On the variability of the observed HF Doppler derived equatorial F-region plasma drifts during evening and morning hours and the chemical corrections therein

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The radar derived F-region vertical plasma drift measurements, especially during evening/morning hours are apparent mainly because of the additional contribution from photochemical loss and/or production. As a consequence, it is very important to delineate the role of chemistry from these drift measurements in order to have a meaningful/realistic interpretation of the actual movement of the plasma in the ionosphere. In this paper, two chemical schemes have been employed separately for evening and morning hours to estimate the apparent drifts produced solely due to the chemistry. This study has been carried out by taking into account the important chemical reactions over equator during these times and for the computation, the neutral density of N₂, O₂, and neutral temperature Tn have been obtained from the Mass Spectrometer and Incoherent Scatter (MSIS) model. The temporal, altitudinal and seasonal variations of the chemical contributions have been theoretically estimated. The observed F-region vertical plasma drift measurements obtained from a multi-frequency HF Doppler radar over Trivandrum (8.5°N, 77°E, 0.5°N dip latitude) are then corrected, by taking into account the reflection height variation. The study reveals that (i) the apparent drift due to chemistry is strongly altitude dependent and can indeed be as high as 10-15 m s⁻¹; (ii) there is a clear cut seasonal pattern for these correction factors with a northern hemispheric (NH) summer (June) minima and a maxima during the NH winter solstice (December).

Keywords: Vertical plasma drift, Equatorial ionosphere, Ionospheric chemistry, F-region plasma drift

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1 Introduction

Radar derived plasma drifts have provided wealth of information regarding the electrodynamics of equatorial ionosphere during the past few decades¹⁻³. In particular, many of the interesting features of equatorial ionosphere during the sunset and sunrise periods have been extensively investigated using the HF Doppler radar measurements⁴⁻⁶. During evening periods, the F-region vertical plasma drifts and the corresponding zonal electric field are characterized by a sharp enhancement after the local sunset, commonly known as pre-reversal enhancement (PRE). It is generally explained to be due to the combined action of F-region dynamo driven by the eastward thermospheric wind near the dusk and the E-region conductivity changes near the sunset terminator at conjugate magnetic latitudes⁷⁻⁹. The PRE exhibits substantial variability, which primarily depends on: (i) variations in F-region wind; (ii) contributions from E-region dynamo; (iii) changes in E/F-region conductivity ratio; (iv) strength of equatorial electrojet (EEJ); (v) asymmetry in the conjugate E-regions of both the hemispheres; and (vi) the separation between the geographic and dip equators¹⁰⁻¹¹. Recently, Sumod et al.¹² have shown that the lower atmospheric forcings (waves and tides) can also produce significant changes in this phenomenon. In this context, it must be mentioned that it is very important to understand the PRE and its variability due to its major role in the post-sunset F-region electrodynamics and controlling the enigmatic phenomenon of equatorial spread-F (ESF). Similar to PRE, the pre-sunrise plasma drift is also characterized by a sudden downward excursion (SDE) followed by an upward drift⁵,¹⁵. Though PRE has been extensively studied, the SDE and its variability has not been properly understood so far mainly due to the difficulty in probing the pre-sunrise ionosphere because of the reduced electron density. Nevertheless, the multi-frequency HF Doppler radar at Trivandrum has provided much valuable information regarding the complex pre-sunrise electrodynamics too⁵,¹⁶.

In this context, it must be mentioned that the upward/downward drift due to the positive/negative
Doppler can also be due to the additional loss/production of electrons. When the layer decays/develops due to the chemical loss/production, it will appear as an apparent upward/downward drift in the Doppler signals. In other words, the measured drifts using the HF Doppler radar include the contribution from both electric field and production/loss of electrons. Simulation studies reiterated the importance of this chemistry in the observed vertical drift during the sunlit ionosphere\textsuperscript{14}. Though there have been considerable improvements in our understanding on the EUV radiation and photoelectron fluxes through both theory and measurements, it is very difficult to have an absolute quantification of the role of chemistry\textsuperscript{16}. Nonetheless, the need of the chemical contribution in the observed HF Doppler derived vertical plasma drift is well apprehended\textsuperscript{17}.

