Vertical Drift Velocities of the Ionospheric F-region
During the Eclipse of 12 November 1966

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(Received August 22, 1968)

Abstract

The temporal variation of the electron density distribution observed by radio soundings at Rio Grande, Brazil during the eclipse of November 1966 has been analyzed. Using five models of chemical reaction coefficients and the lower boundary values of neutral constituents, the variation of an ‘equivalent’ temperature has been calculated. The equivalent temperature is that resulting from a minimization (over a range of heights and times) of the mean-square residual differences between the observed $\partial N/\partial t$ and the values calculated from the continuity equation. The equivalent temperature variations thus calculated may involve implicitly the effects of diurnal variations in the lower boundary values of neutral constituents and vertical drift velocities as well as the actual temperature variations. Assuming that the difference of the variation of the equivalent temperature between the eclipse and control day is mainly due to the difference of the vertical drift velocity, the additional vertical drift velocity on the eclipse day has been calculated; it is largely upward and starts to rise about 30 min. before the ground eclipse for all five models. A simple model calculation indicates that this additional upward velocity could be caused by the effect of the reduced conductivity in the lower dynamo region during the eclipse.

1. Introduction

The analysis of the effects of solar eclipses on the ionospheric $F_2$ region has made considerable progress since electron density profile data have become available as a time series during the eclipse. Although it is sometimes difficult to detect changes in the maximum electron density ($N_{\text{max}}F_2$) accompanying the eclipse, the electron density at fixed heights always shows a remarkable change from the control day variation. This is demonstrated in Fig. 1, which depicts the temporal variation in the electron density at several chosen fixed heights obtained from radio soundings at Rio Grande (52°10′W, 32°5′S, dip angle = 30°18′), Brazil during the eclipse of November 12, 1966. The variation in $N_{\text{max}}F_2$ is illustrated by thick curves. We shall not discuss the experimental nor the data-reduction program here, other than to note that a new prototype ionosonde (the D-1) was employed, and that the ionograms were reduced by the method described by Paul (1966), Howe and McKinnis (1957) and Wright (1967).

Electron density profiles have been analyzed by Savitt (1950), Minnis (1956), and VanZandt et al. (1960) for different eclipses. Most authors assume that the disappearance of electrons occurs by an attachment-like process in the height range of analysis, and deter-
mine the effective value of the attachment coefficient $\beta$ at various heights; it ranges from $10^{-4}$ to $6.8 \times 10^{-4}$ sec$^{-1}$ at 300 km. Although no temporal variations have been considered, the $\beta$ is essentially time-dependent because the temperature and the neutral atmosphere change with time.

Temperature variations and motions of the neutral or the ionized components have also been ignored in these past studies. The analysis of the eclipse of October 12, 1958 at Danger Is., central Pacific (VanZandt et al., 1960) indicated that the photochemical processes alone adequately accounted for the time variation of electron density during that eclipse, but this probably would not be the case for most other eclipses. The time constant for the loss of electrons in the F region seems to be too large to avoid significant motion effects during an eclipse lasting only about two hours.

*Thomas and Robbins* (1956) have tried to evaluate the transport term turning the production and loss rates for electrons tentatively suggested by *Ratcliffe et al.* (1956). The same general temporal variation of transport has been obtained for the three eclipses. However, their attachment coefficient is determined by the nighttime electron density variation and is smaller than any other values determined by eclipse data.

In this study, a more general form of the loss term is used and various terms in the continuity equation are evaluated based upon current knowledge of solar radiation fluxes, chemical reaction coefficients, diffusion parameter, and upper atmospheric composition. Assuming that the temporal variation in the neutral atmosphere does not change much
between the eclipse and control day, the vertical drift velocity of ionization during the
eclipse additional to that on the control day has been calculated. An attempt is made to
interpret this additional drift velocity in the $F$ region as the effect of reduced conductivity
in the lower dynamo region.

2. Assumptions and Method of Analysis

The rate of temporal change in the electron density $N$ at fixed heights is calculated by
the continuity equation

$$\frac{\partial N}{\partial t} = Q - L - \text{div} (Nv),$$

where the three terms of the right-hand side indicate the ionization, loss, and transport term,
respectively; $v$ represents the vertical transport velocity of electrons and could be caused
by diffusion, temperature changes, electromagnetic forces, and neutral winds. The effects
of horizontal transport are relatively small and are neglected.

