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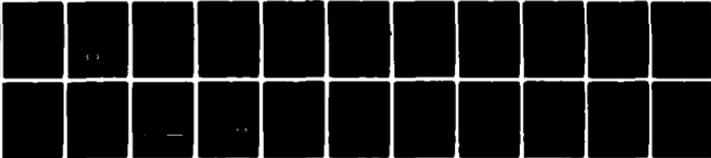
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# ON THE PROSPECTS FOR ARTIFICIALLY INDUCING EQUATORIAL SPREAD F

## 1. Introduction

The Brazil Ionospheric Modification Experiment [BIME] is a project sponsored by the Air Force Geophysics Laboratory [Narcisi, 1982], the aim of which is to produce a perturbation in the electron density of the equatorial ionosphere of sufficient magnitude to trigger (i.e., provide a seed for) the collisional Rayleigh-Taylor/ExB gradient drift instability, the instability believed to be responsible (see the theory review article by Ossakow, 1981 and references therein) for naturally occurring equatorial spread F (ESF). The aim of this experiment is to make possible the observation of the evolution of this instability under more controlled circumstances than those characterizing naturally-occurring ESF. In this report we shall attempt to address each of the factors which might bear on the success or failure of such an experiment, and to suggest ways by which the probability of experiment success might be maximized.

In Figure 1 we show the geometry of the physical problem of interest (see also Zalesak et al., 1982). The BIME experiment involves a rocket-launched chemical release in the equatorial F region ionosphere, the design of which is to deplete or enhance the electron density around the release point. Remote sensing and other rocket probes would then monitor the progress of the (hopefully) induced instability.

## 2. Theory

For the analysis in this section, and for the numerical simulations to be presented later, we make the assumption that the physical state depicted in Figure 1 can be accurately modeled by straightening the magnetic field lines and by representing the distribution of plasma along magnetic field lines as an array of three distinct thin layers of plasma connected by magnetic field lines, as depicted in Figure 2. The center layer represents the equatorial nighttime F region plasma, while the upper and lower layers represent the remaining northern and southern hemisphere plasma respectively, including the E region plasma. This model is described in detail in Zalesak et al. [1982]. At this juncture it should be noted that our previous study on artificially created equatorial spread F (Ossakow et al., 1978) considered only the center layer. Thus, the effects of plasma at lower altitudes away from the the equatorial plane, but on magnetic field lines threading the

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equatorial region, on the bubble dynamics was not considered (in reality that model was valid only when the depletion and not the background ionospheric integrated density and Pedersen conductivity dominate the dynamics). We now list here the primary assumptions in the present model: 1) the electric fields  $\underline{E}$  of interest are electrostatic in nature and hence derivable from a scalar potential:  $\underline{E} = -\nabla\phi$ ; 2) the conductivity along magnetic field lines is sufficiently high that we may treat the magnetic field lines as equipotentials:  $\phi = \phi(x,y)$  (see Figure 2); 3) currents between layers are carried solely by electrons, i.e., there is no ion transport along magnetic field lines; 4) layers 1 and 3 (see Figure 2) are initially uniform in both electron density and Pedersen conductivity, and remain so during all times of interest, enabling us to treat them as a passive electrically conducting load on our system. For further details, the reader is referred to Zalesak et al. [1982].

Within the context of the above model, the  $\underline{ExB}$  gradient drift/collisionally dominated Rayleigh-Taylor instability can be triggered whenever a certain geometric relationship holds between the electron density gradient in the equatorial ionosphere and the forces acting on the plasma. In particular, an infinitesimal perturbation on the system will grow exponentially, i.e., as  $e^{\gamma t}$  where  $t$  is time, with growth rate  $\gamma$  given by (Zalesak et al., 1982)

$$\gamma = \left[ \frac{c \underline{ExB}}{B^2} - \underline{U}_n - \frac{\underline{g}}{v_{in}} \right] \cdot \frac{\Sigma_{P2}}{\Sigma_{P1} + \Sigma_{P2} + \Sigma_{P3}} \frac{v_{n2}}{n_2} - R \quad (1)$$

where  $\underline{E}$  and  $\underline{B}$  are the electric and magnetic fields respectively,  $\underline{U}_n$  is the neutral wind velocity,  $\underline{g}$  is the gravitational acceleration,  $\Sigma_{pi}$  is the magnetic field line integrated Pedersen conductivity of layer  $i$  ( $i = 1,2,3$ ),  $n_2$  is the electron density in layer 2, and  $v_{in}$  is the ion-neutral collision frequency in layer 2.  $R$  is a term due to recombination chemistry, which will be discussed shortly. In Figure 2 it can be seen that  $v_{n2}$  for our unperturbed ionosphere is in the  $y$  direction (vertical in the equatorial plane). Since the vertical component of the neutral wind is in general quite small with respect to the other terms in the growth rate, we may neglect this term in Eq. (1).

The presence or non-presence of the term  $R$  in Eq. (1) is a function of ones choice of a zeroth order profile for the equatorial ionosphere. In the original papers of Scannapieco and Ossakow [1976] and Ossakow et al. [1979], the continuity equation for the electrons was of the form

$$\partial n_2 / \partial t + \nabla \cdot (n_2 \underline{v}) = - \nu_R (n_2 - n_0) \quad (2)$$

where  $\underline{v}$  is the electron velocity. The recombination coefficient  $\nu_R$  represents the sum of the rate-limiting charge exchange reactions of  $O^+$  with molecular oxygen and nitrogen. In this equation  $n_0$  is the assumed equilibrium electron density in the equatorial ionosphere, i.e.,  $\partial n_0 / \partial t = 0$ . Since recombination chemistry itself can only result in a loss of electrons at a rate  $-\nu_R n_2$ , we note that Eq. (2) implicitly assumes the presence of a source of ionization in the equatorial ionosphere of value  $+\nu_R n_0$ . The presence of such a true ionization source in the nighttime equatorial ionosphere is subject to some question and subsequent work by Zalesak et al. [1982] dropped the assumption of the existence of such a term, resulting in an electron density equation of the form

$$\partial n_2 / \partial t + \nabla \cdot (n_2 \underline{v}) = - \nu_R n_2 \quad (3)$$

Note that Eq. (3) does not yield a time-invariant equilibrium for the unperturbed electron density profile, but rather a profile which steadily decays through the night.