Hence, an attempt is made in the present work to investigate the role of the photochemical loss/production mechanisms in the observed HF Doppler radar measurements during post-sunset/pre-sunrise period. Here, two separate chemical schemes have been adopted to account for the additional loss/production of electrons during the evening/morning hours. The altitude, seasonal and temporal variation of this contribution have been theoretically studied. These correction factors have been applied to the observed vertical plasma drift measurements during sunset/sunrise time for different days, incorporating the reflection height variation.

2 Experiments

The multi-frequency HF Doppler radar over Trivandrum (8.5°N, 77°E, dip 0.5°N) has provided unique results pertaining to the equatorial ionosphere especially during evening/morning periods\textsuperscript{4,6,18}. It is a mono-static pulsed coherent system capable of quadrature detection of ionospheric echoes, which can be operated at three different fixed frequencies: 2.5, 3.5 and 4.5 MHz with a cadence of 6 minutes\textsuperscript{19}. The desired signal (f\textsubscript{0}) of a particular frequency is synthesized using a Frequency Synthesizer Unit (FSU) using the direct digital synthesis (DDS) technique. This pulsed RF signal is amplified and transmitted via a broadband transmitter through a three element folded dipole antenna and the Doppler shifted reflected signal (f\textsubscript{0} ± f\textsubscript{D}) from the ionosphere is received by using the same antenna. The received signals are then fed to the phase coherent receivers to extract Doppler signals. This Doppler data is then digitized and Fourier analyzed to evaluate the Doppler frequency (f\textsubscript{D}). The magnitude and direction (up/down) of the vertical plasma drift is evaluated from the Doppler shift (f\textsubscript{D}) as \( V = -f\textsubscript{D} \times \lambda/2 \), where \( \lambda \) is the operating wavelength. A sequential switching is done every minute, with an interval of one minute for data acquisition, so that multi-frequency operation is possible with a cadence of 6 minutes. The reflection height is measured from the time delay between the transmitted pulse and the reflected echo with a maximum uncertainty of 3.0 km since the pulse width used is 20 µs. The uncertainties in the evaluation of the magnitude of the vertical drifts are 0.25, 0.18 and 0.14 m s\textsuperscript{-1} for 2.5, 3.5 and 4.5 MHz, respectively due to the frequency resolution of ~ 0.0042 Hz (Refs 4,19) in the Fourier analysis adopted for the estimation of drifts.

3 Methodology

In the case of multi-frequency HF Doppler radar at Trivandrum, most of the days, the reflection occurs well below 300 km. This necessitates the application of corrections to the observed vertical plasma drift measurements. As mentioned earlier, the observed vertical drift measurements during evening hours are apparent because of the prominent layer decay due to the photochemical loss\textsuperscript{17}. Hence, the vertical drift due to chemical loss should be subtracted from the observed estimates to get the true electrodynamical drift. Similarly, during morning periods, the drift due to photochemical production must be added to the observed ones to get the true electrodynamical drift for accounting the additional layer formation due to production. Overall, as the value of loss term increases, the layer drift increases and becomes positive, i.e. the drift changes from downward to upward direction. Similarly, when the production increases, the layer drift decreases. In the present study, the loss/production term at each time has been estimated by considering the actual reflection height variation and the correction factors are subtracted/added to the observed data to get the actual vertical drift during evening/morning hours. The study is carried out for different days for the multi-frequency observations (2.5, 3.5 and 4.5 MHz) and the temporal variation of the quantitative estimates of the correction factors are presented.

