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Lifetime of a depression in the plasma density over Jicamarca produced by space shuttle exhaust in the ionosphere

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Abstract. When the space shuttle orbiting maneuver subsystem (OMS) engines burn in the ionosphere, a plasma density depression, or "hole," is produced. Charge exchange between the exhaust molecules and the ambient O^+ ions yields molecular ion beams that eventually recombine with electrons. The resulting plasma hole in the ionosphere can be studied with ground-based, incoherent scatter radars (ISRs). This type of ionospheric modification is being studied during the Shuttle Ionospheric Modification with Pulsed Localized Exhaust (SIMPLEX) series of experiments over ISR systems located around the globe. The SIMPLEX 1 experiment occurred over Jicamarca, Peru, in the afternoon on October 4, 1997, during shuttle mission STS 86. An electron density depression was produced at 359 km altitude at the midpoint of a magnetic field line. The experiment was scheduled when there were no zonal drifts of the plasma so the modified field line remained fixed over the 50 MHz Jicamarca radar. The density depression was filled in by plasma flowing along the magnetic field line with a time constant of 4.5 min. The density perturbation had completely vanished 20 min after the engine burn. The experimental measurements were compared with two models: (1) SAMI2, a fully numerical model of the *F* region, and (2) an analytic representation of field-aligned transport by ambipolar diffusion. The computed recovery time from each model is much longer than the observed recovery time. The theory of ambipolar diffusion currently used in ionospheric models seems to be inadequate to describe the SIMPLEX 1 observations. Several possible sources for this discrepancy are discussed. The SIMPLEX 1 active experiment is shown to have the potential for testing selected processes in ionospheric models.

1. Introduction

The ionosphere is a complex system of electrons and ions that can be described with coupled fluid equations for continuity, momentum, and energy. Many such models have been developed over the past 20 years to describe many regions of the ionosphere at a variety of latitudes [*Schunk*, 1996]. Validation of these models typically employs comparison with model outputs of electron density with quasi-equilibrium measurements of electron density profiles. Adjustment of various parameters in the model is often used to minimize differences between the modeled and measured values of electron density. These parameters include transport terms (neutral winds or electric fields), the neutral atmosphere model, or individual coefficients for diffusion or chemistry in the model. Such validation is difficult because ionospheric models have competing influences of ion production, chemical recombination, transport, and plasma heating and cooling. An error in one process could be masked by a compensating error in another process to yield an electron density that matches observations under one condition but gives an unrealistic result for vastly different conditions.

Rather than testing ionospheric models under quasi-equilibrium conditions where inputs vary with timescales of hours, this paper considers a perturbational approach to ionospheric model validation. This approach uses a transient chemical release to produce a

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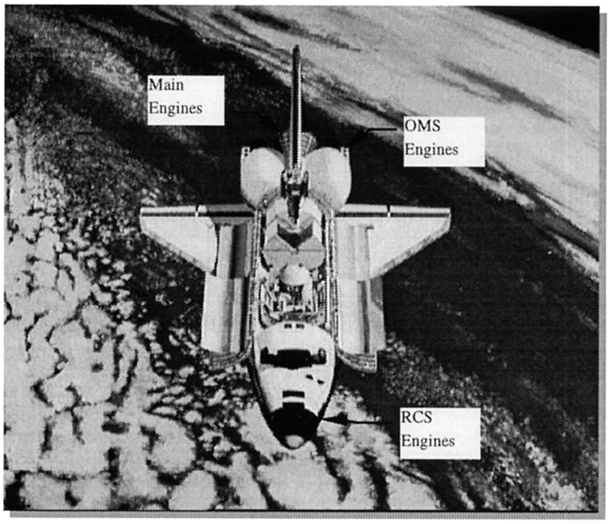

Figure 1. Space shuttle liquid propellant engines. The second largest thrusters on the space shuttle, the orbital maneuvering subsystem (OMS) engines, are used for the SIMPLEX experiments. RCS, reaction control subsystem.

localized depression in the electron density on a magnetic field line. The amount of the release is large enough to produce an electron "hole" that is observed by ground-based incoherent scatter radars. After the hole is formed and the release material has dissipated by diffusion the natural processes of field-aligned diffusion fill in the density depression. This process occurs in a localized region on the scale of kilometers and in a short timescale of minutes.

The engines of the space shuttle are used for the source of the modification chemicals. The space shuttle orbital maneuvering subsystem (OMS) engines (Figure 1) inject known quantities of CO, CO_2, H_2, H_2O, and N_2 into the upper atmosphere during orbit burns. All of these substances react with O^+, the most abundant ion in the *F* region. The space shuttle OMS engines routinely operate in the ionosphere for orbit insertion, trajectory corrections, and deorbit maneuvers. For this study, dedicated firings have been scheduled during the Shuttle Ionospheric Modification with Pulsed Localized Exhaust (SIMPLEX) experiments with the coordination of the Air Force Space Test Program.

The Plasma Physics Division of the Naval Research Laboratory is conducting the SIMPLEX experiments in collaboration with a number of ground-based radar sites around the world. These sites include the Jicamarca incoherent scatter radar (ISR) located in Peru, the Arecibo ISR in Puerto Rico, the Millstone Hill ISR in Massachusetts, the ALTAIR ISR in Kwajalein, and the JINDALEE over the horizon (OTH) radar near Alice Springs in Australia. Previous ionospheric modification experiments using the space shuttle and ground radars were conducted during the Spacelab 2 mission in July 1985 over Millstone Hill [*Mendillo et al.*, 1987] and Arecibo [*Bernhardt et al.*, 1988a, 1988b]. These new series of experiments some 14 years later benefit from improved radar data processing. These improvements lead to higher spatial resolution for densities, drifts, and temperatures. Also, multiple radar beams allow simultaneous observation of both the modified and unmodified ionosphere.

The three primary objectives of the SIMPLEX program are (1) plume technology, (2) ionospheric interactions, and (3) ionospheric model validation. For plume technology the radar measurements of the shuttle plume can provide characteristics of the OMS exhaust such as density, velocity, and temperature. Data of the incoherent radar scatter can be analyzed to provide the composition of the plume such as relative abundance of species and amount of material that condenses. The efficiency and function of engines firing in space can be obtained from these data.

