.0084	O	0.0004
	*OH	0.0006	*OH	0.0045
	HCl	0.5462	*H_2	0.7852
	*H_2	1.3183	*H_2O	0.1404
	*H_2O	0.1730	CO	1.0910
	CO	0.8339	*CO_2	0.0295
	*CO_2	0.0192	*NO	0.0004
	*N_2	0.2869	*N_2	0.7951
	AlCl	0.0011	Al	0.0002
	$AlCl_2$	0.0028	AlO	0.0001
	$AlCl_3$	0.0001	Al_2O	0.0004
	Al_2O_3	0.4057	Al_2O_3	0.4071

*Promotes ionospheric plasma reduction.

Table 2 Typical liquid rocket exhaust species and concentrations

Oxidizer	N_2O_4		O_2
Fuel	MMH		H_2
Mixture ratio (O/F)	1.65		6.0
Theoretical I_s, s	313		388
Combustion temperature, K	3250		2689
Exhaust products, mole fraction	*H_2	0.2411	0.2500
	*H_2O	0.2738	0.7500
	CO	0.0501	0
	*CO_2	0.1216	0
	*N_2	0.3134	0

*Promotes ionospheric plasma reduction.

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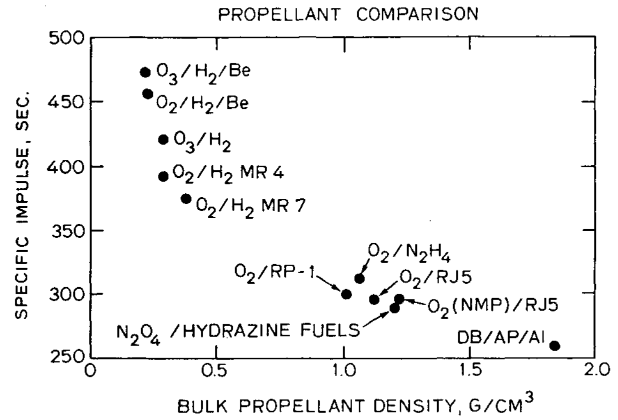

Fig. 1 Performance comparison of 11 propellants.

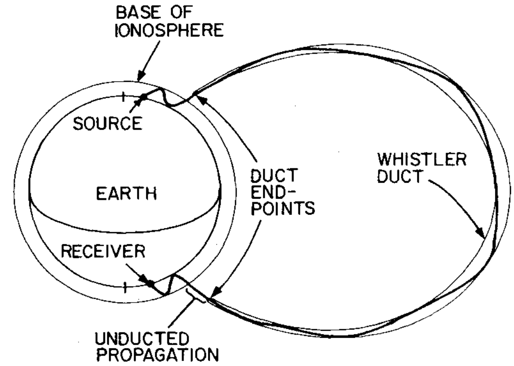

Fig. 2 Schematic of magnetospheric propagation circuit for vlf waves.

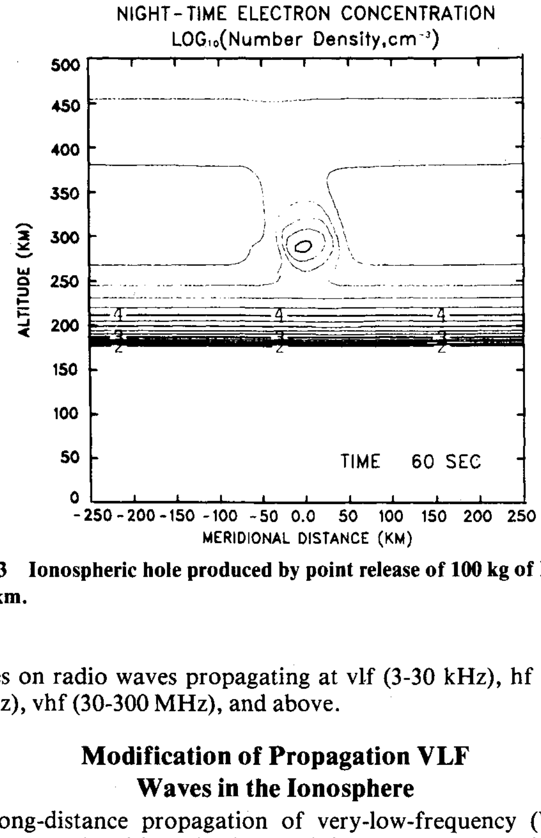

Fig. 3 Ionospheric hole produced by point release of 100 kg of H_2 at 300 km.

these gases will produce plasma depletions if injected into the F-region ionosphere.