Since there were no direct observations of the variation of the solar EUV radiation
during the eclipse, the ionization term is calculated on the assumption that the rate of
photoionization is proportional to the area of the visible sun at the altitude of the ionosphere;
solar radiation fluxes are taken from rocket observations near solar minimum (Hinteregger,
1967), and the absorption and ionization cross-sections are those from the table given by the
same author (Hinteregger et al., 1935).

The loss term is evaluated by the $L$ function given by Shimazaki (1965),

$$L = \frac{\lambda_1 [O_3] + \lambda_2 [N_2]}{N + \lambda_1 [O_3] + \lambda_2 [N_2]} N^2,$$

where brackets indicate the number density of each molecule, and $\lambda_i$ and $\alpha_i$ denote reaction
coefficients of the following chemical reactions,

$(\lambda_1) O^+ + O_2 \rightarrow O_3^+ + O$

$(\lambda_2) O^+ + N_2 \rightarrow NO^+ + N$

$(\alpha_1) O_2^+ + e \rightarrow O' + O''$

$(\alpha_2) NO^+ + e \rightarrow N' + O'$. 

Equation (2) is more general than the pure attachment-like form and is applicable to the
transition region between the $F_1$ and $F_2$ layers. The diffusion term is identified separately
from other transport terms; it requires the diffusion parameter $b(=D_A \cdot \sum n_i)$, where $D_A$
is an assumed ambipolar diffusion coefficient and $n_i$ the number density of the $i$th neutral
constituent. The remaining transport term in this paper thus explicitly excludes diffusion
and should describe motions due to other transport processes.

The evaluation of $Q$, $L$, and the diffusion term depend upon the assumption of a neutral
atmosphere mode as well as upon solar radiation fluxes, chemical reaction coefficients, and
diffusion parameter. Since the neutral atmospheric density and temperature were not
observed on or near the eclipse day at Rio Grande, we have used models calculated by the following assumptions: the temperature profile increases exponentially from a fixed value (355 K) at 120 km to the exospheric temperature $T_\infty$; the exponent of the exponential function is given as a function of $T_\infty$ by Jacchia (1964); the height distribution of each neutral constituent is in diffusive equilibrium above 120 km, where number densities of $O$, $O_2$, and $N_2$ are assumed. Thus, in our analysis, the neutral atmosphere model can be calculated as a function of $T_\infty$ alone.

Table 1. Five aeronomic models considered in this study. Underlined figures indicate values obtained by laboratory experiments or rocket observations.

<table>
<thead>
<tr>
<th>Model</th>
<th>$\lambda_1$ (cm$^3$ sec$^{-1}$)</th>
<th>$\lambda_2$ (cm$^3$ sec$^{-1}$)</th>
<th>$[O]_{120}$ (cm$^{-3}$)</th>
<th>$[O_2]_{120}$ (cm$^{-3}$)</th>
<th>$[N_2]_{120}$ (cm$^{-3}$)</th>
<th>$b$ (cm$^{-1}$ sec$^{-1}$)</th>
<th>$\bar{E}_{800}$ (sec$^{-1}$)</th>
<th>$\sqrt{\bar{r}_{800}^2}$ (cm$^{-1}$ sec$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10^{-11}$</td>
<td>$10^{-12}$</td>
<td>$4.2 \times 10^{10}$</td>
<td>$3.8 \times 10^{10}$</td>
<td>$2.8 \times 10^{11}$</td>
<td>$1.5 \times 10^{19}$</td>
<td>$9.2 \times 10^{-5}$</td>
<td>8.13</td>
</tr>
<tr>
<td>2</td>
<td>$4 \times 10^{-11}$</td>
<td>$1.8 \times 10^{-12}$</td>
<td>$4.2 \times 10^{10}$</td>
<td>$3.8 \times 10^{10}$</td>
<td>$2.8 \times 10^{11}$</td>
<td>$1.5 \times 10^{19}$</td>
<td>$7.6 \times 10^{-5}$</td>
<td>64.9</td>
</tr>
<tr>
<td>3</td>
<td>$4 \times 10^{-11}$</td>
<td>$1.8 \times 10^{-12}$</td>
<td>$2.4 \times 10^{11}$</td>
<td>$2.9 \times 10^{10}$</td>
<td>$3.92 \times 10^{11}$</td>
<td>$1.5 \times 10^{19}$</td>
<td>$5.5 \times 10^{-4}$</td>
<td>37.7</td>
</tr>
<tr>
<td>4</td>
<td>$4 \times 10^{-11}$</td>
<td>$1.8 \times 10^{-12}$</td>
<td>$1.2 \times 10^{11}$</td>
<td>$2.9 \times 10^{10}$</td>
<td>$3.92 \times 10^{11}$</td>
<td>$1.5 \times 10^{19}$</td>
<td>$1.7 \times 10^{-4}$</td>
<td>28.3</td>
</tr>
<tr>
<td>5</td>
<td>$4 \times 10^{-11}$</td>
<td>$1.8 \times 10^{-12}$</td>
<td>$6 \times 10^{10}$</td>
<td>$1.8 \times 10^{11}$</td>
<td>$2.9 \times 10^{10}$</td>
<td>$1.5 \times 10^{19}$</td>
<td>$1.2 \times 10^{-4}$</td>
<td>9.9</td>
</tr>
</tbody>
</table>