A linear stability analysis of the full set of equations describing the dynamics of the ExB gradient drift/collisionally dominated Rayleigh-Taylor instability in the equatorial ionosphere [see Ossakow et al., 1979], shows that

$$R = \begin{cases} \nu_R & \text{for Eq. (2)} \\ 0 & \text{for Eq. (3)} \end{cases} \quad (4)$$

Thus the effect of recombination chemistry on the instability growth rate is determined by ones choice of a model for the ambient ionosphere.

Equation (1), together with a choice of the ambient ionospheric state, as just discussed, provides us with a criterion for determining whether or not an infinitesimal perturbation to the ionosphere will be amplified; but since the experiment is not constrained to infinitesimal perturbations, one is led to consider both of the following scenarios:

- A) the ambient ionosphere is stable to infinitesimal perturbations
- B) the ambient ionosphere is unstable to infinitesimal perturbations

Case A, that of a linearly stable ionosphere, implies that ones only hope of producing artificial ESF is to perturb the ionosphere with sufficient amplitude to drive the dynamics fully into the nonlinear regime immediately. A series of numerical simulations could be used to analyze this case thoroughly, but the results will undoubtedly depend strongly on both the degree of stability and on the mechanism providing the stabilization, as well as on how hard the ionosphere is driven by the chemical release.

Case B, that of a linearly unstable ionosphere, immediately leads one to ask: why has ESF not already occurred? In fact, one is generally tempted to treat the non-occurrence of ESF as an indication of the stability of the ionosphere. In this case one is hoping to find an ionosphere which has only been subject to extremely small amplitude perturbations, or one whose growth rate is positive but relatively small, or both, in which instance he can be reasonably sure of triggering the instability with the chemical release. However, it may be difficult to prove a posteriori that ESF would not have occurred even in the absence of the release.

In either case A or B above, one would be advised to monitor the ionosphere using ionosondes and other instrumentation for many nights prior to the launch in order to get a "feel" for the statistics of natural ESF occurrence.

It is our view that case A above represents an untenable approach to this experiment. In addition to the problems already mentioned, the chances of driving the dynamics fully into the nonlinear regime via the chemical release would appear to be quite slim with existing payloads (such as those in BIME, considered by Narcisi, 1982). The physics of the instability depends on the total magnetic field line integrated Pedersen conductivity as well as the field line integrated electron density in level 2 (not simply the electron

density exactly at the magnetic equator). Anderson and Bernhardt [1978] have shown that even a 10 kg H<sub>2</sub> release (a large release) at 350 km altitude will yield only a maximum of 6% reduction in total field line integrated Pedersen conductivity. The task of finding an unstable but as yet unstructured ionosphere (case B above) would appear to be much easier. However (and we cannot stress this point too strongly) one must be certain that he has not misidentified a stable ionosphere.

### 3. Numerical Simulations

Details of the numerical techniques used in this simulation and of the general computational procedure may be found in Ossakow et al. [1979] and Zalesak et al. [1982] and in the references therein. Briefly, the numerical calculations to be presented were performed on a two-dimensional Cartesian mesh using 40 points in the x (east-west) direction and 140 points in the y (vertical at the equator) direction. The uniform grid spacing was 3 km in the y direction and 5 km in the x direction. Periodic boundary conditions were imposed on  $n$ ,  $n_2$  and on the electrostatic potential  $\phi$  in the x direction. At the top boundary in y we set  $\partial n/\partial y = \partial n_2/\partial y = \partial \phi/\partial y = 0$ , while at the bottom boundary we set  $\partial n/\partial y = \partial n_2/\partial y = \phi = 0$ . Here  $n$  is the electron density exactly at the magnetic equator, to be distinguished (see below) from  $n_2$ , the average electron density in layer 2. In principle, each of the three layers must be represented on a separate 2-D mesh, but this need not be done here since one of our assumptions is that layers 1 and 3 are uniform and remain so during the course of the calculation and since  $\phi$  is identical on each mesh. Both the continuity equation (of the form of Eq. 3 rather than Eq. 2) and an elliptic equation for the electrostatic potential  $\phi$  are solved on this grid (see Zalesak et al., 1982). Realistic values for the ion-neutral collision frequency  $\nu_{in}$  and recombination coefficient  $\nu_R$  in layer 2 were used, and are given in Ossakow et al. [1979]. Layers 1 and 3 were each assigned an integrated Pedersen conductivity equal to 6% of the maximum of that found in layer 2 for our "unstable" case B (to be described shortly).

