ROLE OF CONJUGATE AND LOCAL TERMINATORS FOR IONOSPHERIC DYNAMICS AT ARECIBO

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Abstract

Using some recent Plasma drift data at Arecibo, we present evidences of Electric Field (*E*) changes induced by sunrise and sunset transitions at both local and conjugate regions. Field perpendicular plasma drifts in the *F* region are used as unambiguous diagnostic of the Electric Field. We present evidences of a downward velocity started around the conjugate sunrise and reaching minimum around the local sunrise, when it turns around and merges with normal daytime behavior, controlled by the dynamo region. During sunset, the upward drift increase at local sunset and shows a dip at the conjugate sunset, when it turns around. Afterwards, the *F* region is isolated and behaves in regular night time fashion. The entire behavior can be explained by coupled behavior of the *E* and *F* region, where the terminator line switches the coupling and affects charge separation at the boundaries.

1. Introduction

Ionospheric Electric fields (*E*) can be produced through a myriad of causes, originating from sources internal to the ionosphere, magnetospheric and interplanetary sources and extending to atmospheric and terrestrial sources. While, evidences for all these sources exist, the most prominent sources are internal, due to the motion of winds blowing the conducting plasma across the magnetic field lines. The lower *E* region of the ionosphere having the most conductivity plays the dominant role in establishing the electric fields in the entire ionosphere, although the *F* region gets decoupled from the dynamo region (E region) at night and can generate its own *E* fields. Because of the high conductivity of the ionosphere along the field lines, the electric fields are transmitted instantaneously (in microsecs) and the entire ionosphere needs to be considered in the circuit comprising the generators (dynamo) and the loads (motors). The mapping of the *E* fields along the field lines is significant in observation of the *E* field at any location and the field can set the ionosphere and consequently the atmosphere in motion as well. The *E* field circuits must extend in the global sense.

Plasma drifts and *E* field observations are routine observations at Arecibo continuing for over 40 years. Comprehensive plots of plasma drift components are available [1]. Broadly, the eastward *E* field (pole ward drift) is positive during the day and negative during the night; whereas, the equator ward *E* field (eastward drift) is mostly negative during the day and positive during most of the night. There are significant variability's in day to day observations and the average results have been explained by using conventional dynamo/motor explanations; both qualitatively and by some average global thermosphere/ionosphere models [2-3].

Systematic departures from the average behavior during the transition hours were suspected earlier during the 1970's. This is corroborated using some recent data, where we demonstrate evidences of some departures from the average behavior caused by the charge accumulation at the sunrise/sunset (SR/SS) transitions at local and conjugate regions.

The large time difference between the local and conjugate region SR/SS transitions allow inferences to be drawn regarding the relative roles of the *F* region dynamo and the *E* region dynamo and motor effects for both the local and conjugate regions. When the *E* layer is sunlit. It almost completely shorts the *F* region polarization field. The transition between the local and conjugate *E* region build up, provides interesting situations. Charge accumulation can occur at the terminator lines, which when mapped to the *F* region produces field-perpendicular drifts in the zonal and meridional planes. The terminator also acts as switches connecting or disconnecting the local and conjugate *E* regions to the *F* region circuit. Figure 1 shows the SR/SS times (at different heights) for December 13, 2012, plotted against Local time at Arecibo (LT). During the winter at Arecibo (December), differences between the local sunrise and conjugate sunrise can be around 3 to 5 hours (for 100km and 400km of altitude, respectively), allowing temporal signatures in the observed data to infer about the cause and effects.