To evaluate each term of (1) five models are considered in the present study; these are listed in Table 1. The underlined values are those obtained by laboratory experiments or rocket observations. Chemical reaction coefficients in models 2–5 are taken from laboratory measurements which are summarized by Ferguson (1967), while those in model 1 are assumed in accord with Nicolet (1963) to meet the mass-spectrometric observations of neutral constituents by rockets. $\alpha_1$ and $\alpha_2$ have been assumed as $2 \times 10^{-7300} \frac{300}{T}$ and $10^{-7300} \frac{300}{T}$ cm$^3$ sec$^{-1}$, respectively, for all models. Two values have been used for $b$ at 1000 K; the larger value, $1.5 \times 10^{19}$ cm$^{-3}$ sec$^{-1}$, is calculated from the probability of charge exchange, which is based on potential energy curves obtained by a semiempirical valance-bond method using spectroscopic data (Knof et al., 1964).

The number densities of $O$, $O_2$, and $N_2$ at 120 km in models 1 and 2 are assumed to be the same as mass-spectrometric values observed by rockets in June 1963 (Hedin et al., 1964). The values in our model 3 are taken from the atmospheric model by Norton et al., (1962). Since this model appears to have too much $O$ in comparison with the recent observations (Vanzandt, 1967), $[O]_{120}$ is reduced by half in our model 4. In model 5, $[O]_{120}$ is assumed to increase linearly from $6 \times 10^{10}$ cm$^{-3}$ at 8:00 to $1.8 \times 10^{11}$ cm$^{-3}$ at 14:00. The reason for assuming this variation will be discussed later.

The present analysis is concerned with a period of about 5 hours centered on the eclipse maximum, and with an 80 km range of heights extending to within 20 km of the $F2$ layer.
We compare the eclipse day with a mean 'control day' obtained by the composite method (Wright 1962) from the Rio Grande ionogram observations of the period 1-15 November 1966.

We initially calculate the variation of $T_\infty$ for the control day; this minimizes the mean square residual difference between the observed $\partial N/\partial t$ and the values calculated from the continuity equation over a range of heights and times. The variation of $T_\infty$ thus calculated, of course, does not indicate the actual temperature variation, but might include (implicitly and among other effects) the normal diurnal variations of the lower boundary values of [O], [O$_2$], [N$_2$] and $T$, and the vertical drift velocity $w$. We will call this temperature the "equivalent temperature", $T_v$.

Applying the same procedure to the eclipse day we find a quite different variation of $T_v$. Among the principal differences between the eclipse and control day, we assume that the atmospheric model and uneclipsed solar radiation energy are about the same, and that the significant difference appears as an additional vertical drift effect. We then calculate the additional vertical drift velocity during the eclipse. We assume for further simplicity that $w$ is independent of height in the range treated.

While the procedure and assumptions used here are admittedly crude, we find that each of the 5 models agree in requiring an additional drift effect of substantial magnitude with similar temporal variations. These results are given and discussed in the following section.