The form of the ionospheric hole caused by the chemical release was taken to be

$$n(x,y)/n_0(y) = 1 - 0.95 \exp[(r/37)^{-2.35}] \quad (5)$$

where  $n$  is the electron density exactly at the magnetic equator,  $n_0$  is the ambient electron density at the equator in the absence of the chemical release, and  $r$  is the distance in kilometers from the point of release. Note that we distinguish between  $n$ , the electron density exactly at the equator, and  $n_2$ , the average electron density in layer 2. In the absence of the perturbation, we take  $n = n_2$  at  $t = 0$ . Hence  $n_0$  represents the ambient profile for both  $n$  and  $n_2$ . The form and coefficients of Eq. (5) were chosen to approximate the Natal 1900 LT release in Fig. 5 of Mendillo [1981]. The form of  $n_0(y)$  is identical to that used in our previous work [Ossakow et al., 1979]. Note that Eq. (5) gives a large (95%) depletion in electron density at the center of the hole. However, this figure is expected to hold only exactly at the release point (presumably the magnetic equator). Recalling that our layer 2 is meant to comprise all of the plasma within several degrees of the magnetic equator, it is appropriate to substantially reduce the effect of the release in terms of its effect on the total magnetic field line integrated electron density in layer 2. We therefore take

$$n_2(x,y)/n_0(y) = 1 - 0.05 \exp[(r/37)^{-2.35}] \quad (6)$$

where  $n_2$  is the field-line averaged electron density in layer 2 and  $r$  is now two-dimensional. The 5% maximum depletion given in Eq. (6) was chosen to be in the general range of estimates of  $H_2$  releases larger than BIME given by Anderson and Bernhardt [1978], and from Eq. (5) corresponds to layer 2 being approximately 1000 km thick (along  $\underline{B}$ ).

In order to clarify the roles of  $n_2$  and  $n$ , and for the sake of completeness, we enumerate here the equations which we solve numerically:

$$\partial n_2 / \partial t + \nabla_{\perp} \cdot (n_2 \underline{v}) = - v_R n_2 \quad (7)$$

$$\partial n / \partial t + \nabla_{\perp} \cdot (n \underline{v}) = - v_R n \quad (8)$$

$$\nabla_{\perp} \cdot [(v_{in} n_2 + C_b) \nabla_{\perp} \phi] = \frac{\partial}{\partial x} [(E_{ox} - \frac{Bg}{v_{in} c}) v_{in} n_2] \quad (9)$$

$$\underline{v} = \frac{c}{B} (\underline{E}_0 - \nabla_{\perp} \phi) \times \underline{B} \quad (10)$$

$$C_b = 0.12 \text{ Max}(v_{in} n_o) \quad (11)$$

$$\underline{E}_o = E_{ox} \hat{x} \quad (12)$$

$$\nabla_{\perp} = \partial/\partial x \hat{x} + \partial/\partial y \hat{y} \quad (13)$$

$$g = + 980 \text{ cm/sec}^2 \quad (14)$$

Note that we have written Eq. (9) to show explicitly the lack of any dependence on  $n$ .

In light of the above discussion, plots of both  $n$  and  $n_2$  will be shown, with the understanding that while it is  $n$  which is likely to be measured with rocket probes or other sensors at the equator, it is  $n_2$  which drives the physics. In terms of the numerical calculations to be shown,  $n$  can be thought of as a tracer fluid which merely describes what is happening exactly at the equator (neglecting parallel to  $\underline{B}$  diffusion effects), but whose effect on the dynamics can only be felt by integrating along  $\underline{B}$ , an effect which is already folded into the computation of  $n_2$ . Two kinds of plots will be presented: contours of constant  $n_2(x,y,t)$ ; and contours of constant  $n(x,y,t)$ . Superimposed on each contour plot is a dashed line depicting  $n_o(y)$  for reference purposes. Our  $n_o(y)$  profile is such that the minimum electron density scale length  $L = n_o(\partial n_o/\partial y)^{-1}$  is 10 km, and varies in the runs to be presented only in terms of the altitude of the F2 peak, as can be seen in the plots to be shown.

We chose to perform two calculations which represent the two possible scenarios previously discussed: the stable ionosphere (case A) and the unstable ionosphere (case B). Since we have chosen Eq. (3) as our continuity equation, we have implicitly assumed that recombination chemistry cannot affect the growth rate (see Eq. 4), so the only truly stabilizing mechanism we have at our disposal is westward ambient electric field  $\underline{E}_o$ . We can also mitigate the effect of the positive  $g/v_{in}$  term in (1) by lowering the ionosphere (which increases  $v_{in}$ ). Accordingly, our simulations were run with the following parameters

	<u>Case A</u>	<u>Case B</u>
F2 peak altitude	375 km	430 km
chemical release altitude	320 km	375 km
$\underline{E}_0 \times \underline{B}$ velocity	70 m/sec downward	0

Case A is such that the entire ionosphere is linearly stable. Case B is such that large regions of the bottomside F region are linearly unstable, and in fact this run is identical to calculation 2LE in Zalesak et al. [1982] except for the form of the perturbation. Figures 3-6 show the results of the simulations at selected times. Plots of both  $n$  and  $n_2$  are shown. Note in case A that although the ionosphere is changing (due to the downward  $\underline{E}_0 \times \underline{B}$  velocity and recombination chemistry) the perturbation is in fact damped. Also note that the perturbation in  $n$  will never totally damp even though that in  $n_2$  (the one driving the dynamics) will. In case B we see that we indeed initiated artificial ESF with the chemical release. The important thing to note is that linear stability theory is an accurate predictor of the experimental success or failure, especially when the chemical release cannot reach the nonlinear regime immediately.