3.1 Contribution of chemical loss during evening hours

As is well known, O\textsuperscript{+} ions are normally dominant above 220 km height\textsuperscript{20}. If the ions are assumed to be
purely $O^+$, then every term of continuity equation for the electrons as a function of time is exactly the same for the ions also. The major $O^+$ loss reactions at the lower F-layer are:

\[ O^+ + O_2 \rightarrow O_2^+ + O \]  \hspace{1cm} (1)

\[ O^+ + N_2 \rightarrow NO^+ + N \]  \hspace{1cm} (2)

where, $k_1$ and $k_2$ are the rate constants of the respective reactions. It must be born in mind that though there is considerable improvement in the understanding about the numerical values of these rate constants, there are uncertainties, as reported, regarding their values which vary by a factor of two. The overall chemistry in the F2 layer is complex and difficult to completely isolate the effects of processes like production, loss and diffusion. However, in the lower F-region, the analysis can be simplified by the assumption of the photochemical equilibrium and it is possible to determine the relative values of some of the important parameters. It must be mentioned that though such an assumption is applied for evening and morning hours in this paper, strictly speaking this is valid only during noon time.

From Eqs (1 and 2), the linear F2 layer loss coefficient can be defined as $\beta = k_1 n [O_2] + k_2 n [N_2] + k_3 n[X]$; where, $k_1$, $k_2$, and $k_3$ are the rate coefficients of the ion-atom interchange reactions of $O^+$ with $O_2$ and $N_2$ as given above. The rate coefficients $k_1$ and $k_2$ are calculated using the relations, $k_1 = 2 \times 10^{-11} (T_n/300)^{-1/2}$ and $k_2 = 7 \times 10^{-13}$ as given by Anderson & Rusch. The number densities of $O_2$, $N_2$ and the neutral temperature $T_n$ are calculated using MSIS model. Under geomagnetically quiet conditions over F2 region altitudes, the ratio of $n[N_2]/n[O_2]$ is ~ 10 and the currently accepted ratio $k_1/k_2$ is ~ 10, therefore, neither reaction can be neglected. The third term in the loss coefficient is included to take into account the possibility that some other constituent X might become important under certain geomagnetic conditions, for instance during the geomagnetic storms. In the present work, however, all the days considered are geomagnetically quiet. Therefore, the third term is neglected for further calculations. The velocity due to chemical loss is then given by $\beta H$. The parameter, $H$, is the F-region electron density scale height. During evening hours, Hari et al. using ionosonde observations at Trivandrum have evaluated the electron density scale height during evening hours in the F-region to be 10 km between 2.5 and 3 MHz. Similarly, for 4 MHz observations, Ramesh & Sastri also assumed a scale height of 10 km for explaining the seasonal variation in F-region vertical drifts. Though the scale height varies with altitude, in the upper F-region the gradients of scale height are very small ($dH/dh \approx 0.1$ above 220 km). As a consequence, the convenient assumption of a constant scale height should not be seriously in error as suggested by Rishbeth & Setty.

### 3.2 Contribution of photochemical production during morning period

A similar method is used for the calculation of vertical drift due to production also. In the F-region, electrons are produced by the photo ionization of atomic oxygen, the radiation absorbed by the molecular nitrogen does not contribute appreciably to the observed ionization because molecular ions are short lived in the F-region. Hence, the chemistry of ions in the sunlit F-region is primarily governed by the formation of $O^+$ ions through the reaction:

\[ N^+ + O_2 \rightarrow NO + O^+ \]  \hspace{1cm} (3)

where, $k_4 = 2 \times 10^{-11} \text{ cm}^3\text{s}^{-1}$ as given by Torr & Torr. The production coefficient in the lower altitude is defined as $\rho = k_4 n [O_2]$ (Ref. 13). The vertical plasma drift due to production mechanism is given by $\rho H$, where, $H$, is the scale height as explained earlier.

### 4 Results and Discussion

Figure 1 shows the time evolution of the vertical velocity due to the photochemical loss (recombination) on a typical day 30 March 2006,
estimated theoretically by following the method as discussed earlier. Different symbols correspond to different altitudes in the range 250-325 km at an interval of 25 km. From the figure, it is evident that the drift due to loss is highly altitude dependent. As the height increases, there is an exponential decrease of the loss contribution due to the recombination. It is interesting to note that the loss contribution varied between 1-2 m s\(^{-1}\) at an altitude of 275 km, whereas, it was 3-5 m s\(^{-1}\) at 250 km during 16:00-06:00 hrs IST. Further, in order to understand whether the chemical contribution will undergo any seasonal variation, the same estimation procedure is repeated for different seasons at a fixed height of 275 km. The monthly mean neutral climatology is taken using the MSIS model. As evident from Fig. 2, it is observed that as the season advances from winter to summer (December to June), the correction factor due to loss shows a descending trend. It is found that the loss is maximum during winter and it gradually decreases to September equinox and the loss contribution becoming the least for summer solstice. Nevertheless, the temporal behaviour of all seasons/altitudes shows a similar pattern with maximum values during early evening hours.