The ionospheric interactions are determined by observations of radar backscatter and optical emissions. The incoherent scatter from the plume provides the magnitude of the disturbance after the OMS engine firings. The ISR spectra are significantly modified in the space shuttle plume region [*Bernhardt et al.*, 1995, 1998]. This is the result of pick-up ions moving super-sonic velocities (3–10 km s^{-1}) in the plume and the enhance scatter from electrons in the presence of these ions. When the pickup ions recombine, they leave neutrals in excited states. Sensitive optical instruments detect these states as airglow enhancements [*Bernhardt*, 1987].

Following the initial pickup ion formation and recombination, an ionospheric hole is left in the plasma [*Mendillo et al.*, 1975]. The evolution of this hole is studied to provide ionospheric model validation. Ionospheric models, used to describe the day-to-day variability of unmodified ionosphere, are tested with an initial perturbation that is not usually found in nature.

This paper describes the first SIMPLEX experiment, which occurred over the Jicamarca Radio Observatory in Peru. The burn was designed to study the recovery of the ionosphere from an artificial distur-

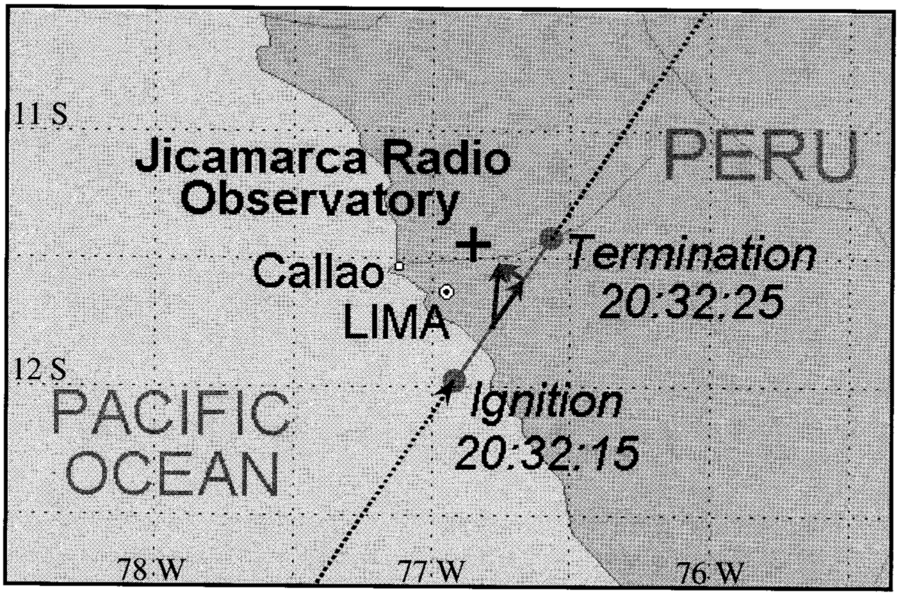

Figure 2. Trajectory of the 10 s OMS burn over Jicamarca. Times are given in UT.

bance. Section 2 describes the experimental setup to follow the evolution of the modified ionosphere. Section 3 presents an analytic diffusion model study of the ionospheric recovery phase. The discussion in Section 4 describes possible sources for the differences between the observations and the simulations of the SIMPLEX 1 experiment.

2. Experiment

The SIMPLEX 1 campaign occurred on October 4, 1997, during the STS 86 flight of the space shuttle. The altitude of the orbit was 359 km. The orbiter flew on a ground track that was within 29 km horizontal distance of being over the ISR at the Jicamarca Radio Observatory (JRO) near Lima, Peru. Figure 2 illustrates the location of the ground track, the burn, and the velocity vectors for the orbiter, engine firings, and exhaust species. The 49.98 MHz Jicamarca radar is located at 11.95°S latitude and 76.87°W longitude. The burn started at 12.372°S latitude and 76.908°W longitude with a horizontal distance of 46.8 km from the radar. At a magnetic declination of 0.45° the field line intersecting the start of the burn went 4.4 km to the west of the geographic location the radar antenna. The burn stopped at 11.862°S latitude and 76.525°W longitude, 37 km to the east of the radar.

A single OMS engine was fired for 10 s. The orbital speed was 7.7 km s^{-1} with an azimuth of 36° east of north. The engine injected the material at 3.07 km s^{-1} relative to the space shuttle. The OMS engines were oriented perpendicular to the orbit in the direction of the JRO ISR. The vector sum of the orbital motion and the engine injection velocities yields an exhaust velocity of 8.29 km s^{-1} at an azimuth of 14°, nearly in the northward direction (Figure 2). The exhaust material was injected at an angle of 9° with the magnetic field lines. This arrangement was chosen so that all exhaust materials were injected along the magnetic field lines where the ionospheric modification occurred. The mean free path was estimated to be 9.3 km for high-speed molecules using the Mass Spectrometer Incoherent Scatter (MSIS) 86 atmosphere and the formula $\lambda = (\Sigma n_i \, Q_i)^{-1}$, where n_i and Q_i are the density and collision cross section for species i. This paper assumes that the injected material traveled two mean free paths (18.6 km) and then began to diffuse in the neutral atmosphere.

Each OMS engine produced 2.5×10^{26} molecules of exhaust per second with a molecular composition given in Table 1. This table shows that the reaction rates for CO and N_2 are strongly dependent on the molecular speed. The high velocities of the injected molecules affected the reactions in the plume and the composition of the pickup ions. During the 10 s burn, 25×10^{26} molecules, or 87 kg, were deposited over 77 km distance. The altitude of the burn was 359 km.

Table 1. OMS Exhaust Composition and Rate Constants for Reactions With O^+

Species	Mole Fraction	Thermal Rate Constant k_1, $cm^3\ s^{-1}$	Orbital Speed Rate Constant k_1, $cm^3\ s^{-1}$	Photodissociation Rate ν_1, s^{-1}	Photoionization Rate ν_2, s^{-1}
CO	0.050	0.0	6.0×10^{-11}	0.32×10^{-6}	0.324×10^{-6}
CO_2	0.122	9.0×10^{-10}	6.0×10^{-10}	1.22×10^{-6}	0.803×10^{-6}
H_2	0.241	1.7×10^{-9}	1.7×10^{-9}	0.044×10^{-6}	0.064×10^{-6}
H_2O	0.274	2.3×10^{-9}	2.4×10^{-9}	11.4×10^{-6}	0.404×10^{-6}
N_2	0.313	1.0×10^{-12}	3.0×10^{-10}	0.66×10^{-6}	0.365×10^{-6}

The exhaust materials are effective for ionospheric modification because H_2O, CO_2, and H_2 are 100–1000 times more reactive with O^+ than the ambient N_2 and O_2 molecules.