#### 4. Finding an Unstable Ionosphere

The primary finding of the results of the numerical simulations presented in Section 3 is that they bear out the validity of a linear stability analysis in terms of analyzing the BIME experiment. Accordingly, we conclude that the most viable approach to take in the BIME experiment is to find an unstable, but as yet unstructured ionosphere. As mentioned before, the drawback to this approach is the possibility of having misidentified a stable ionosphere. Therefore let us appeal to Eq. (1) and to other known stabilizing influences in the equatorial ionosphere and draw up a list of possible stabilization mechanisms of which we must beware:

- 1) recombination chemistry, if we believe there to be a true source of ionization present (Eq. (2)) such as to keep  $n_0(y,t) = n_0(y,t=0)$ ;
- 2) a westward ambient electric field;
- 3) shear stabilization, caused by a vertical shear in the horizontal plasma motion of the ambient ionosphere [Perkins and Doles, 1975]; and

- 4) inordinately small positive growth terms in Eq. (1), such as large  $v_{in}$ , small gradients in  $n_2$ , or a large background conductivity  $\Sigma_{p1} + \Sigma_{p3}$ .

Optimization of BIME success probability can be reduced to minimizing the impact of each of the above mechanisms. If we believe recombination chemistry to be a problem, then since we know that  $v_R$  decreases with altitude, we conclude that we should only launch into ionospheres which are reasonably high in altitude. A westward electric field can be avoided by noting that such a field would produce downward plasma velocities. An ionosonde with doppler capabilities could detect such an occurrence and generate a "no-go" signal. The shear stabilization mechanism is not well understood, but it should be noted that large plasma shears are an indication of large background conductivities [Zalesak et al., 1982], and hence should be avoided on both counts. Large values of  $v_{in}$  can be avoided by the same mechanism as that of avoiding recombination chemistry, i.e., launching only into reasonably high ionospheres, since  $v_{in}$ , like  $v_R$ , decreases with altitude. Ionosondes can be used to measure gradients in  $n$ , which presumably reflect gradients in  $n_2$  for the undisturbed ionosphere. As was already mentioned, although background conductivities cannot be measured directly, the degree of plasma shear can be used to give an indication of their size. Better yet would be a measure of the difference between the plasma and neutral gas zonal velocity (see Eq. 38 in Zalesak et al. [1982]).

## 5. Conclusions and Recommendations

It is our conclusion that the success of the BIME experiment (and any other that cannot reach the nonlinear regime immediately) depends crucially on one's ability to find an unstable but as yet unstructured ionosphere. This is not a trivial task. The only means of truly ensuring that this is the case involves in-situ measurements of several physical quantities all along magnetic field lines and throughout the equatorial ionosphere. Realistically, the best one can do is to try to minimize the risk by avoiding those specific situations which would indicate ionospheric stability. Specifically, we recommend the following:

- 1) Try to launch into a high ionosphere, in order to maximize the term  $g/v_{in}$  in the linear growth rate, and to minimize the stabilizing effects, if any, of recombination chemistry.

- 2) Try to launch into an ionosphere that is rising, or at the very least one which is not falling, in order to minimize the chance of encountering a stabilizing ambient westward electric field. An ionosonde with doppler capabilities would be very useful for this purpose.
- 3) Try to avoid launching into regions of large horizontal shear in plasma motion.
- 4) Try to have available in the field the ability to measure logarithmic electron density gradients, compute the approximate altitude of maximum growth from Eq. (1), and perform the chemical release of that altitude.
- 5) Monitor the ionosphere using ionosondes for many nights prior to launch to get a "feel" for the statistics of natural equatorial spread F occurrence.

## EQUATORIAL SPREAD F MODEL

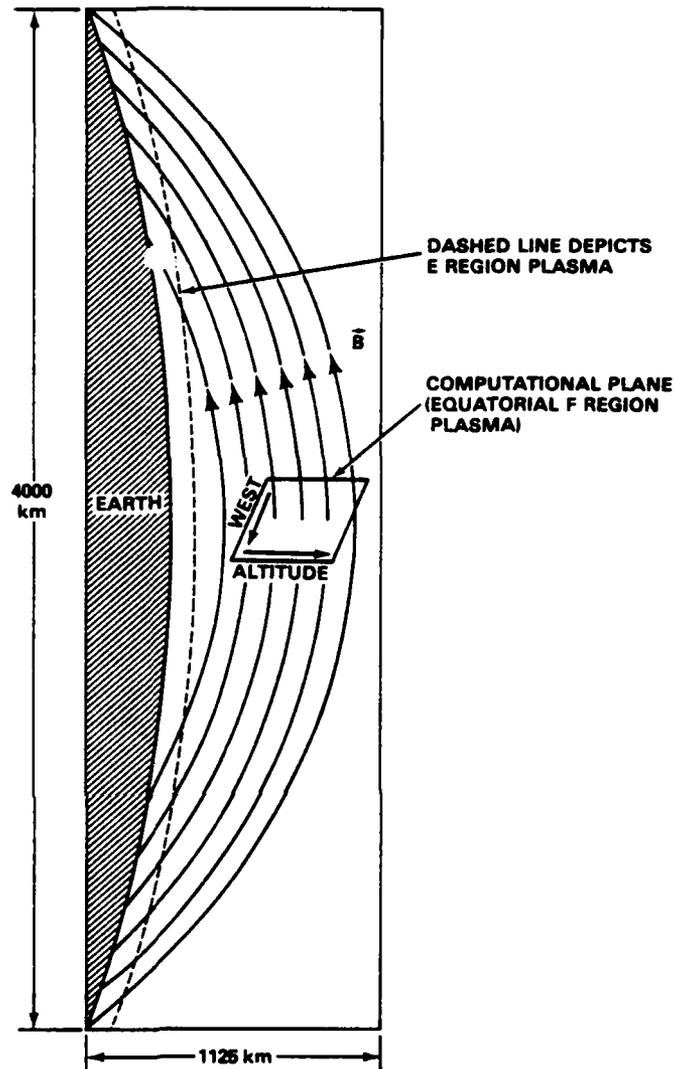


Fig. 1 — Diagram of the equatorial ionosphere and of the neighboring regions which have physical relevance to equatorial spread F (ESF) processes, including the E region plasma at higher and lower latitudes. These regions are electrically coupled to the equatorial F region ionosphere by the high conductivity along magnetic field lines. Plasma is actually distributed all along these field lines, but in this study we shall make the assumption that this system can be modeled accurately by three planes of plasma connected by straight field lines, as shown in Fig. 2. One of these three layers (layer 2 in Fig. 2) is shown here as the “computational plane.”