The spatial extent of the ionospheric modification is affected by the total amount of exhaust released and the manner the exhaust vapors are layed down.[2,3] The amount released depends on the engine flow rates and the duration of the engine burn. The flow rate of the Space Shuttle orbital maneuvering subsystem is 8.71 kg s^{-1} engine^{-1} and of the Space Shuttle main engine (SSME) is 468.4 kg s^{-1} engine^{-1}. The proposed heavy lift launch vehicle (HLLV) for the SPS uses 14 SSMEs, producing a flow of 6557.6 kg/s.

Chemical Mechanisms for Ionospheric Hole Formation

A complete description of ionospheric hole formation involves chemistry, gasdynamics, diffusion, and thermal processes. The details of these processes can be found in several reports.[4,5]

Briefly, plasma holes are formed by chemical reaction of vapors in rocket plumes with ions in the F layer. Normally, the O^+ ion, which makes up the bulk of the ionosphere, is removed by the following reaction

$$O^+ + N_2 \rightarrow NO^+ + N \quad \text{rate: } 1.3\times10^{-12}\text{cm}^3/\text{s}$$

The rate of this reaction is at least 1000 times lower than the rates for the reactions between O^+ and most rocket exhaust species. Consider competing reactions with rocket exhaust

$$O^+ + H_2 \rightarrow OH^+ + H \quad \text{rate: } 2\times10^{-9}\text{cm}^3/\text{s}$$

$$O^+ + H_2O \rightarrow H_2O^+ + H \quad \text{rate: } 2.3\times10^{-9}\text{cm}^3/\text{s}$$

$$O^+ + CO_2 \rightarrow O_2^+ + CO \quad \text{rate: } 1.2\times10^{-9}\text{cm}^3/\text{s}$$

The relatively large rates for these reactions cause the rapid removal of the O^+ ion. The molecular ions (NO^+, OH^+, H_2O^+, and O_2^+) quickly recombine with electrons at rates around 2×10^{-7} cm^3/s. Similar reactions can cause reduction of the H^+ and He^+ ions in the magnetosphere.

After the exhaust vapors are released, they will disperse mainly through diffusive expansion.[2] The lifetime of the ionospheric hole is influenced by the transport of ions into the affected region as well as by reionization of the neutrals by the sun's extreme ultraviolet radiation. The size of the hole is controlled by the expansion and transport of the injected exhaust vapors. All of these processes are contained in the numerical models used in the studies.[4,5]

The models are used to generate estimates of disturbances produced by the release of vapors in the ionosphere. The changes in radio wave propagation are investigated by tracing rays through the perturbed ionospheric regions. The rest of this paper describes typical effects of artificial ionospheric holes on radio waves propagating at vlf (3-30 kHz), hf (3-30 MHz), vhf (30-300 MHz), and above.

Modification of Propagation VLF Waves in the Ionosphere

Long-distance propagation of very-low-frequency (VLF) waves may be either via the Earth-ionosphere waveguide or via aligned ducts in the Earth's magnetosphere. The first type of propagation employs the Earth's surface and the lower edge of the ionosphere for guiding the waves. Any modification of the ionosphere's lower boundary will change the characteristics of the Earth-ionosphere waveguide.

The lower ionosphere is composed of positive polyatomic ions such as NO^+, O_2^+ (in the D and E region), negative polyatomic ions such as O_2^- (D region), and hydrated positive ions such as $H \cdot H_2O$ (D region). These ions are not nearly as sensitive to the chemical changes as are the O^+ ions of the F layer. Consequently, the effect of rocket exhaust on propagation via the Earth-ionosphere waveguide is expected to be small.