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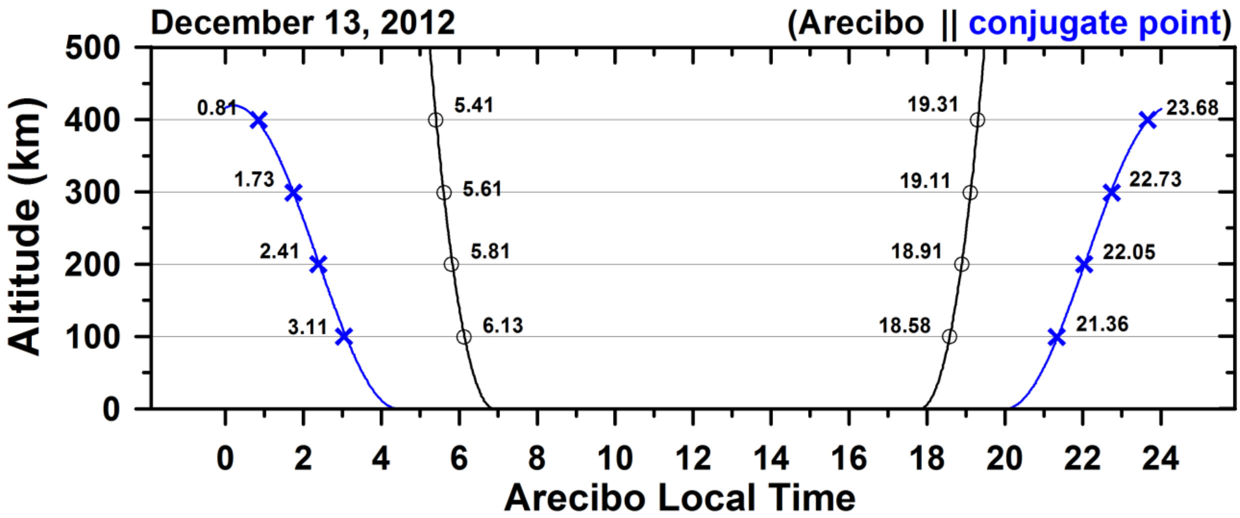

Figure 1. Sunrise and sunset times for Arecibo (18.35^{o}N; 66.75^{o}W) and conjugate region (46.60^{o}S; 64.70^{o}W) ionosphere (black and blue solid lines, respectively). Shadow heights obscured by a solid earth are plotted against the Arecibo Local Time (LT=UT-4hours) for December 13, 2012.

Ionospheric sources of electric fields mostly originate at the *E* region dynamo, where the **U**x**B** (**U** and **B** being the neutral winds and magnetic field, respectively) drift of ions produces charge accumulation at the sunrise/sunset terminators and the zonal and meridional *E* fields map to the *F* region. Mapped to the *F* region, zonal winds produces vertical drifts up during the day and down during the night. During the daytime, the *F* region is connected with the dynamo region, which acts both as a dynamo and also as a sink (motor). This prevents polarization field building up in the *F* region. Polarization field due to *F* region dynamo can build up when the field lines are disconnected from the *E* region, as in the night time. Interesting transitions take place during the sunrise and sunset times. The *PRE* (Pre Reversal Enhancement) in the equatorial sunset ionosphere has been well investigated and explained in terms of charge build up in the *F* region dynamo due to the presence of strong conductivity discontinuity near the sunset transition region [4,5]. Kelly's treatise [6] (page 100-102) explains the various plausible mechanisms for the equatorial situations.

While the equatorial ionosphere does not indicate any such discontinuity related effects during the sunrise, the Arecibo data clearly demonstrates some systematic behavior during sunrise (and also sunset) which are evidences of charge separation at the sunrise/sunset terminators and complex interplay of *F* region dynamo and *E* region circuits. Interestingly, the *E* region circuit extends both to the local and the conjugate regions and the effects of the conjugate region can be clearly evidenced with Arecibo data.