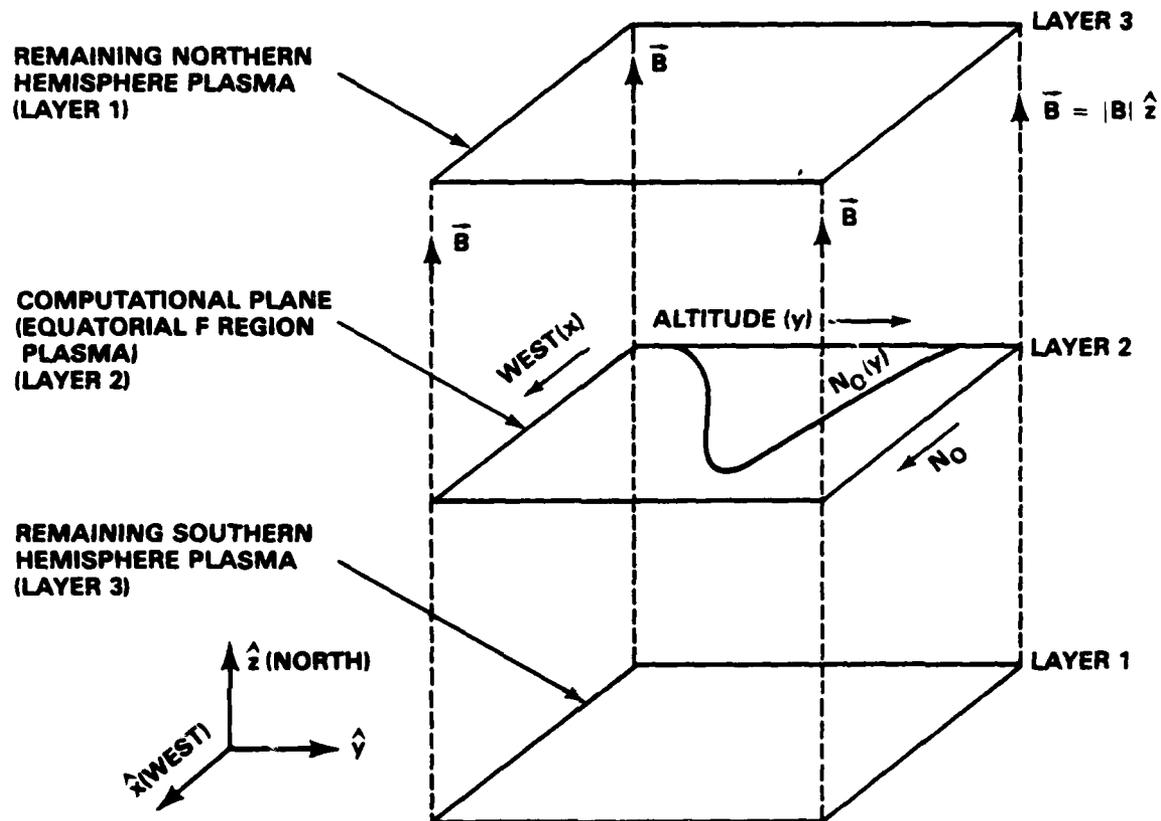


Fig. 2 — The “three layer” model of the physical system depicted in Fig. 1. All plasma in the vicinity of the equatorial plane has been compressed into layer 2, while the remaining northern and southern hemisphere plasma has been compressed into layers 1 and 3 respectively. Further, the magnetic field lines have been straightened so we can deal in cartesian coordinates  $x$ ,  $y$ , and  $z$  as shown in the figure. The plasma in layers 1 and 3 is assumed to be uniform and free of any external driving force. The equatorial layer 2 is assigned a realistic initial distribution of electron density  $N_0(y)$ , and ion-neutral collision frequency. In addition, gravity points in the negative  $y$  direction.