The space shuttle trajectory was constrained to fly near enough to modify the ionosphere over Jicamarca but far enough to minimize the direct echo of the radar from the space shuttle (Figure 3). Direct scatter from the orbiter would have obscured the much weaker incoherent scatter from the plasma. This SIMPLEX 1 experiment was optimized for the study of ionospheric recovery from a transient event. The experiment was designed to reduce the density of the plasma along a magnetic field line the extended over Jicamarca and to observe the subsequent refilling process. The electron loss process consisted of ion-molecule charge exchange followed by electron-ion dissociative recombination. The reactions with the water vapor component of the exhaust are as follows:

$$O^2 + H_2O \rightarrow H_2O^+ + O,$$

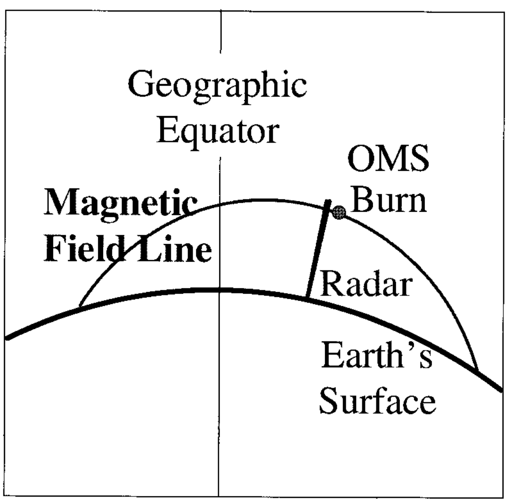

Figure 3. Geometry of the chemical release to record modification of the plasma along a magnetic flux tube.

with rate constant k_1 (see Table 1), and

$$H_2O^+ + e^- \rightarrow OH + H,$$

with rate constant $k_2 = 6.5 \times 10^{-7}\ (300/T_e)^{0.5}$ $cm^3\ s^{-1}$. The net reaction is to neutralize the plasma and dissociate the water molecule:

$$O^+ + e^- + H_2O \rightarrow OH + H + O.$$

Similar reactions occur with the other molecules listed in Table 1.

The molecular chemistry had added complexity from (1) photodissociation reactions of the form

$$H_2O + h\nu \rightarrow HO + H,$$

with rate ν_1 (see Table 1), (2) photoionization reactions by sunlight such as

$$H_2O + h\nu \rightarrow H_2O^+ + e^-,$$

with rate ν_2 (see Table 1), and (3) ion-molecule reactions between product ions and injected neutrals such as the example

$$H_2O^+ + H_2O \rightarrow H_3O^+ + OH,$$

with rate constant $k_3 = 1.67 \times 10^{-9}\ cm^3\ s^{-1}$. A complete set of ion-molecule and dissociative-recombination reactions for releases of H_2O, CO_2, H_2, N_2, and CO is given by *Bernhardt* [1987], *Ikezoe et al.* [1987], and *Bernhardt et al.* [1988a, 1988b].

The neutralization process was expected to produce an ionospheric hole by chemical reactions with the exhaust produced by the OMS burn. In order to distinguish this hole from naturally occurring density reductions, measurements of the modified and unmodified ionosphere were made simultaneously. This was accomplished by splitting the radar pattern into two beams (Figure 4). The east radar beam was positioned at a 90° azimuth and a zenith angle of 3°. The east radar beam intersected the modified field lines at a distance $x_0 = 49.7$ north of the OMS burn.

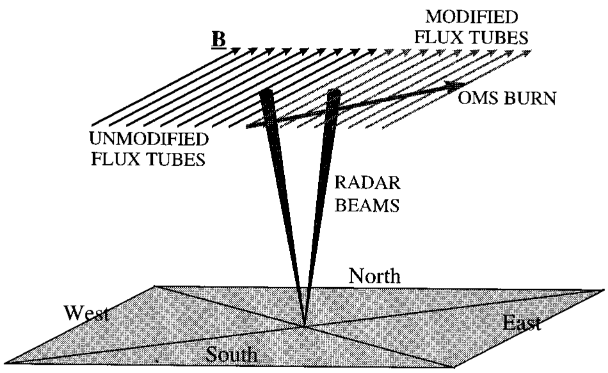

Figure 4. Split beam format for the Jicamarca radar used during the STS 86 SIMPLEX burn.

The west radar beam was placed with an azimuth of 270° and a zenith angle of 3° on unmodified field lines. The separation between the two beams (6°) was 38 km at the altitude of the release. The radar operated at 49.98 MHz with 15 km resolution. The data were acquired at 5 s intervals with a total of four receivers, two receivers at each antenna beam direction.

The ambient conditions were ideal for the SIMPLEX 1 experiment. The burn occurred at 1532 local time when the east-west plasma drift was less than 5 m s^{-1}. At this speed it would take the modified plasma over 60 min to drift out of the east radar beam. There was a slight vertical drift of the plasma of 10 m s^{-1} upward. These drifts were measured using the split beam configuration shown in Figure 4. Since the plasma convection was very small, the modified plasma field lines stayed fixed in the east beam of the radar. Any variation in the plasma density was due to refilling of the modified magnetic flux tube by diffusion toward the release point at 359 km altitude. Local production at the burn altitude is not important because photoionization of neutrals occurs primarily below 200 km altitude.

Individual profiles of electron density are illustrated in Figure 5 for the west (unmodified) and east (modified) radar data. The magnitude of the density depression in the ionosphere is 34%, $t_1 = 45$ s after the start of the burn. The density profiles are normalized to the peak density of the F region at 325 km, which was determined to be 8.3×10^6 cm^{-3} using ionosonde data. The E region densities (near 100 km altitude) are larger than the daytime F region peak densities. Polynomial equations are used to fit the