The second type of VLF propagation (called whistler mode) is illustrated in Fig. 2. A VLF electromagnetic wave is transmitted from a source into the Earth-ionosphere waveguide. Some of the wave energy leaks upward through the bottomside ionosphere, traveling in an unguided mode. If this energy is captured by an enhanced column of plasma (called an enhancement duct), the wave can be guided along the Earth's magnetic field lines to the conjugate hemisphere. Amplification may occur as the wave interacts with the

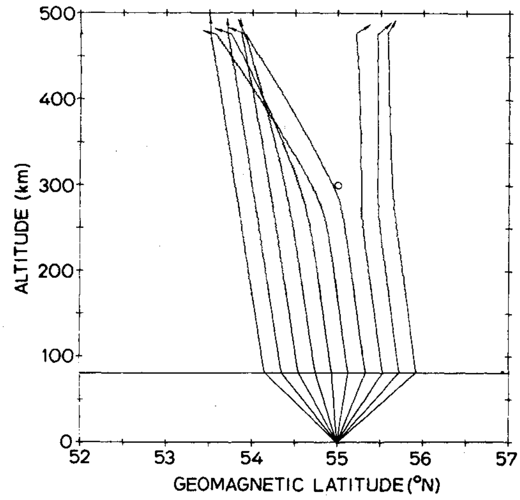

Fig. 4 Defocusing of 5 kHz rays by an ionospheric hole.

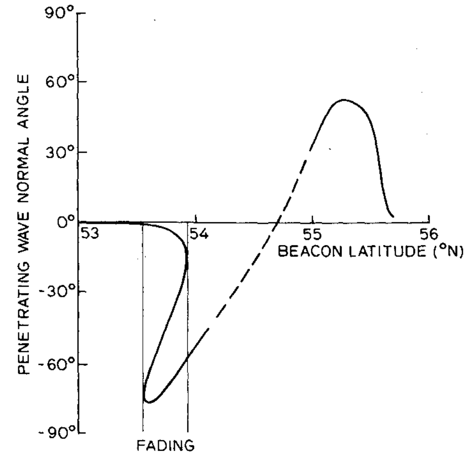

Fig. 6 Required wavenormal angle at 500 km altitude for ground reception of a 5 kHz wave (angles are defined with respect to vertical).

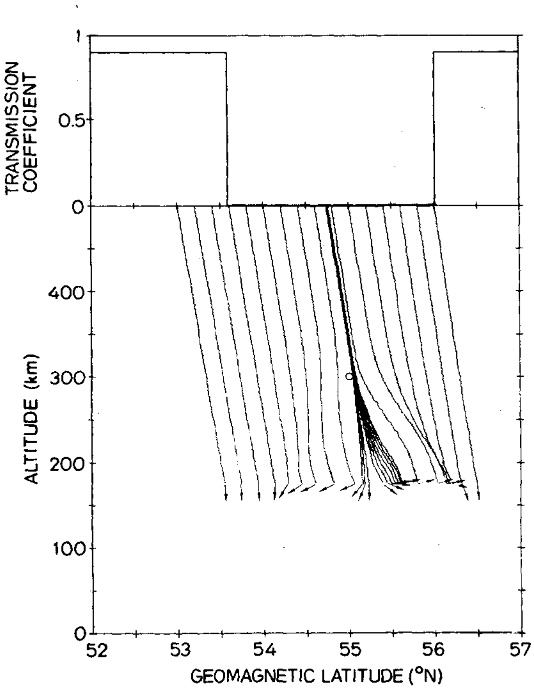

Fig. 5 Refraction of downward propagating rays by an F-region depletion.

radiation belt particles in the magnetosphere.[6] Radio rays leaving the duct will travel in an unducted mode to the bottomside ionosphere. If the ray direction is nearly perpendicular to the ionosphere, signals will couple into the Earth-ionosphere waveguide and may be received on the ground. Further details on whistler mode propagation can be found in the text by Helliwell.[6]

Modification of the F region ionosphere will change the coupling between the Earth-ionosphere waveguide and the ducts in the magnetosphere. This is demonstrated by tracing 5 kHz rays through an ionosphere that was modified by the release of 100 kg of H_2 at 300 km altitude. The electron density contours 1 min after the H_2 release are illustrated in Fig. 3. At this time, the central plasma concentration is reduced by a factor of 10.