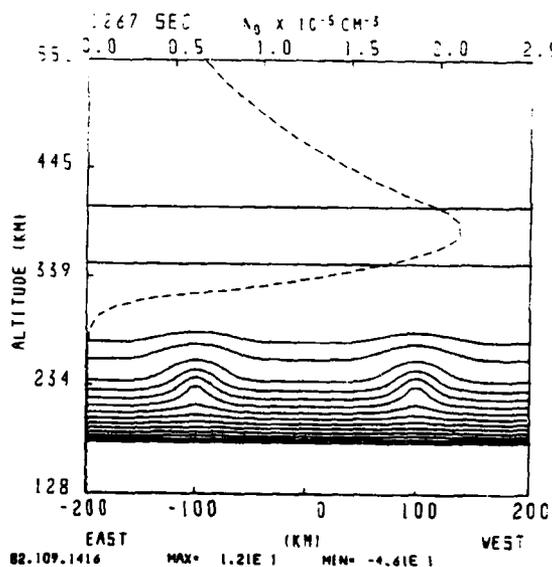
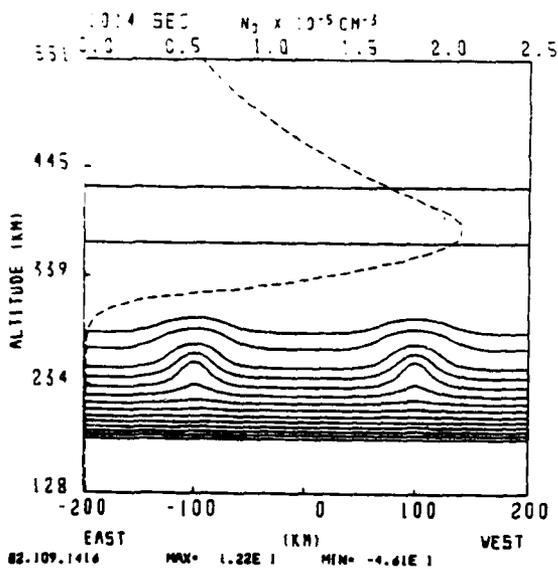
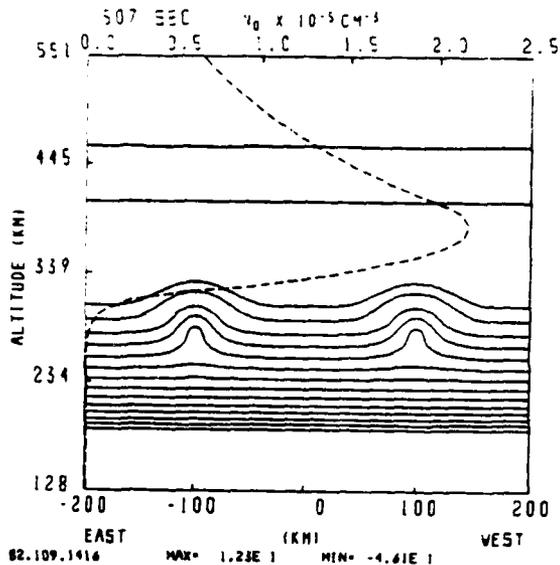
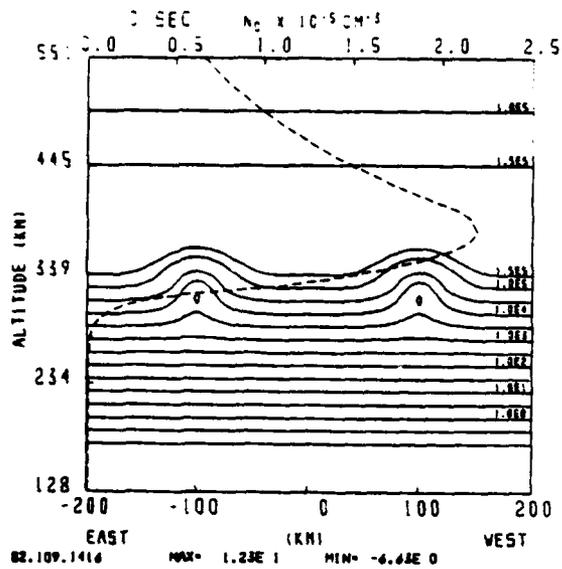


Fig. 3 — Contours of constant  $n$  for case A (stable ionosphere) at various times in the calculation. At time 0 seconds the contours are labeled in units of electrons/cm<sup>3</sup> in E format notation (1.0 E1 =  $1 \times 10^1$ , etc.). The unperturbed ionosphere was initially laminar (independent of  $x$ , the east-west direction) and is exhibited by the dashed curve showing  $n_0(y)$ . This curve is labeled at the top of the figure. The perturbation shown at 0 seconds is described by Eq. (5). Two full periods of the calculation are shown to emphasize the periodic boundary conditions used in the  $x$ -direction. The observer is looking southward so that  $\underline{B}$  is out of the figure.