As the actual radar measurements reveal, the reflection height varies with time as well as the probing frequency. Therefore, the loss contribution must be estimated for different frequencies incorporating the measured reflection height variation. Keeping this in view, the correction factor due to the loss processes is estimated on 10 March 2004 for all the three radar frequencies and plotted in Fig. 3. The measured reflection height variation is also shown in the same figure. From the figure, it is clear that the reflection height varies substantially in the range 215-300 km and as a result the loss contribution varies in the range 1-15 m s\(^{-1}\). This is due to the strong dependency of the loss coefficient variation with altitude. It must be mentioned that the vertical drift of ~20 m s\(^{-1}\) actually corresponds to an electric field of 0.5 mV m\(^{-1}\), the magnetic field being 25000 nT at F-region altitudes\(^4\). From Fig. 3, it is obvious that the correction factor becomes more significant at 2.5 MHz frequency as compared to 3.5 and 4.5 MHz.

These correction factors have been properly accounted for and the resulting drifts on 10 March 2004 are plotted along with the observed ones for 2.5 (top panel), 3.5 (middle) and 4.5 MHz (bottom) in Fig. 4 (left panel). As is evident from the figure, the vertical drift starts increasing at ~19:00 hrs IST reaching a maximum at ~19:15 hrs IST, then decreasing to downward drift at ~19:45 hrs IST. This
sort of change in drift is due to the well known electrodynamic phenomena, namely the pre-reversal enhancement (PRE). In this context, a clear-cut PRE can be seen around 19:15 hrs IST. As is evident, the correction factors are significant before and after the PRE. This is due to the height dependence of the reflected echoes. It is seen that the corrected vertical drift corresponding to 2.5 MHz are greater at lower altitudes than that at the higher altitudes associated with 3.5 and 4.5 MHz.

The above mentioned aspect indicates that there exists a negative height gradient in the vertical plasma drift. In fact, Nayar & Sreehari\textsuperscript{19} reported that the average height gradient in the vertical plasma drifts over Trivandrum is negative around PRE time and its magnitude decreases with altitude below F-region peak. This clearly indicates the curl-free nature of the low-latitude electric field and also the partial signature of the post-sunset velocity vortex at the equatorial F-region. However, positive height gradient

![Multi-frequency observations of the observed vertical plasma drift on 10 March 2004 (left panel) and 29 June 2004 (right panel) along with the corrected drift after applying the contribution due to the photochemical loss (top, middle and bottom panels represent the drifts values for 2.5, 3.5 and 4.5 MHz, respectively)](image-url)

Fig. 4 — Multi-frequency observations of the observed vertical plasma drift on 10 March 2004 (left panel) and 29 June 2004 (right panel) along with the corrected drift after applying the contribution due to the photochemical loss (top, middle and bottom panels represent the drifts values for 2.5, 3.5 and 4.5 MHz, respectively)
in the evening F-region vertical drifts have also been shown to exist using simultaneous data from Trivandrum and Kodaikanal.

Figures 4 and 5 depict the corrected vertical drift estimates along with the observed ones for three more days. On 29 June 2005, the drift estimates due to the chemical contribution is maximum during the early evening, whereas it showed a gradual decrease in the late evening. On 02 September 2004 and 09 February 2005, the loss contribution was highly significant during the early evening periods and showed a gradual decrease thereafter. On 09 February 2005, a clear cut PRE was seen. On this day, the correction factors were found to be important only in the early evening times. This is due to the strong altitude dependence of loss coefficient during the time interval 19:00-19:30 hrs IST, when the reflection height was well above 300 km (not shown here). The mean of these correction factors for evening hours along with their standard deviation for different days are tabulated in Table 1, which clearly shows that the loss contribution is

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Fig. 5 — Multi-frequency observations of the observed vertical plasma drift on 02 September 2004 (left panel) and 09 February 2005 (right panel) along with the corrected drift after applying the contribution due to the photochemical loss (top, middle and bottom panels represent the drifts values for 2.5, 3.5 and 4.5 MHz, respectively)
very important and is indeed high, ranging from 5.5 ± 4.5 to 2.2 ± 1.6 m s⁻¹, for 2.5 MHz observations.