For rays to be captured by a whistler duct, their wavenormal components must be nearly aligned with the Earth's magnetic field. At high geomagnetic latitudes, the magnetic field lines are nearly vertical. Upward propagating VLF waves have their wavenormals refracted vertically as they enter the ionosphere at the lower boundary. As these waves propagate in a horizontally stratified ionosphere, the wavenormals tend to remain vertical and the waves tend to couple into any enhancement ducts they encounter.

The wavenormals of the rays are sharply bent by the plasma gradients of an ionospheric hole. Figure 4 illustrates the bending of 5 kHz rays by the ionospheric hole of Fig. 3. The rays are emitted from a ground station located at 55 deg geomagnetic latitude. The three rays to the left of the hole are unaffected. In the vicinity of the hole, the rays are defocused and their wavenormals are bent. (The wavenormal directions are indicated by the arrows at the end of the ray trajectories.) These rays cannot couple into ducts in the magnetosphere.

A reciprocal effect occurs for signals exiting a dust over an ionospheric hole. Figure 5 illustrates the defocusing and wavenormal bending for 5 kHz rays propagating downward. Without the hole, all rays would cross the lower ionosphere and propagate to the Earth's surface. Between 53.6 and 56 deg geomagnetic latitude, the ionospheric hole prohibits transmission to the ground of the 5 kHz wave.

Figure 6 illustrates the required wavenormal angle(s) at 500 km altitude for propagation through the ionospheric hole to the Earth's surface. The wavenormal direction is defined with respect to the vertical. The dashed portion of the curve shows where strong defocusing occurs. Rays leaving enhancement ducts have wavenormal angles usually less than 15 deg. In regions where the penetration wavenormal angle is greater than this value, coupling between whistler ducts and the Earth-ionosphere waveguide does not occur.

Fading of the signal amplitude will occur if two or more rays reach the ground receiver, each ray having propagated on a disjoint path. Between 53.6 and 53.9 deg latitude, rays with three different wavenormal angles can reach the Earth's surface. Consider a VLF satellite transmitting a 5 kHz omnidirectional signal from a 500 km orbit. When this satellite enters the fading region (Fig. 6), amplitude fluctuations will be perceived on the ground.

One further way that VLF propagation in the magnetosphere may be modified by exhaust vapors is with the creation of artificial ducts. When the F layer is locally depleted, plasma flows along magnetic field lines from the magnetosphere into the depleted region. This flow will produce a tube of reduced plasma concentration extending up into the magnetosphere. This "depletion duct" takes 3 h or more to form.

Bernhardt[4] has made estimates of the amount of reduction in the content of a magnetic flux one would expect from vapor releases. For instance, 1000 kg of H_2 released at 300 km altitude into the daytime ionosphere is calculated to produce 10% reduction in the electron content of a tube centered along a $L=4$ (Earth radii) magnetic field line. The radius of this depleted tube will be 650 km at the equator.

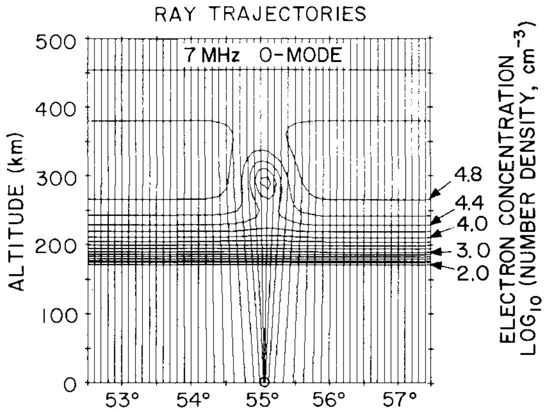

Fig. 7 Propagation of an O-mode wave through an ionospheric hole.