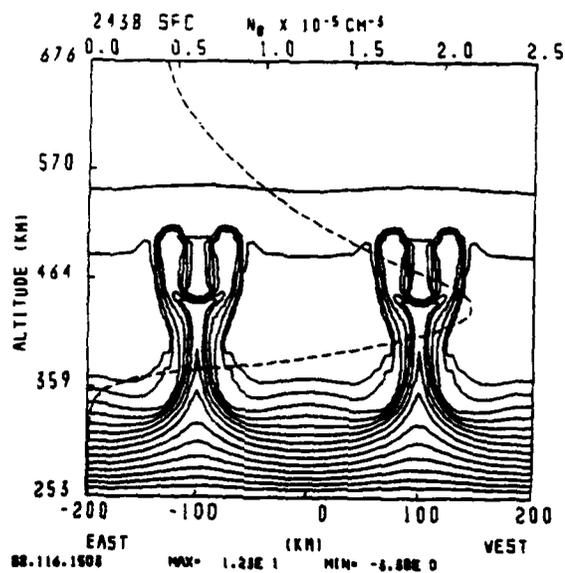
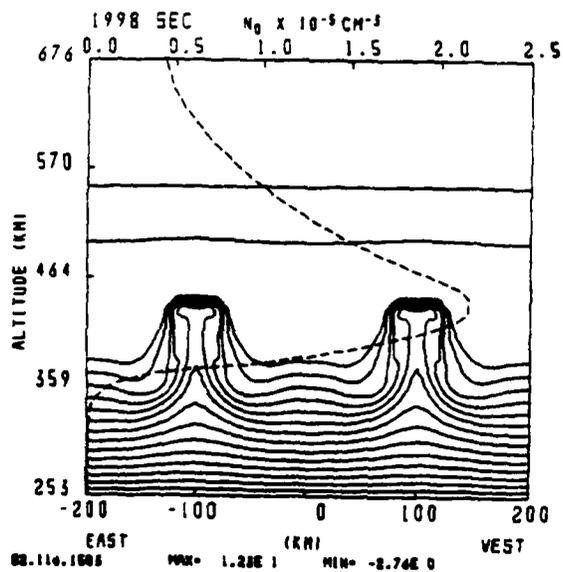
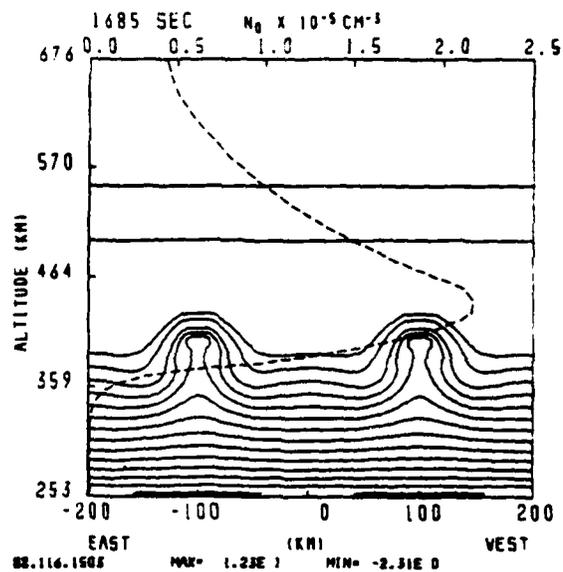
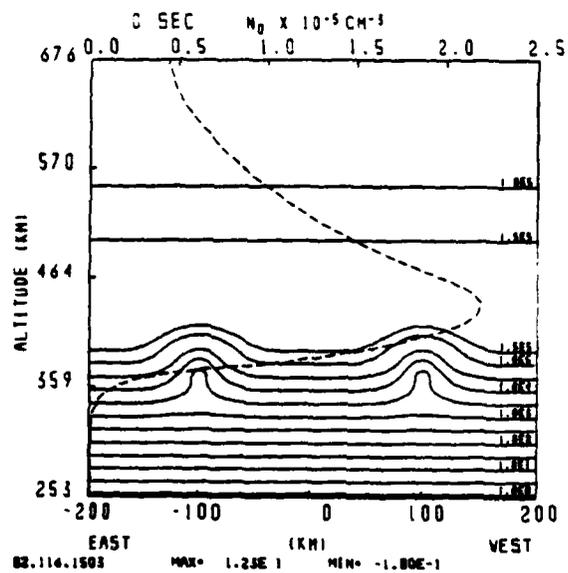


Fig. 4 — Same as Fig. 3 but for contours of constant  $n$  for case B (unstable ionos, here)

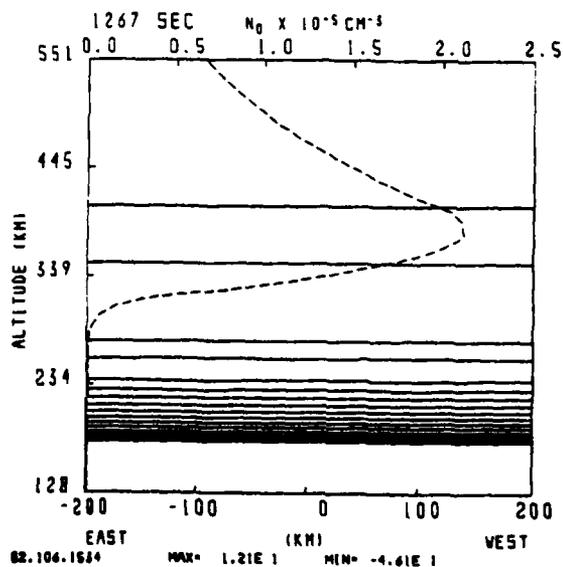
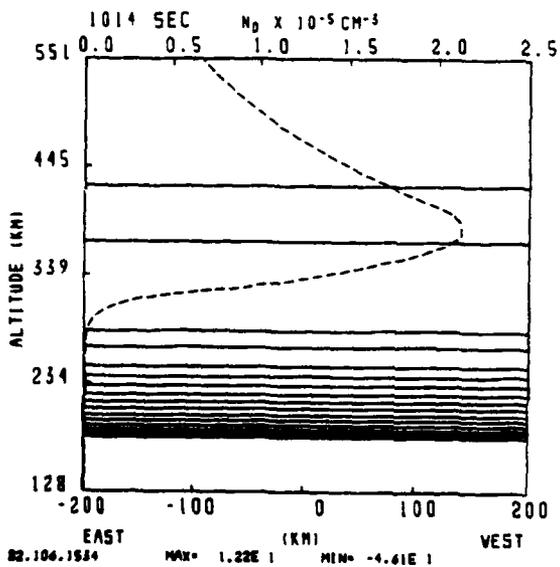
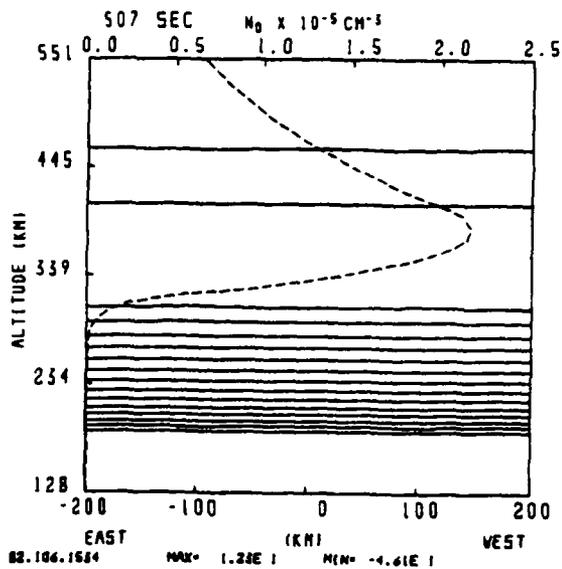
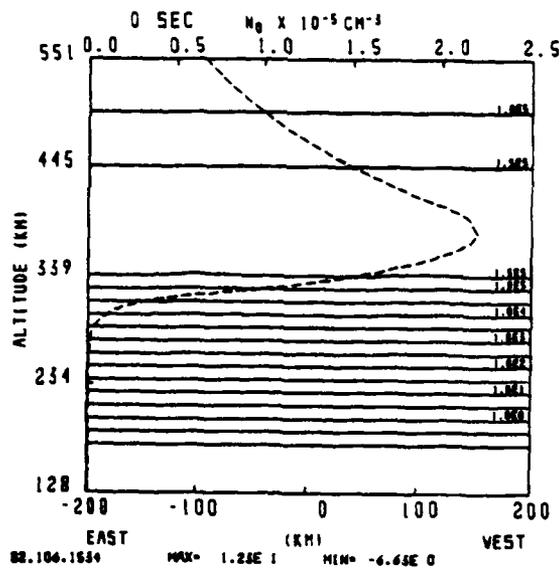