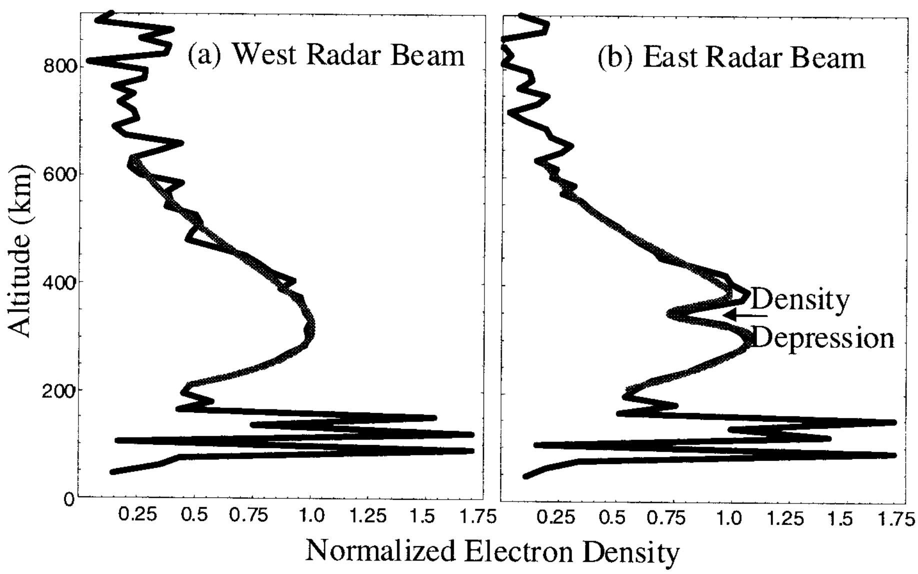

Figure 5. Incoherent scatter radar profiles of the ionosphere for (a) unmodified field lines and (b) chemically modified field lines. The data were obtained with the Jicamarca Radio Observatory ISR on October 4, 1997, at 2033 UT, 45 s after the start of the burn. To emphasize the relative density reduction, the densities are normalized to the peak value of 8.3×10^5 cm^{-3}. A 34% density depression is observed 25 km from the OMS burn that occurred 45 s earlier. Polynomial fits to the profiles are shown in gray. The density depression has a half width $L_z = 23$ km.

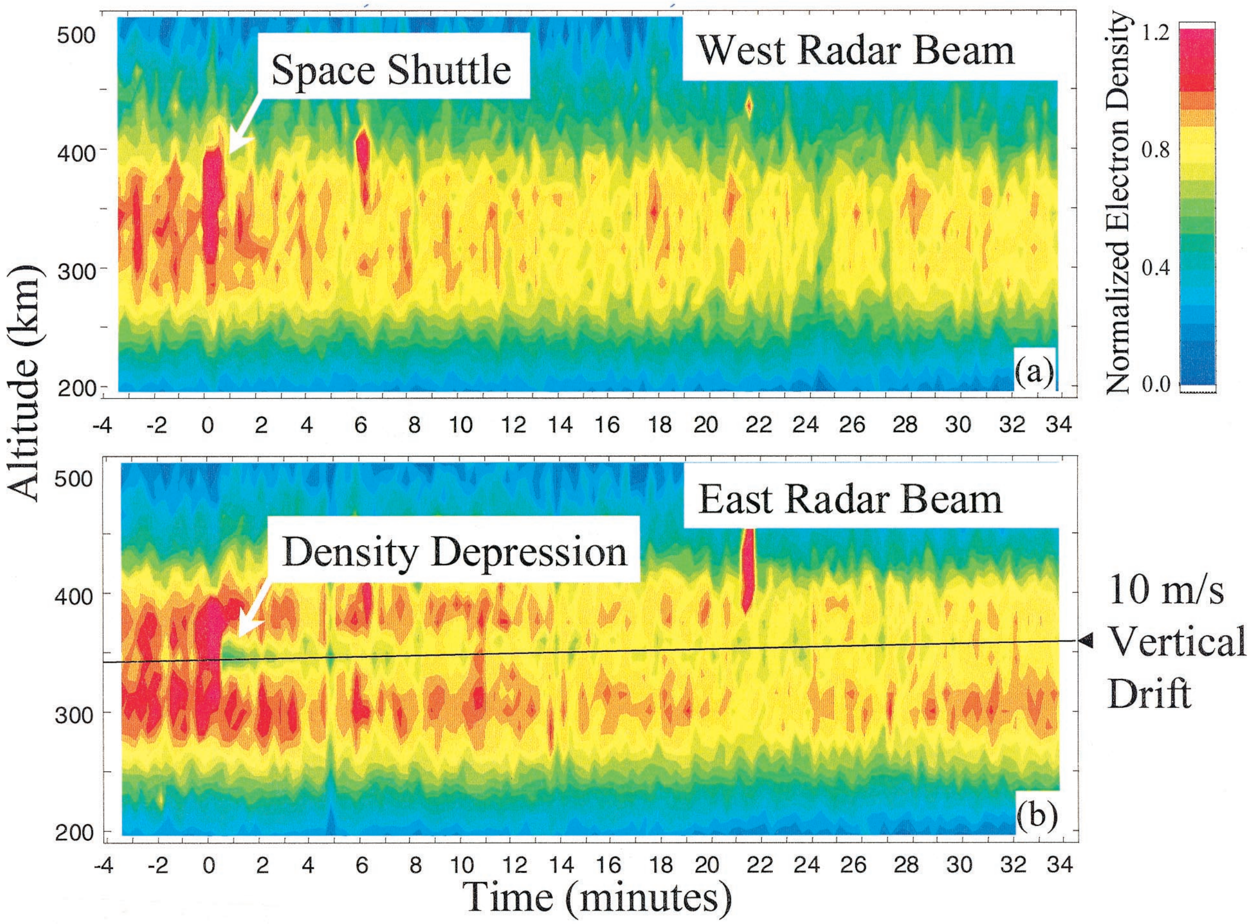

Plate 1. Incoherent scatter observations at Jicamarca Radio Observatory (JRO) for (a) west radar beam and (b) east radar beam. The time is relative to 2032:15 UT on October 4, 1997. Both radar beams show strong echoes from the space shuttle orbiter. The east radar beam records the effects of the exhaust release. The scale of the density is normalized to a peak value of 8.3×10^5 cm^{-3}.

electron density profiles for both data sets. The modified profile is accounted for by a Gaussian density hole of the form

$$G(z) = 1 - A_z \exp(-z^2/L_z^2), \tag{1}$$

where depression magnitude A_z equals 0.34 and hole scale size L_z equals 23 km.

One can estimate a radial speed v_r of the exhaust gases from the size of the ionospheric hole. Assuming uniform radial expansion, $v_r = L_z/t_1 = 500$ m s^{-1}. The axial speed of the exhaust is $v_a = 3070$ m s^{-1}. The radial speed varies from 0 to 1500 m s^{-1} at the edge of the 25° exhaust cone [*Bernhardt et al.*, 1995]. The measurement of v_r indicates that most of the modification effects occur within an axial angle $T = \tan^{-1}(v_r/v_a) = 9°$.