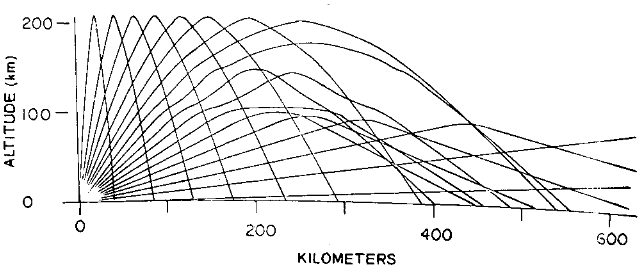

Fig. 8 Ray path trajectories in an undisturbed ionosphere with $X_{max} = 4$ (from Ref. 10).

This type of duct may be able to guide VLF waves in the magnetosphere. As mentioned previously, enhancement ducts are efficient guides of VLF waves. Depletion ducts can also guide VLF, using one of two modes. The first mode involves large wavenormal angles for rays which do not penetrate the lower ionosphere to the ground. The second mode involves trapping at the lower edge of the depletion duct.[7] This "one-sided" mode can be excited from the ground for guiding a wave to the conjugate hemisphere. A depletion duct of 10% should be sufficient for this type of guiding.

Artificial Changes in High-Frequency (3-20 MHz) Waves

The peak concentration of the F layer defines a lower limit for the frequency of penetration of HF waves. This frequency is given by $f_0F2 = [80.6\ N_{max}]^{1/2}$ Hz where N_{max} is the peak concentration in electrons/m^3. An ionospheric hole located at the F-layer peak will decrease f_0F2, allowing lower frequency (HF) waves to penetrate. This effect was proposed by Papagiannis and Mendillo[8] for use in low-frequency radio astronomy.

Refraction of an HF wave by the plasma gradients of the ionospheric hole will greatly distort the propagating phase front. The magnitude of this distortion is a function of the wave frequency, the plasma gradients in the hole, and the direction of wave propagation through the hole.

Figure 7 is an example of downward propagating HF rays through the ionospheric hole shown in Fig. 2. The rays are superimposed on contours of constant electron concentration. The ordinary left-hand circularly polarized mode is designated the O mode. The effect of the reduction in plasma concentration is to focus the downgoing waves. This is in contrast with the defocusing of VLF waves discussed in the previous section. In the example shown in Fig. 7, the focal point for the 7 MHz O-mode lies on the ground. The ionospheric "lens" produced by a 100 kg release of hydrogen at 300 km altitude is roughly equivalent to a perfect lens with a diameter of 36 km. The use of such a lens for radio astronomical observations has been proposed by Bernhardt and da Rosa.[9]