Fig. 5 — Same as Fig. 3 but for contours of the average electron density in layer 2,  $n_2$ , for case A (stable ionosphere)

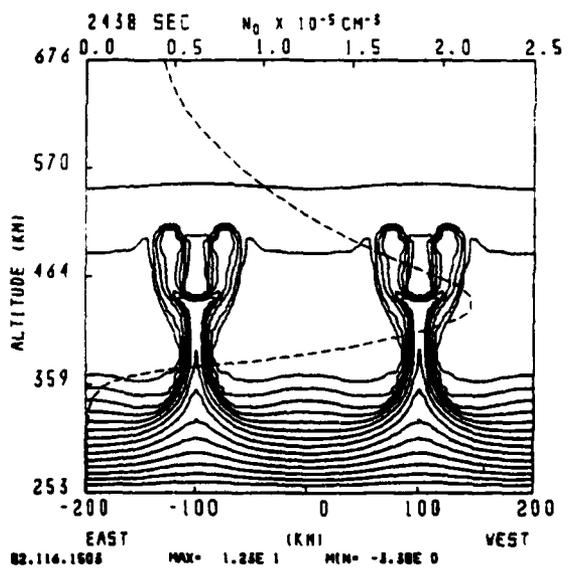
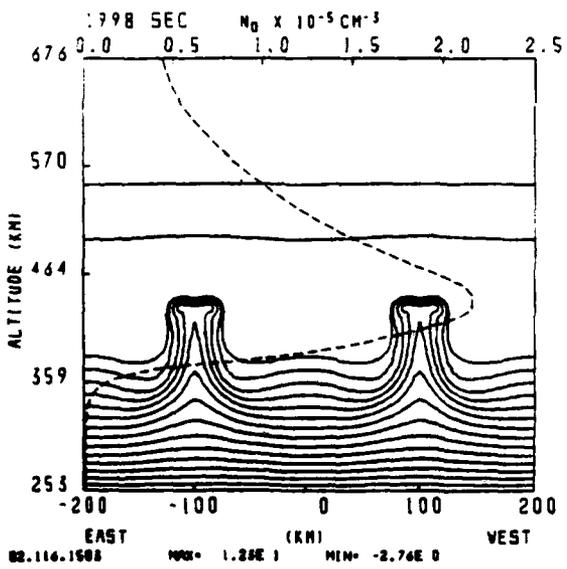
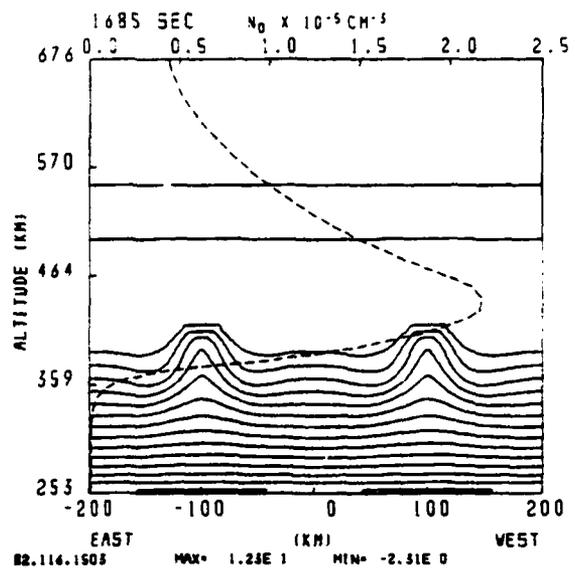
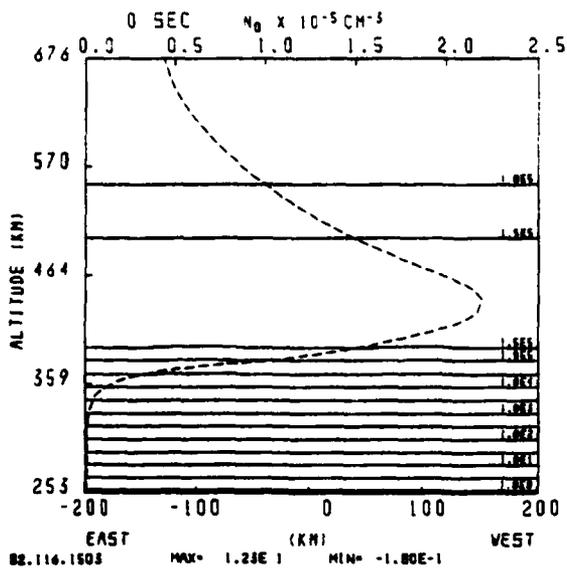


Fig. 6 — Same as Fig. 3 but for contours of the average electron density in layer 2,  $n_2$ , for case B (unstable ionosphere)

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