A temporal history of the electron density is shown by the contours of Plate 1. Initially, both beams detected the space shuttle with echoes off the body of the spacecraft. The orbiter flying through different sidelobes of the radar beams produces the structure in these echoes. These echoes mask the initial formation of the ionosphere hole. After the space shuttle clutter vanished from the radar data a 15 min depression was left in the electron densities. Examination of the ion line spectra from the radar did not show any unusual features. Modified spectral shapes would be expected if the radar was scattering directly from the region of fast-moving, pickup ions [*Bernhardt et al.*, 1998]. The 10 m s^{-1} vertical drift causes a slight rise in the position of the ionospheric hole as illustrated with the solid line in Plate 1.

3. Models of the Density Depression

Two model studies were conducted to simulate the artificial density depression over Jicamarca. First, a numerical model is used to provide a description of the electron densities from a point release that is designed to simulate the exhaust trail from the OMS engines. Second, an analytical model is used to describe the recovery phase of the experiment.

3.1. Numerical Modeling of the SIMPLEX 1 Release

The Naval Research Laboratory (NRL) SAMI2 ionospheric simulation code [*Oran et al.*, 1974; *Huba et al.*, 2000] has been used to provide a complete description of the ionospheric evolution including multiple-ion species, field-aligned transport between hemispheres, plasma temperatures, electron and ion fluxes, photoionization of neutrals, and plasma/neutral chemistry. This code was driven by a neutral gas expansion and chemical reactions using formulas given by *Bernhardt et al.* [1988a].

The ionospheric modification produced by the STS 86 burn over Jicamarca is modeled using a numerical description of the plasma density coupled to a description of the neutral gas expansion. A procedure for this coupling is described by *Bernhardt et al.* [1991]. For this numerical study, the fluid equations for the ions and electrons in the SAMI2 model [*Huba et al.*, 2000] are solved in conjunction with steady state momentum equations for the ions including ion inertia. The computations are restricted to individual magnetic field lines extending from one hemisphere to the other. The field-aligned tube of plasma is confined to magnetic field lines that may be transported with **E** × **B** drifts. The code models the dynamic plasma and chemical evolution of seven ion species (H^+, He^+, N^+, O^+, N_2^+, NO^+, and O_2^+) along the Earth's dipole field from hemisphere to hemisphere. The atmospheric neutral species are specified using the empirical codes MSIS 86 and horizontal wind model (HWM) 93. For this study, SAMI2 was modified to include three additional neutral (H_2O, CO_2, H_2) and ion (H_2O^+, OH^+, H_3O^+) species.

The evolution of the exhaust neutral gas is modeled using a simple point release diffusion model

$$n_0(x, y, z, t) = \frac{N_0}{(4\pi D_0 t)^{3/2}} \exp\left[-\frac{x^2+y^2+z^+}{2D_0 t} - \frac{t}{\tau}\right], \quad (2)$$

where $D_0 = kT/m_n \nu_n$, with ν_n as the neutral collision frequency, τ is the O^+ loss rate by ion-neutral reaction rates given in Table 1.

The following parameters are used in the simulation study. The geophysical parameters are $F10.7 = 180$, $Ap = 2$, day is 173, and year is 1999. The computational mesh is 201 × 32, and the time step is $\Delta t = 1$ s. A total of 32 flux tubes are used in the altitude range 298–453 km in 5 km increments. The release parameters are geographic longitude $\phi_g = 283.15°$, geographic latitude $\theta_g = -12.36°$, altitude equals 358 km, and $N_0 = 100 \times 10^{26}$. This value of N_0 was adjusted to be roughly 4 times larger than estimated from shuttle burn parameters to yield the measured density reduction. There are no **E** × **B** drifts used in the simulations. The time of the release is 1530 LT.

Plate 2 shows the results for the calculation of the electron density versus time. The contour plot of the electron density as a function of altitude and time shows a clear hole generated in the *F* region centered at the release point. The reduction in electron density extends from 300 to 400 km altitude, which is a larger altitude range than observed with the ISR. The electron hole is largest ~2 min after the release. Subsequently, the electron hole fills in by plasma diffusion, and the effects of the release are no longer evident >30 min after the release. A plot of the normalized electron density (Figure 6b, thick curve labeled SAMI2 results) is taken at the release point as a function of time. The minimum electron density in the hole is roughly 70% of the density at the time of the release. The hole then fills on a timescale of ~20 min.

Overall, the results of the simulation are qualitatively in agreement with the experimental observations and the simple one-dimensional (1-D) diffusion model. However, there are some quantitative differences. First, using the standard MSIS 86 and HWM 93 atmospheric models, we find that the peak electron density at the time of the release is $\sim 2 \times 10^6$ cm^{-3}, which is higher than the measured peak electron density, 8.5×10^5 cm^{-3}. The fact that the modeled ionosphere is much more dense than the ionosphere during the SIMPLEX experiment may explain why we had to use a larger release to obtain the observed ~70% reduction in electron density. Also, the hole takes 2 min to fully form while the observations show that maximum density reduction occurs by 45 s after the burn. Possibly, dynamical rather than chemical effects are responsible for the rapid formation of the