As discussed, the chemical contribution to the drift for morning hours has also been estimated to account for the additional production of the ionization. The temporal evolution of the correction factor calculated for different altitudes i.e. 225, 250 and 275 km are shown in Fig. 6, as the typical reflection height as seen during the morning observations in the range 225-275 km. As is evident from the figure, similar to loss contribution, the production term is also highly altitude dependent. Nevertheless, unlike the loss term, its contribution increases temporally showing the importance of chemistry (production) in the sunlit ionosphere. It is intriguing that the production contribution in the vertical drift reaches a value of ~10 m s⁻¹ even at the altitude of 225 km, which is the typical altitude of reflection during the morning observations. The seasonal pattern, shown in Fig. 7, also behaves in the similar manner as that of loss estimation, which increases from summer minimum to equinox, reaching the maximum during the winter solstice. However, the temporal evolution of the vertical drift due to production during all the seasons does not vary in the similar manner.

Figure 8 shows the estimates of the correction factors due to the photochemical production for three different frequencies along with the reflection height variation. Top panel shows the time evolution of the correction factor on 09 March 2004 for 2.5 (left), 3.5 (middle) and 4.5 MHz (right panel), respectively. The corresponding reflection height variations are shown in the bottom panels. As is obvious from the figure, the production contribution is as high as 13 m s⁻¹ for 2.5 MHz frequency. A comparison reveals that during morning hours, the correction factors are indeed higher than those during the evening, due to the lowering of the reflection height during these times. The maximum correction terms for 3.5 and 4.5 MHz observations were found to be 10 and 5 m s⁻¹, respectively on this day.

As discussed, the vertical drift due to the production has been added to the observed drift and the corrected drift estimates along with the observed ones for 09 March 2004 are shown in Fig. 9 (left

<table>
<thead>
<tr>
<th>Day of Observation</th>
<th>Time, hrs LT</th>
<th>2.5 MHz</th>
<th>3.5 MHz</th>
<th>4.5 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>10 March 2004</td>
<td>1830-2158</td>
<td>5.55</td>
<td>4.59</td>
<td>3.51</td>
</tr>
<tr>
<td>09 June 2004</td>
<td>1800-2000</td>
<td>2.94</td>
<td>1.86</td>
<td>1.91</td>
</tr>
<tr>
<td>02 September 2004</td>
<td>1800-1900</td>
<td>4.32</td>
<td>1.11</td>
<td>3.65</td>
</tr>
<tr>
<td>09 February 2005</td>
<td>1800-1930</td>
<td>2.19</td>
<td>1.60</td>
<td>1.37</td>
</tr>
</tbody>
</table>
Fig. 8 — Correction factor (top panels) due to the photochemical estimated for different frequencies 2.5 (left), 3.5 (middle) and 4.5 MHz (right) along with their reflection height variations (bottom panels) for a typical day, 19 March 2004.

Fig. 9 — Multi-frequency observations of the observed vertical plasma drift on 19 March 2004 (left panel) and 15 December 2004 (right panel) along with the corrected drift after applying the correction due to production of ionization (top, middle and bottom panels represent the drifts values for 2.5, 3.5 and 4.5 MHz, respectively).
From the figure, it is obvious that the vertical drift increases 05:30 hrs IST onwards reaching a maximum at ~06:20 hrs IST. Thereafter, it starts decreasing. This sudden downward excursion (SDE) during the pre-sunrise period followed by an upward turning makes the morning electrodynamics fascinating. As evidenced from the Fig. 9, the vertical drift on 19 March 2004 was downward (westward electric field) throughout the morning for all the three frequencies and the clear-cut signature of SDE was observed only when the proper correction was applied, especially for the 2.5 MHz observations. It is also evident from the figure that the correction is highly significant for all the three frequencies. As seen in Fig. 9 (right panel), the above mentioned features are not seen on 15 December 2004, which could be due to the smaller data duration. Nevertheless, the correction factors are found to be substantial during this day too. On this day, measurements at 4.5 MHz were not possible as the foF2 was found to be less than 4.5 MHz. Therefore, observations corresponding to 2.5 and 3.5 MHz only are presented here. Due to the paucity of the data, the present calculations are restricted only for these two days. Table 2 depicts the mean and standard deviation of the correction factor estimated due to the production for these days.