2. Results

Arecibo is the most powerful and capable IST radar in the world. It has been observing the unambiguous plasma drifts, electron densities, electron temperatures, etc. with extreme accuracies for over 50 years. Most recently, the techniques have been improved further and we present the plasma drift components with magnetic field lines as reference frame as well as electron densities (*Ne*), electron temperature (*Te*), plotted against local time (LT) and for different altitudes, in several panels for visual correlations. Figures 2 to 4 cover the sunrise periods (02:00 to 07:00 LT) while Figures 5 to 7 (17:00 to 24:00 LT) cover the sunset periods. Figures 2 to 7 are showing from the left to the right columns of panels the velocity perpendicular to the magnetic field (*Vpe*) (eastward positive), antiparallel velocity (*Vap*) (positive in the upwards direction and to the south), velocity perpendicular to magnetic field (*Vpn*) (positive towards north and upwards), electron density (*Ne*) (m^{-3}) and electron temperature (*Te*) (K). All the data are for December 11 to 14, 2012.

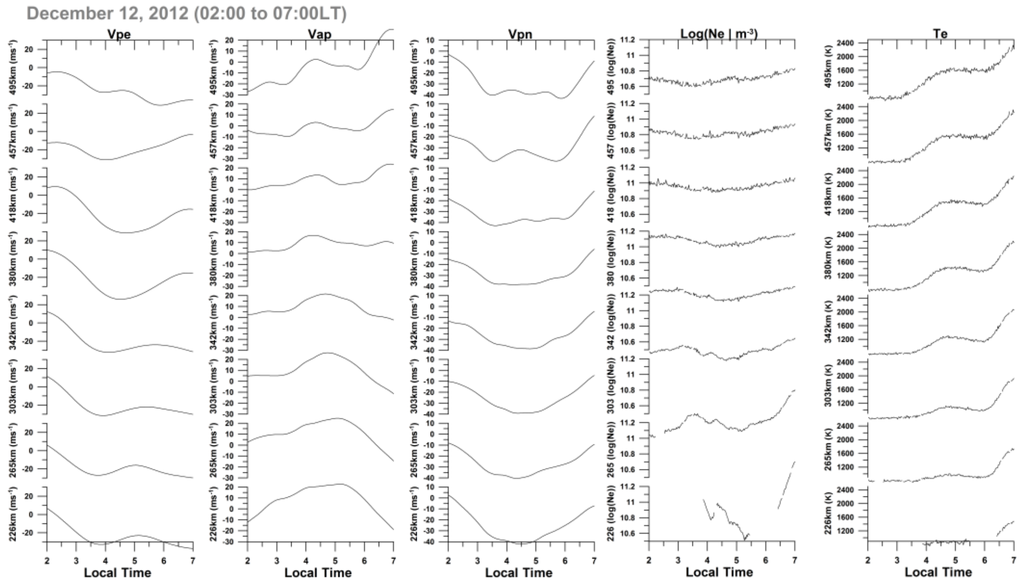

Figure 2. Plasma drift components, Electron densities (*Ne*) and Electron Temperatures (*Te*) at selected heights are plotted against time (LT) encompassing the sunrise period for December 12, 2012. Plasma drift components have been derived for *Vpe* (perpendicular to magnetic field and positive towards East), *Vpn*(perpendicular to the magnetic field and positive towards North and upwards) and *Vap*(parallel to the magnetic field and positive in the upwards direction and to the south). Note: *Vap* is opposite to the *Vpa* components published in some earlier references.