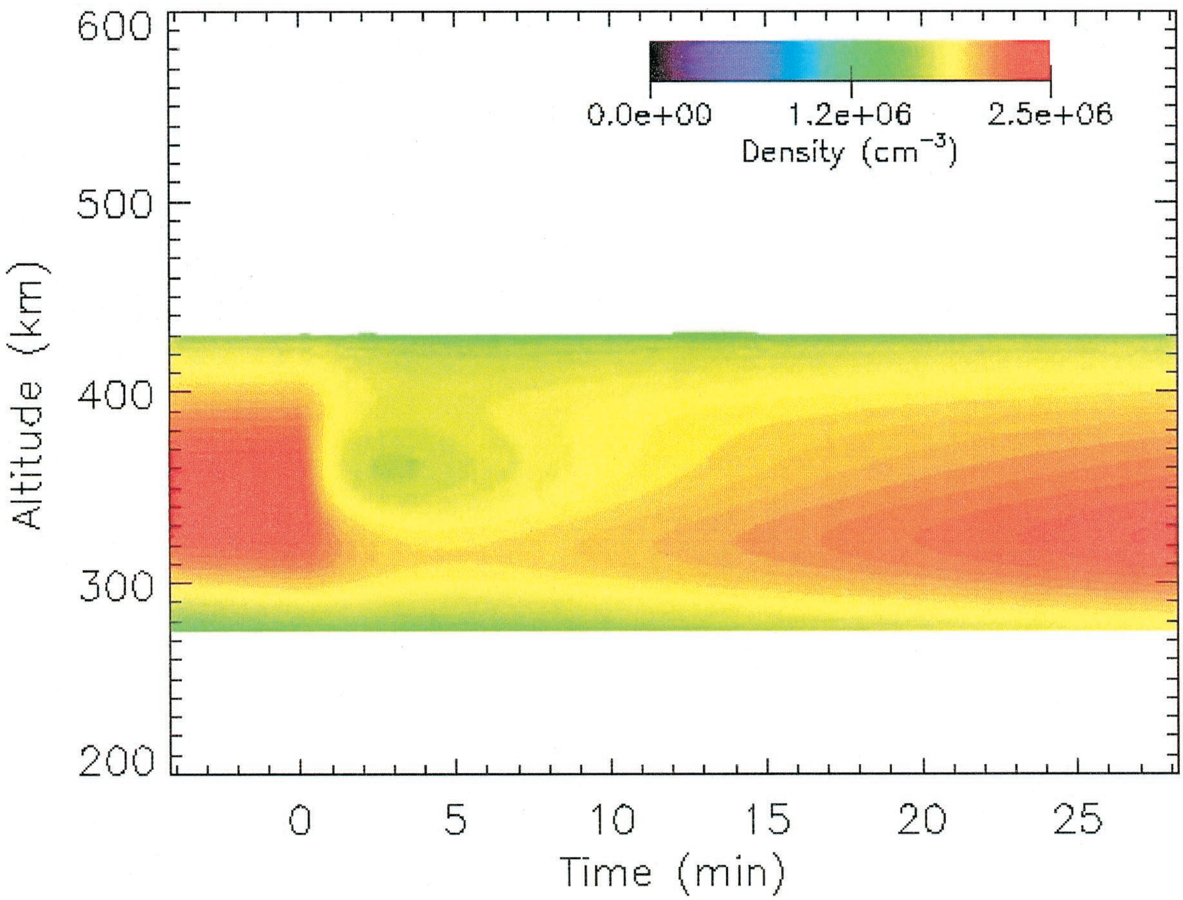

Plate 2. Electron densities near the exhaust release meridian computed using the SAMI2 numerical model. The simulated densities are characterized by rapid formation and slow recovery from the release. The simulation results are longer lived and cover a larger altitude range than is shown by the radar observations in Plate 1b.

ionospheric hole [*Bernhardt et al.*, 1988b]. Finally, the recovery time observed in the simulation study is roughly a factor of 4 larger than that observed. This process is investigated in section 3.2. We intend to perform a more complete simulation study in the near future to resolve these differences.

3.2. Analytic Model of Ionospheric Recovery

Because of the discrepancies with the numerical SAMI2 model, a simplified approach has been devised to gain further insight into the evolution of the plasma hole and to focus on the discrepancy of the relatively slow recovery produced by the diffusion theory. An analytic expression is derived using approximations appropriate for modification of a high-altitude magnetic field line near the equator. The first radar observations are made 45 s after the engine burn because of interference by direct echoes from the space shuttle vehicle. The exhaust density at that time is approximately given by $n_g = N_0/(4\pi D_g t)$, where $N_0 = 3.25 \times 10^{20}$ molecules cm^{-1} is the exhaust deposition rate, $D_g = 8 \times 10^{10}$ cm^2 s^{-1} is the exhaust diffusion coefficient, and $t = 45$ s is the time after release [*Bernhardt et al.*, 1988a]. The maximum exhaust density at this time, found to be $n_g = 7.2 \times 10^6$ cm^{-3}, is too low to produce any significant ionospheric modification. Thus, after 45 s, the effects of chemistry are largely ignorable, and only diffusion processes need to be considered. Consequently, the formation of the ionospheric hole was not recorded by the radar and will not be modeled with the simplified analysis. The first measurement of the ionospheric hole will be used as an initial condition for the theoretical computation of its evolution.

The geometry for the SIMPLEX 1 experiment is simple enough that a useful description of the ionospheric hole can be obtained analytically. The primary simplification comes from placing the release on a horizontal portion of the magnetic field line. Under these conditions, gravity does not affect the field-aligned motion, and background neutral densities are independent of the distance along the field line. In the F region, O^+ is the predominant ion. With this simple geometry the motion of the modified plasma along the field line is simple described by the one-dimensional diffusion equation

$$\frac{\partial n_i}{\partial t} = D_a \frac{\partial^2 n_i}{\partial x^2} + P_i - L_i, \tag{3}$$

where n_i is O^+ ion or electron density, D_a is the ambipolar diffusion coefficient, P_i is the ion or electron production rate, L_i is the ion or electron loss rate, x is distance along the field line, and t is time. The production rate at 345 km altitude is on the order of 300 ions cm^{-3} s^{-1} and is much less than the production rate of >3000 ions cm^{-3} s^{-1} at 150 km altitude. The ion production rate can be neglected ($P_i = 0$) for the 20 min period of the radar measurements. The ion loss rate involves charge exchange between O^+ and background neutral species O_2 and N_2, as well as the exhaust species. After the OMS exhaust has dissipated, the loss term in (3) is written as $L_i = \beta n_i$, where $\beta = \gamma_1[N_2] + \gamma_2[O_2]$ and γ_1 and γ_2 are ion-molecule rate coefficients.

Assume that a Gaussian-shaped ionospheric hole is formed in the ionosphere by the chemical release. After the release material has dissipated by diffusion the remaining hole will evolve according to (3). For an initial electron density disturbance of the form

$$n_i(x, y, z, t = t_0) = n_0(z, t_0) \cdot \left\{1 - A_0 \exp\left[-\left(\frac{x^2}{L_x^2} + \frac{y^2}{L_y^2} + \frac{z^2}{L_z^2}\right)\right]\right\}, \tag{4}$$

where n_0 is the background O^+ density, x is the coordinate along the magnetic field line, and (y, z) are the horizontal and vertical coordinates, respectively, perpendicular to $\mathbf{B}$. The origin of the coordinates is the center of the release.