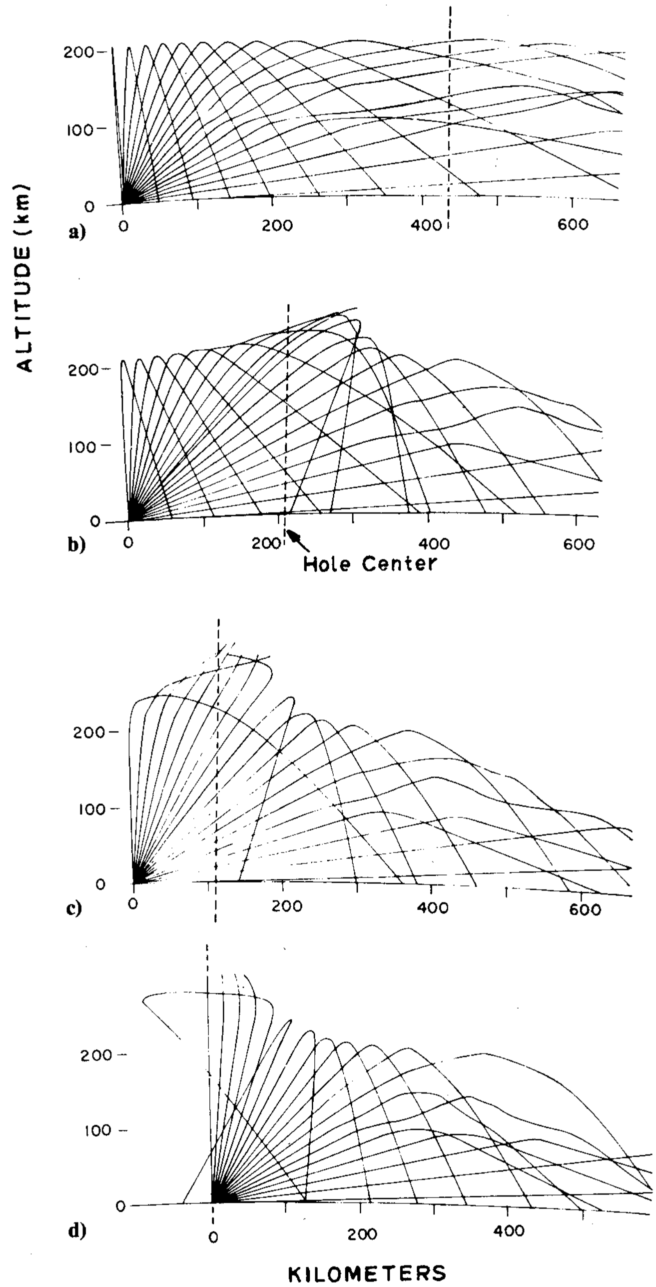

Fig. 9 Ray path trajectories as function of location for a hole with depression ratio of 0.1, halfwidth of 222 km, and $X_{max} = 4$ (from Ref. 10).

Ionospheric plasma holes can also affect the propagation of high-frequency waves between two points on the Earth's surface (called subionospheric propagation). Depending on the geometry of the transmitter, receiver, and ionospheric hole, the HF signals can experience focusing, defocusing, and/or fading.

Representative effects of ionospheric holes on HF propagation are taken from the work of Helms and Thompson.[10] They traced rays through an ionospheric perturbation which we estimate could be produced by the release of 3000 kg of H_2 into the nighttime F layer. In their work, the electron concentration is normalized by square of the frequency, as follows: $X = 80.6\ N_e/f^2$ where f is the wave frequency in Hz and N_e is the electron concentration in m^{-3}. X_{max} is the value at the F-layer peak given by $X_{max} = 80.6\ N_{max}/f^2$.

The following is a summary of the discussion presented by Helms and Thompson.[9] With $X_{max} = 4$ (for example, with $N_{max} = 1 \times 10^{12}$ m^{-3} and $f = 4.5$ MHz), the unperturbed ionosphere produces the O-mode trajectories shown in Fig. 8. The ionospheric holes modify the trajectories as shown in Fig.

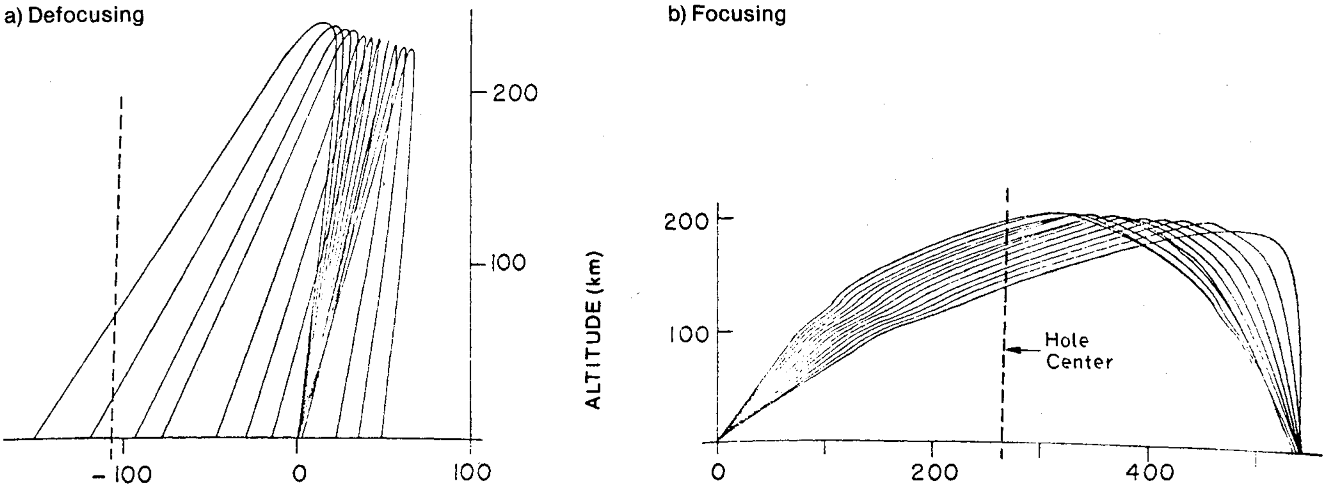

Fig. 10 Focusing and defocusing effects due to propagation through an ionospheric hold (from Ref. 10).