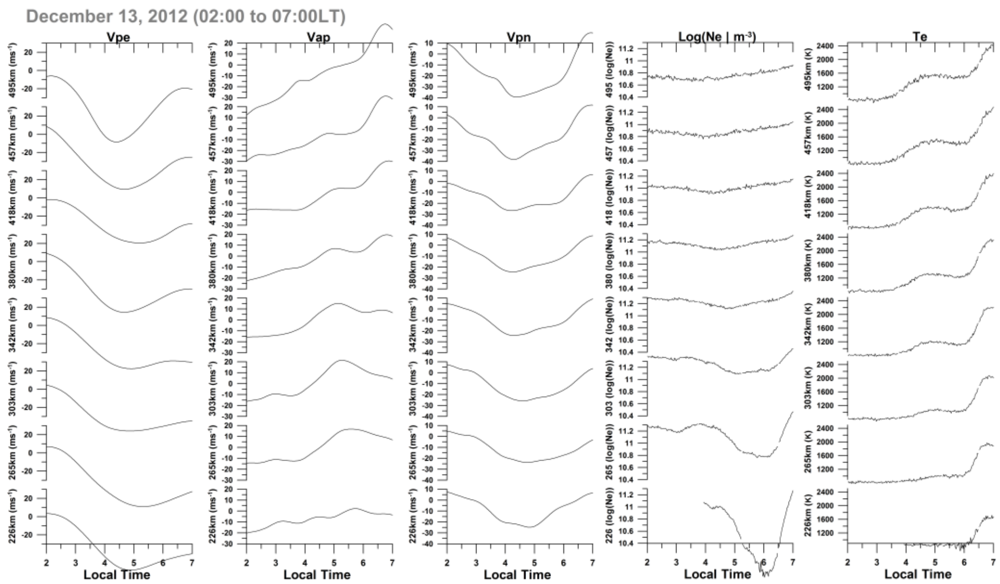

Figure 3. Similar to Figure 2 but for December 13, 2012.

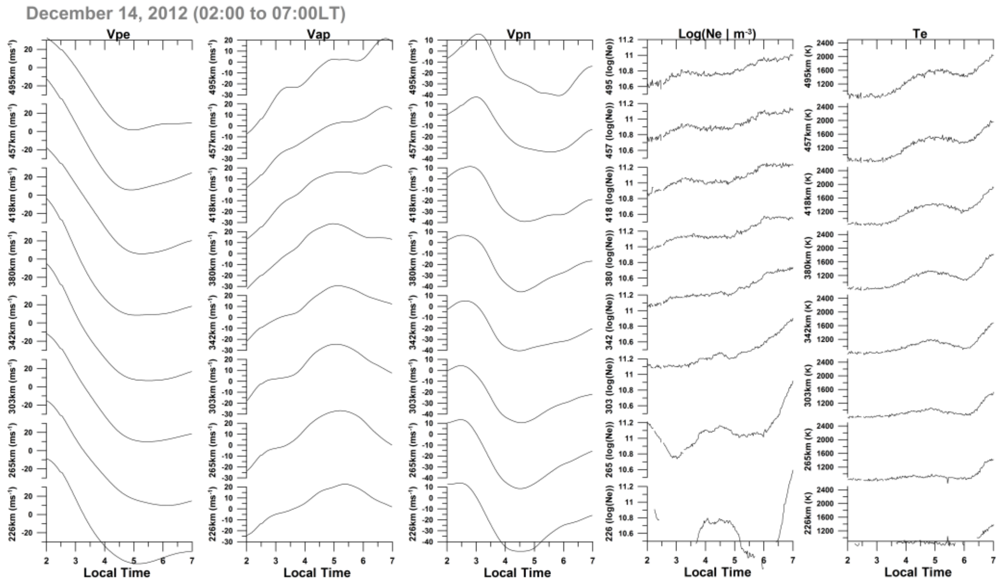

Figure 4. Similar to Figure 2 but for December 14, 2012.