With (4) as an initial condition the analytic solution to (2) is found to be

$$n_i(x, y, z, t) = n_0(z, t_0) \exp(-\beta t') \cdot \left\{1 - A_0 \exp\left[-\left(\frac{y^2}{L_y^2} + \frac{z^2}{L_z^2}\right)\right] \frac{L_x}{\sqrt{4D_a t' + L_x^2}} \cdot \exp\left[-\left(\frac{x^2}{4D_a t' + L_x^2}\right)\right]\right\}, \tag{5}$$

where $t' = t - t_0$ is time relative to the initial disturbance. This function is fit to the radar observations by nonlinear least squares fit for the parameter β. Instead of a constant value of decay rate β the best fit to the data is obtained using a third-order polynomial for the decay function. As shown in section 2, $L_z = 23$ km. The OMS plume crosses the magnetic field lines at an angle of 36° along a horizontal trajectory. Geometric projection of an elongated hole aligned with the space shuttle orbit gives $L_x = L_z/\sin(36°) = 39$ km and $L_y = L_z/\cos(36°) = 28$ km.

The function given in (5) is numerically fit to the measured electron density on the field line that intersects the OMS burn. With the geometry of the SIMPLEX 1 measurements the coordinates of the radar observations on the modified field line are $(x, y, z) = (x_0, 0, z)$, where $x_0 = 49.7$ km. The electron density profile at the radar is found to be

$$n_i(x_0, 0, z, t) = n_0(z, t)\left\{1 - A_0 \exp\left[-\left(\frac{z^2}{L_z^2}\right)\right] \cdot \frac{L_x}{\sqrt{4D_a t' + L_x^2}} \exp\left[-\left(\frac{x_0^2}{4D_a t' + L_x^2}\right)\right]\right\}, \tag{6}$$

where $n_0(z, t)$ is the density variation of the unmodified ionosphere. Figure 6 shows the numerical fit to the electron density variation at 345 km altitude for the unmodified ionosphere in the west beam (Figure 6a) and the modified ionosphere in the east radar beam (Figure 6b). The temporal variation of the unmodified ionosphere is best fit with a third-order polynomial of the form

$$n_0(z, t) = n_0(z, t_0) \exp[-\beta_1 t' + \beta_2 t'^2 + \beta_3 t'^3)] \tag{7}$$

as shown by the thick solid curve in Figure 6a. This polynomial represents the decay of the natural ionosphere with coefficients $\beta_1 = 2.6 \times 10^{-4}$ s^{-1}, $\beta_2 = -1.9 \times 10^{-7}$ s^{-2}, and $\beta_3 = 4.2 \times 10^{-11}$ s^{-1}. The natural variation is the dashed curve in Figure 6b. The modified ionosphere follows this variation except for the 10 min following the engine burn.

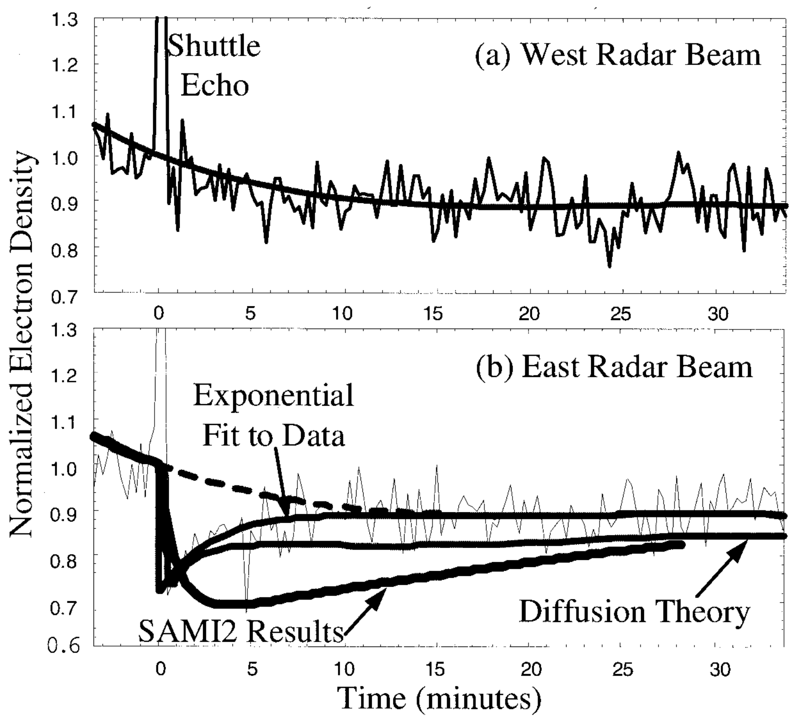

Figure 6. Electron density in the (a) unmodified and (b) modified F region obtained with the JRO ISR on October 4, 1997. The time is relative to 2032:15 UT. The unmodified ionosphere decays with a time constant of 190 min. The electron density in the modified ionosphere (Figure 6b) recovers with a time constant of 3.7 min, more rapidly than predicted using field-aligned diffusion from either SAMI2 or the analytic diffusion theory. The simulation curves eventually return to the line of observations for times longer than 1 hour. The densities are normalized to 8.3×10^5 cm^{-3}, the peak density at the start of the burn.

The ambipolar diffusion coefficient is $D_a = (1 + T_e/T_i)\, D_{in}$, where T_e and T_i are the electron and ion temperatures, respectively, $D_{in} = kT_i/m_i \nu_{in}$ is the ion-neutral diffusion coefficient, and ν_{in} is the ion-neutral collision frequency. The Jicamarca ISR cannot measure ion and electron temperatures because of limitations provided by scatter nearly perpendicular to the magnetic field direction. For this calculation we use $T_e = 3000$ and $T_i = 1000$ K. The ion-neutral diffusion coefficient is calculated using the formulas given by *Banks and Kockarts* [1973] for diffusion in O, N_2, O_2, and He. The MSIS 86 model provides the required neutral densities and temperature (T_n = 895 K) for this calculation. The computed D_{in} is 3.2×10^{10} cm^2 s^{-1}, and $D_a = 12.8 \times 10^{10}$ cm^2 s^{-1}.