9. The center of the hole is indicated by a dashed, vertical line.

Without the hole, the point of maximum ray altitude for rays with 20-40 deg elevation angles is 220 km from the transmitter. With the hole placed 440 km away from the transmitter (Fig. 9a) the same rays propagate greater distances, reaching maximum altitudes as much as 600 km away from the transmitter. This could have a desirable effect on long-distance communications.

Moving the hole closer to the transmitter affects rays with higher initial elevation angles. For hole-transmitter separations less than 200 km, some of the rays are reflected back to the transmitter (Figs. 9b and 9c). Finally, for separations less than 120 km, some rays escape through the ionospheric hole (Fig. 9c). When the hole is directly over the transmitter (Fig. 9d) the rays are reflected once or twice by the sides of the hole before reaching the ground.

In some cases, an ionospheric hole can produce focusing or defocusing of HF waves. Reflection from the side of the hole tends to spread the ray trajectories (Fig. 10a). By lowering the wave frequency from 4.5 ($X_{max} = 4$) to 2.8 MHz ($X_{max} = 10$) focusing of the reflected rays can be produced (Fig. 10b).

An attempt was made to observe perturbations of HF communications by rocket-induced ionospheric holes. On Sept. 20, 1979, a large hole was created by the Centaur stage of a rocket placing the HEAO-C satellite into orbit (see Mendillo et al.[11]). Radio amateurs were solicited to participate in an experiment to observe the effects of the hole on communications.[12] Beacon transmissions 3.6, 7.1, 14.1, 21.1, 28.1, and 50.1 MHz were made from Puerto Rico. Signal strength measurements from over 150 amateurs in the continental United States are reported. The reports indicated that some small communication effects may have been produced. These effects, however, were of the same magnitude that one would expect with the ionosphere's normal variability. The communication effects of the HEAO-C launch are still under study.

From the theoretical examples, we see that ionospheric holes can produce a variety of changes on subionospheric HF communications. Holes directly over a transmitter will defocus the wave components with large elevation angles. Under certain specialized conditions, holes several hundred kilometers from a transmitter can produce focusing resulting in an enhancement of signal amplitude. Multipath propagation produced by the hole may cause fading.

Effects at VHF and Above (Frequencies Greater than 30 MHz)

As the frequency is increased above 30 MHz, the refraction by the ionospheric gradients becomes less pronounced. Above 100 MHz, the ray bending is so weak that propagation between two points on the ground (via ionospheric reflection) becomes unlikely. Consequently, the only effects of interest occur from transionospheric propagation. An example of this might be signals propagating from a satellite through the ionosphere to the ground.

Focusing will occur for VHF (30-300 MHz) signals traveling vertically through an ionospheric hole. The phenomenon is similar to that shown in Fig. 7 but to a much lesser degree. For frequencies above 30 MHz, the amplitude increase on the ground is approximately given by

$$G = 1 + (\lambda z \epsilon / 2\pi a^2)$$

where λ is the wavelength, z the altitude of the hole, a the half-width of the hole, ϵ the phase change through the center of the hole, and G the amplitude gain resulting from propagation through the hole.[4] The phase perturbation can be found from the integrated vertical electron content with and without the hole

$$\epsilon = (8.44 \times 10^{-7} \Delta I)/f$$

where ΔI is the reduction in electron content (in m^{-2}) through the center of the hole and f is the wave frequency in Hz.

As an example, consider an ionospheric hole centered at an altitude of 300 km with a content reduction $\Delta I = 6 \times 10^{16}$ m^{-2} and a size $a = 20$ km. For a wave frequency $f = 140$ MHz, one obtains an amplitude gain $G = 1.1$. This 0.8 dB gain is small compared with naturally occurring variations in signal amplitude.