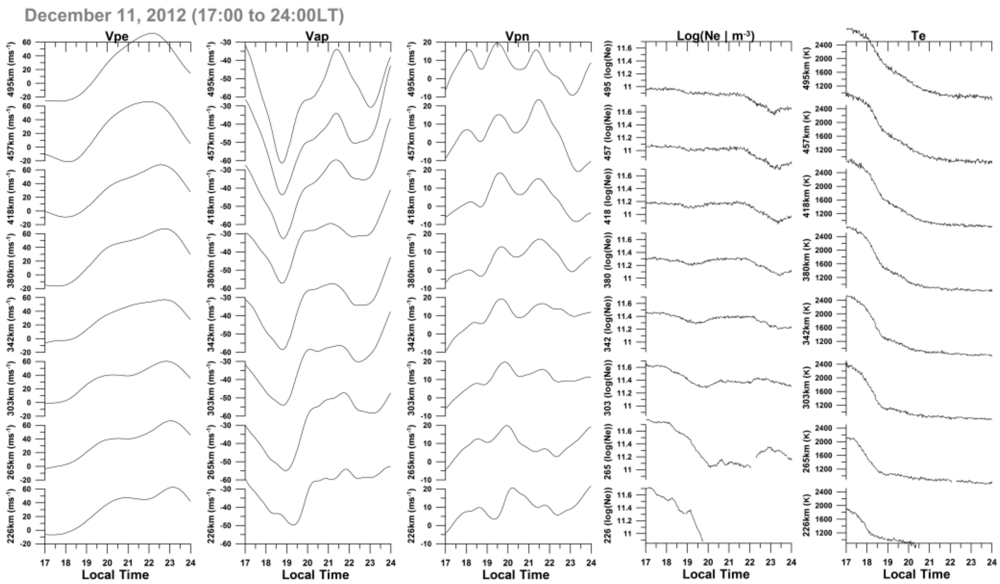

Figure 5. Similar to Figure 2 but for sunset periods and December 11, 2012.

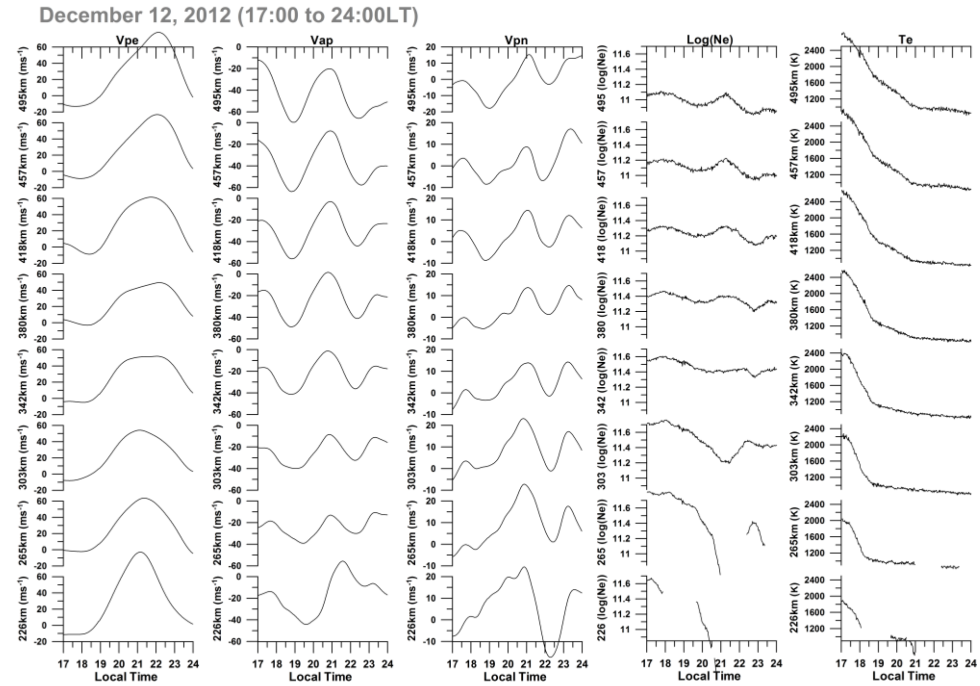

Figure 6. Similar to Figure 2 but for sunset periods and December 12, 2012.