The modified ionosphere recovers much more rapidly than predicted by the ambipolar diffusion theory. The gray, diffusion theory curve in Figure 6b was obtained from (5) using $A_0 = 0.38$ and $D_a = 12.8 \times 10^{10}$ cm^2 s^{-1}. The diffusion theory fits observations only for the first few minutes. The observations show an ionospheric hole that recovers with an exponential time constant of 3.7 min. The solution to the diffusion equation predicts that the effects of the release should be observable 30 min after the engine burn. This is because for times $t' \gg L_x/4D_a$ the density on the modified field line should vary as

$$n_i(x_0, 0, 0, t) \cong n_0(0, t_0) \exp(-\beta t') \left(1 - A_0 \frac{L_x}{\sqrt{4D_a t'}} \right). \tag{8}$$

The slow ($\approx 1/\sqrt{t}$) decay is the result of one-dimensional, diffusive transport along a magnetic field line.

The minor oscillation in the diffusion theory curve in Figure 6b between 5 and 35 min after the burn is a result of combining the background time decay with the diffusive decay given by (8). The one-dimensional, diffusion theory curve in Figure 6b eventually merges with the observations 70 min after the burn. Various parameters were used to try to provide a better match between the diffusion theory and the observations. The failure to provide this match indicates that this ambipolar diffusion theory is inadequate to describe the radar data except for the first 2.5 min of the observations. Mechanisms for the anomalous recovery rate in the data are discussed in section 4.

4. Conclusions

The observations during the STS 86 flight of SIMPLEX 1 are the first daytime radar measurements for the evolution of an artificial ionospheric hole at the equator. These are the only measurements at the equator of refilling when the modified ionosphere was in view of the radar for an extended period of time. Consequently, the SIMPLEX 1 experiment provided a unique opportunity to isolate the mechanism of ambipolar diffusion in the ionosphere.

After the production of the localized disturbance the radar observations show some indications of the density perturbation 15 min after the engine burn (Plate 1). A careful look at the density on the field line at the center of the OMS burn shows that most of the recovery occurs within 10 min (Figure 6b). This observation contradicts the results of the ambipolar diffusion both with the SAMI2 model and the analytic theory, which predicts an effect lasting longer than 30 min (Figure 6b). Possible explanations for this difference between theory and observations include the following: (1) The hole was transported out of the radar viewing volume by either plasma drifts perpendicular to **B** or a meridian component of neutral wind; (2) the plasma in the hole was replenished by photoion production; (3) plasma entered the hole by cross-field diffusion; (4) there was collisionless plasma expansion into a vacuum; or (5) the background ionosphere was not correctly specified. The first possibility in process 1 (i.e., $\mathbf{E} \times \mathbf{B}$ drift) can be ruled out because it would have taken over 60 min for the ionospheric hole to have drifted away from the radar beam with the measured (5 m s^{-1}) drift speed. The second possibility in process 1 (i.e., field-aligned neutral wind) would have required a neutral wind greater than the parallel diffusion velocity of the plasma. From (4) the location of the edge is given by

$$x = \pm\sqrt{4D_a t + L_x^2}.$$

The speed of that point is

$$v_x = \frac{2D_a}{\sqrt{4D_a t + L_x^2}}. \tag{9}$$

Ten minutes after the engine burn, this speed is $v_x = 143$ m s^{-1} using $D_a = 12.8 \times 10^{10}$ cm^{-2} s^{-1} and $L_x = 39$ km. For the geomagnetic quiet conditions of the SIMPLEX 1 experiment the meridional wind speed is expected to be smaller than 50 m s^{-1} [*Rees*, 1989], so a neutral wind that exceeds the diffusion speed (143 m s^{-1}) is unlikely. Process 2 (i.e., photoionization) can be ruled out because, at 350 km altitude, neither the exhaust materials nor the background neutrals can produce ions at a rate greater than 200 ions cm^{-2} s^{-1}. At that rate, over 80 min would be required to refill the ionospheric hole.

Process 3 (i.e., cross-field diffusion) is considered next. The diffusion coefficient for transport across magnetic field lines is $D_\perp = kT_i\nu_{in}/m\omega_c^2$, where $\omega_c = e\mathbf{B}/m_i$ is the ion gyrofrequency. In the *F* region, $\omega_c \gg \nu_{in}$ and $D_\perp \ll D_a$. At the SIMPLEX 1 release altitude, $D_\perp = 4.6 \times 10^4$ cm^2 s^{-1}, cross-field, collisional diffusion is negligible. Wave particle diffusion is another source of transport across magnetic field lines. Wave particle diffusion denotes charged particle scattering due to fluctuating electrostatic fields produced by instabilities. *Bernhardt et al.* [1982], however, point out that density gradients comparable to an ion gyro are needed to excite the drift instabilities that generate the electric fields. The ion gyroradius is ~2 m at the release altitude, so the $L_z = 23$ km density gradients produced by the OMS burn are too weak to excite wave particle diffusion.

Process 4 (i.e., collisionless expansion) was used to explain the rapid filling in of the wake for the space shuttle during the Spacelab 2 mission [*Stone et al.*, 1988]. Charge separation at the wake boundary appears to produce an electric field that accelerates the ions into the wake of the orbiter. This process, however, occurred for a different geometry than described here. During the Spacelab 2 measurements of the space shuttle wake the Plasma Diagnostics Package (PDP) satellite was parked 13.7 m from the orbiter. For the SIMPLEX 1 measurements, the orbiter was hundreds of kilometers from the radar diagnostics. It does not seem likely that collisionless expansion and the formation of wake electric fields could have played a role in the rapid filling in of the ionospheric hole.

Finally, the validity of the background ionosphere illustrated in Plate 1a and Figure 6a needs to be questioned. This ionosphere was obtained at a distance of 38 km. The natural variability in the ionospheres separated by this distance may be large enough to discount the use of the unmodified ionosphere in the west beam as a reference for the modified plasma in the east radar beam. This type of spatial variability will be studied in the future using the SAMI2 model.

In summary, the SIMPLEX 1 ionospheric modification experiment over the Jicamarca incoherent scatter radar has yielded the first observations of shuttle-produced ionospheric modifications at the equator. The size and motion of the electron density hole are in good agreement with size determined from radial expansion of the exhaust vapors and vertical drifts of the plasma. The rapid recovery of the electron densities requires further investigation. Future SIMPLEX experiments with incoherent scatter radars should be used to examine the transient behavior of an artificially created ionosphere hole. The validation of the theory to describe plasma recovery from a localized disturbance will hopefully ensure that the proper physics is used in ionospheric models that describe the natural upper atmosphere.

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