3. Results and Discussion

The temporal variations of $T_v$ on the control day are calculated for the five models listed in Table 1; the result is shown in Fig. 2. Most of these models give a maximum value of $T_v$ at 10-11 hrs.; this would suggest that the effects of the lower boundary conditions and

![Fig. 2 Temporal variations in the equivalent temperature $T_v$ on the control day.](image-url)
of the vertical drift velocities on the determination of $T_v$ are important. The assumption of a linear increase of $[O]_{120}$ with time in model 5 is considered in order to shift the time of the maximum $T_v$ toward noon. An increase of $[O]_{120}$ toward the afternoon is expected because of the increasing dissociation of $O_2$ during the day, but changes larger than in model 5 would be hard to justify.

The temporal variation of $T_v$ on the eclipse day, shown in Fig. 3, is very different from that on the control day. The difference between the two days is illustrated in Fig. 4, from

Fig. 3 Temporal variations in the equivalent temperature $T_v$ on the eclipse day.

Fig. 4 Difference between the equivalent temperature $T_v$ on the eclipse day and on the control day.
which it is interesting to see that the apparent $T_v$ on the eclipse day is considerably higher than the control day $T_v$ for all modes. It is not, of course, reasonable to expect the increase of actual temperature in the eclipse represented by $\Delta T_v$ in Fig. 4. Changes in the lower boundary conditions also cannot explain this result, as we should then need an increase of temperature in the atmosphere below 120 km, which is even less likely. Thus, it seems most probable that the increase of $T_v$ on the eclipse day is caused by an additional vertical drift velocity attributable to the eclipse. After estimating the magnitude of this effect, we shall discuss its probable origin in the additional electrostatic fields generated near the region of eclipse totality in the dynamo region.

Fig. 5 illustrates the vertical drift velocity on the eclipse day additional to that on the control day. Short period variations are not reliable, but there is a general tendency that the velocity is largely upward during the eclipse, particularly at the earlier phase of the eclipse. It decreases with time (becoming downward at the later phase of the eclipse on some models), and becomes almost zero after the eclipse.

A component of vertical drift velocity in the $F$ region is produced by the electrostatic fields communicated along magnetic field lines from the lower dynamo region, where the geomagnetic $Sq$ current flows. Based on the observed geomagnetic $Sq$ variations, Maeda (1955) calculated this velocity; his result indicates upward velocity over the local time period 09:00–12:00. Thus, our additional vertical drift occurs in the same direction as the vertical drift velocity produced by the usual $Sq$ fields in the dynamo region.

It has been shown by Nagata et al. (1956) that the electrical conductivity decreases appreciably in the dynamo region during the eclipse. An additional polarization electric field therefore develops within the region of reduced conductivity in the same direction as

![Fig. 5 Vertical drift velocities on the eclipse day additional to the control day.](image)
the large scale electrostatic ‘applied’ field which is produced at lower latitudes by the
dynamo action at higher latitudes. The large-scale field on the eclipse day should therefore
not differ greatly from the control-day field at Rio Grande (21°12′S geomagnetic latitude),
but the additional polarization field in the eclipsed region should amplify the control-day
field and its F-region effects. As a result, the additional upward drift velocity in the F region
during the eclipse may be explained.

We now estimate roughly the effect of the reduced conductivity. Considering a two
dimensional model of the thin dynamo region, we assume that the conductivity is reduced
from \( \sigma \) to \( \sigma' \) in a circular region (radius \( r_0 \)), where \( \sigma \) is the conductivity in the surrounding
area. When the external field \( E_0 \) is applied (say, to the east direction), the uniform polariza-
tion field parallel to \( E \) is produced inside the circle and is calculated as

\[
E_\perp = \frac{2\sigma}{\sigma + \sigma'} E_0. \tag{3}
\]

If \( \sigma' = -\sigma/3 \), as is obtained by Nagata et al. (1956), the amplification factor of the electric field
would be 4/3. The additional drift velocity near totality is about 8 m/sec for model 5 (see
Fig. 5); therefore, the total drift velocity would be about 32 m/sec. This is a reasonable
value for the vertical drift velocity and coincides, perhaps by chance, with the values (30–
40 m/sec) obtained at Jicamarca, Peru by a different technique using the incoherent back-
scatter data for the same eclipse (Peterson et al. 1968).