Table 2 — Mean and standard deviation of drift estimates due to the photochemical production

<table>
<thead>
<tr>
<th>Day of Observation</th>
<th>Time, hrs LT</th>
<th>2.5 MHz</th>
<th>3.5 MHz</th>
<th>4.5 MHz</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>Standard deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>19 March 2004</td>
<td>0430-0700</td>
<td>7.19</td>
<td>4.06</td>
<td>4.75</td>
</tr>
<tr>
<td>15 December 2004</td>
<td>0615-0700</td>
<td>3.60</td>
<td>1.46</td>
<td>1.82</td>
</tr>
</tbody>
</table>

In this context, it must be mentioned that in most studies, it is suggested that the chemical contribution to the observed drift is small and in the range 1-2 m s\(^{-1}\) (Ref. 27). This is true for stations like Kodaikanal, where most of the days, reflection occurs above 300 km. However, this is not the case for Trivandrum, where the reflection height is found to be within the chemistry dominated regime, i.e. well below 300 km most of the days. As a consequence, the correction factors for Trivandrum amounts to typically 10-15 m s\(^{-1}\), which is significantly large. These corrections are found to be more significant in the morning electrodynamics. It is believed that the asymmetry in the relative contribution of the chemistry, i.e. more apparent drift during morning as compared to that in the evening hours has strong implications in understanding/exploring the PRE/SDE or the interdependency of these two phenomena, if any, more comprehensively.

5 Summary and Conclusions

In the present work, the contribution of the chemistry in the observed vertical plasma drift during the evening/morning times has been quantified. The theoretical estimation showed that both the loss/production correction factors are highly altitude dependent, the correction being low at higher altitudes and becoming insignificant above 300 km. Most of the days, over Trivandrum, it was found that the reflection height is well below 300 km during evening/morning periods, which necessitates the application of the chemical correction to the observed vertical drift. The altitude variation of the loss/production can be explained due to the exponential decrease of the molecular species O\(_2\) and N\(_2\), thereby altering the loss/production coefficient and hence, the drift estimates. The seasonal variation of both loss and production was found to have a summer minima increasing to equinoctial months and reaching a maximum during the winter months. It is because during the winter months, due to the atmospheric compression, there can be an overall enhancement in the concentration of the molecular species (O\(_2\) and N\(_2\)) in the altitude regime 200-300 km, thereby, increasing the loss/production terms therein. The converse happens during the summer months, resulting in the summer minimum.

In this context, it must be mentioned that the net thermospheric circulation increases the column integrated O/N\(_2\) in the winter side of equator despite the fact that production of O due to photo dissociation of O\(_2\) is greatest in the summer hemisphere\(^{28}\). Nevertheless, during winter months, there is a substantial increase in the O\(_2\) and N\(_2\) in the regime, i.e. 200-300 km due to the downwelling of
atmosphere as mentioned above. These composition changes, which are locally produced during winter months, are smoothed out by horizontal winds, as a part of the large circulation changes. As a consequence, thermospheric density shows larger values during the winter solstice. Recent simulation studies by Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIE-GCM) as well as observations corroborate the same.

In view of the above, the correction factor estimation for loss/production, as estimated in the present study, shows that the chemical contribution can indeed be as high as 10-15 m s\(^{-1}\), depending on the reflection height and also exhibit a definitive seasonal pattern. Therefore, it becomes very important to apply proper chemical correction in the observed vertical plasma drift measurements in order to have a meaningful interpretation of the electrodynamics especially during evening/morning times.

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