The reduction in electron content associated with ionospheric holes produces changes in the phase and polarization of VHF waves. Measurements of these changes have been made by a number of holes.[13-16] Recent measurements made after the launch of the HEAO-C satellite are shown in Fig. 11. The data for this figure were provided by Stanford University, Boston University, Air Force Geophysical Laboratory, and the Department of the Army, Fort Monmouth. More details can be found in the paper by Mendillo et al.[11]

The previous discussion concentrated on fluctuations in radio wave propagation due to the smooth plasma gradients which form the plasma hole. The scale size of these gradients is the order of tens of kilometers or more. One should consider, however, the possibility of the hole breaking up into irregularities. As suggested by Anderson and Bernhardt[5] and by Ossakow et al.,[20] holes created in the bottomside F region at the magnetic equator may become unstable. This

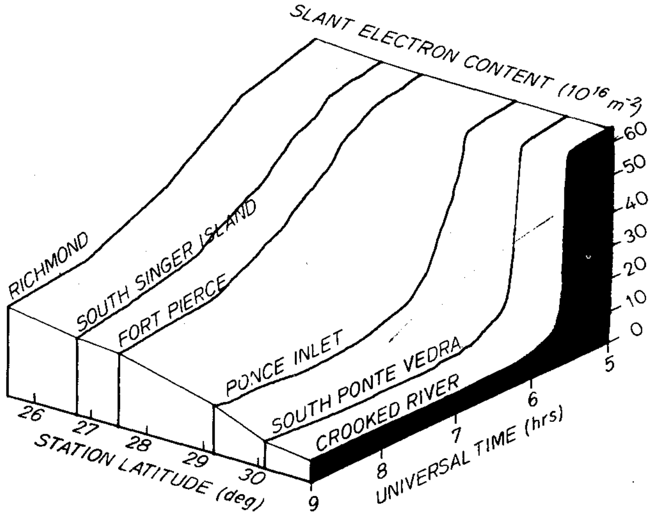

Fig. 11 Electron content changes associated with launch of HEAOC.

phenomena occurs naturally and has been reported by a number of researchers.[17-19]

The instability growth rate increases as the bottomside plasma gradients become steeper. This growth rate, however, is decreased by enhanced electron-ion recombination in the region. In the case of exhaust releases, the mechanism which steepens the bottomside F layer also increases the recombination in the region. Consequently, the exhaust vapors may damp out any instabilities which would otherwise form. If the plasma hole and the exhaust vapors become separated, the instability can grow. Electric fields and/or neutral winds may be adequate for transporting the hole and the exhaust vapors away from each other.

The effects of the irregularities on VHF (and higher frequency) propagation depends on the size and distribution of the irregularities. Naturally occurring irregularities have been known to produce severe amplitude and phase scintillations in transionospheric propagating signals.

Conclusion

Current plans for the Solar Power Satellite[21] call for the multiple launches of chemical rockets for transportation of cargo and crews. The heavy lift launch vehicle (HLLV), the personnel launch vehicle (PLV), and the personnel orbit transfer vehicle (POTV) may deposit a substantial amount of exhaust vapors in the upper atmosphere. The magnitude and the duration of the ionospheric plasma reductions produced by the engine burns depends on the particular burn profiles. These plasma reductions can be simulated with a number of existing models.[2-5,22] The refraction effects by the chemically produced plasma gradients can be readily accomplished by coupling ray tracing to the ionospheric models.

The major uncertainty in this field of research is whether or not exhaust releases will trigger irregularities in the equatorial ionosphere. This is of special interest to the SPS program because the HLLVs are expected to conduct orbit circularization burns at the equator. The amount of material released during one of these burns may be as much as 8×10^5 kg over a region 1200 km long. Should the HLLV make an expected 390 flights per year, the exhaust vapors may continually stimulate ionospheric irregularities which could adversely affect transionospheric propagation in the disturbed region. More theoretical and experimental work needs to be done in this area.

Acknowledgment

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