Special attention must be given to the fact that although the electric field is amplified
in the circle by the reduced conductivity, the electric current will be decreased such that

\[
j' = \frac{\sigma}{\sigma + \sigma'} j = \frac{2\sigma'}{\sigma + \sigma'} j, \tag{4}
\]

where \( j \) is the current for the non-eclipsed condition. If \( \sigma' = \sigma/2 \), the reduction factor is \( 2/3 \).
Thus, the geomagnetic \( Sq \) variation observed on the ground should be diminished during
the eclipse, contrary to the \( F2 \) region effect.

The polarization field outside the circle can be derived from a potential function
\( (E_\perp = -\Delta \varphi) \)

\[
\varphi = -\frac{\sigma - \sigma'}{\sigma + \sigma'} E_0 \varphi_0 \frac{\cos \theta}{r}, \tag{5}
\]

where \( \theta = 0 \) is taken as the direction of \( E_0 \). The EW component of the field is calculated as

\[
(E_\perp)_{EW} = -\frac{\sigma - \sigma'}{\sigma + \sigma'} E_0 \left( \frac{r_0}{r} \right)^2 \cos 2\theta. \tag{6}
\]

Although \( E_\perp \) is small and decreases rapidly with \( r \), it is interesting to note that \( (E_\perp)_{EW} \) has
an opposite direction to \( E_0 \) in the region within ±45° from east or west direction. Thus, a small downward additional drift velocity may be expected at stations whose overhead \( F \)
region is connected with the abovementioned region.

Since only the EW component of the electric field is effective in producing vertical drifts
in the \( F \) region, the orientation (as well as the magnitude) of the additional polarization
field is important in predicting the F region effect at particular stations. Detailed calculation of the effect of the reduced conductivity is also complicated by the anisotropic character of the conductivity when the magnetic field is taken into account and by the short circuit effect at the conjugate point (dynamo region) in the northern hemisphere, where there is no reduction of the conductivity, and is not attempted here.

In Fig. 5 we can see that a large upward drift motion starts even 30 min. before the onset time of the ground eclipse and becomes very small just after the end of the eclipse. This may be explained by the shape and size of the area of reduced conductivity. It is evident that the conductivity in the dynamo region is reduced over an area much greater than the shadow of optical totality on the ground (Nagata et al., 1956); we assume in Fig. 6 a pear-shaped boundary for this area moving along the direction of the eclipse path from NW to SE. The magnetic line of force through the F region over Rio Grande is connected with the dynamo region about 275 km to the south; P and Q in the F region on the eclipse path in Fig. 6 are connected with P' and Q' in the dynamo region, respectively. Thus, eclipse effects in the F region attributable to the polarization field will start at the time when the position of Rio Grande relative to the shadow is indicated by P and should taper away at the time when its relative position is indicated by Q.

Height distributions of various terms in the continuity equation are compared in Fig. 7 for the control and in Figs. 8 and 9 for the eclipse day. All figures illustrate the results at 11:10 (near totality) of model 5. In Figs. 7 and 8, the effect of vertical drift velocity is included implicitly in the evaluation of $T_v$. Fig. 9 calculates the effect of the additional $w$ on the eclipse day explicitly. The thermal expansion and contraction term is calculated on the assumption that $T_v$ is the actual temperature; this is not true, but the error will not seriously affect the calculation of $\partial N/\partial t$, because the thermal term is small compared with other transport terms in our present case.

On the control day (Fig. 7) $Q$ and $L$ are the dominant terms and are well balanced with each other. On the eclipse day (Figs. 8 and 9), however, $Q$ is extremely small at the times near totality and the transport terms play important roles in the continuity equation. The ion production due to causes other than the solar EUV radiation may be appreciable, but it should not be large enough to change this conclusion. Fig. 8 uses $T_v$ determined for the

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**Fig. 6** Schematic illustration of the assumed area of reduced conductivity. P and Q in the F region are connected with P' and Q' in the dynamo region, respectively, by the magnetic line of force.
Fig. 7 Height distributions of various terms in the continuity equation at 11:10 on the control day (model 5). The effect of vertical drift velocities is included implicitly in the evaluation of $T_r$. Solid curves indicate positive values, broken curves the negative values. Dotted curves show the calculated $\partial N/\partial t$ to be compared with the observed values. The ionization and loss terms are the dominant terms and are well balanced with each other.

Fig. 8 Height distributions of various terms in the continuity equation at 11:10 on the eclipse day (model 5). The effect of vertical drift velocities is included implicitly in the evaluation of $T_r$. Solid curves indicate positive values, broken and broken-dotted curves the negative values. Dotted curves show the calculated $\partial N/\partial t$ to be compared with the observed values. The loss and diffusion terms are the main competitive terms.
eclipse day by including the effect of vertical drifts implicitly; the loss and diffusion terms are the two main competitive terms, while Fig. 9 indicates the effect of the additional vertical drift velocities explicitly; the diffusion and drift terms are the two main competitive terms above ~310 km and the loss term becomes one of the main terms at lower heights. A better coincidence between the observed and calculated $\delta N/\delta t$ can be seen in Fig. 9 than in Fig. 8.

Table 1 also lists the root-mean-square value of the residual at 300 km for the period 09:00–13:30 for each model. This should be compared with the corresponding value of the observed $\delta N/\delta t$, about 64.9 cm$^{-3}$ sec$^{-1}$. For all models a smaller value of $b$ gives the smaller residual, and models 1 and 5 give particularly small values for the residual. Model 2, which has been based on laboratory determined chemical reaction coefficients and mass spectrometric values of neutral constituents observed by rockets, seems to be the worst, because it gives the largest residual among the 5 models. vonZahn (1967) recently reviewed critically the mass spectrometric measurements of atomic oxygen and concluded that all previous values of $[O]/[O_2]$ should be increased by a factor of 4; this indicates that our models 4 and 5 may not be inconsistent with rocket observations.

The average value of the effective attachment coefficient $\beta$ at 300 km is also listed in Table 1. It is found in our calculation that $\beta$ varies by a factor of about 3 during the period
of calculation; its manner of variation almost follows that of the number density of molecular constituents. The direct temperature dependence of $\beta$ is relatively small. The average value of $\beta_{\text{iso}}$ ranges from $7.6 \times 10^{-5} \text{sec}^{-1}$ in model 2 to $5.5 \times 10^{-4} \text{sec}^{-1}$ in model 3, but the most probable value may be around $1.2 \times 10^{-4} \text{sec}^{-1}$ in model 5.

4. Concluding Remarks

The increase of vertical drift velocity in the $F$ region during the eclipse, over that on the control day has been calculated based upon five models of chemical reaction coefficients and the lower boundary values of neutral constituents. The results are in agreement for all models that the additional velocity is largely upward over Rio Grande; it amplifies the drift velocity on the control day. This amplification of the vertical drift velocity in the $F$ region during the eclipse may be explained by the effect of an additional polarization electric field developed in the area of reduced conductivity in the lower dynamo region. The additional drift velocity might instead have become slightly downward if the $F$ region were connected with some area adjacent to the region of reduced conductivity. It is therefore desirable to make eclipse observations of $N-h$ profiles at several selected locations in order to test our theory.

Near totality of the eclipse, the ionization term due to EUV radiation is very small, and the transport terms due to diffusion and drift velocities are the largest competitive terms, whereas large ionization and loss terms are well balanced at the same local time on the control day. The ionization due to causes other than EUV radiation at the totality should not be large enough to change this conclusion.

As for the relative merit among the five models, model 2 gives the largest discrepancy between the calculated and observed $\partial N/\partial t$. We therefore conclude, with other authors (Rishbeth, 1961; Ferguson, 1967; von Zahn, 1967) that the laboratory-determined reaction coefficients and mass-spectrometric values of neutral constituents (particularly atomic oxygen) observed by rockets are not compatible.

5. Acknowledgements

This study has been initiated at the suggestion of Mr. J.W. Wright to whom we are grateful. We appreciate the system design and field operation efforts of Mr. E.J. Violette and Mr. W. Plywaski, and the excellent support given to our expedition by Dr. F. deMendonça of the Brazilian National Space Commission.

References