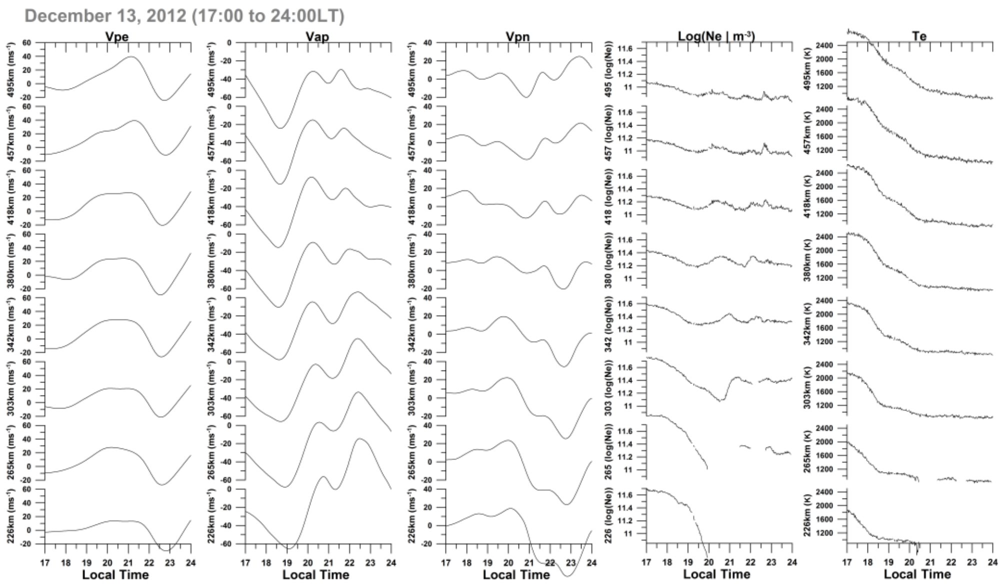

Figure 7. Similar to Figure 2 but for sunset periods and December 13, 2012.

2.1. Sunrise Observations

1) *Vpe* and *Vpn* both show a pre-dawn decrease.
2) The decrease starts several hours before the local sunrise at *E* region, maximizes at around 4 to 05:00 LT and starts reversing at around the local *E* region sunrise around 06:00 LT.
3) As the local *E* region builds up, the decrease in *E* fields are reversed.

Using a simplified lumped circuit model consisting of *F* region dynamo and local and conjugate *E* region dynamos with resistive loads and remembering that the lumped circuit model in reality is composed of distributed parameters comprising the complex conductivities in the entire *F* region and extending to the E regions, we can make some intuitive deductions. Recalling the situation before local sunrise at Arecibo, the conjugate region is sunlit. We can picture the local *E* region out of the circuit and only the dynamo *F* region and conjugate *E* region are effective.

Combined actions of the *F* region polarization field and the conjugate *E* region fields build up a downward and westward plasma drift as evidenced in both *Vpn* and *Vpe*, respectively. Recall that around 02:00 to 04:00 the local ionosphere (all heights) are well into darkness and the negative vertical drift in the lower heights are indicative of the fields being mapped from heights higher in altitudes. This could only be due to the *F* region and conjugate region fields.

The negative vertical drift reaches maximum at around the local sunrise at *E* region around 06:00 LT. (scattering from earth's geocorona produces some slight early signatures). The time resolution of the plasma vector data is not better than 15 to 30 minutes and might have caused the slight early turn over as seen in the figures. As the local *E* region starts building up (see the Ne panel), the drift reverses and ultimately reaches the daytime values dominated by the dynamo region.

Further clues justifying the inference are observed in the slight time shifts for the start of the SR decrease as is clear in *Vpn*, particularly for December 14. Furthermore, the *Vpn* reaches the minimum little earlier than *Vpe*, consistent with the conductivity along EW to be formed earlier than those along the NS and the fact that it is mostly the Hall conductivity (perp. to both B) which produces the *E* region circuit.

The field aligned plasma velocity components are also shown in the panels. The field aligned velocities do not represent direct *E* field effects. Instead, they represent the response of the ionospheric plasma to the combined actions of *E* field and pressure gradients [7]. Behnke and Harper [8] observed the anticorrelation between the *Vpn* and *Vpa*. Using a simplified model of the *F* region dynamics Rishbeth et al. [7] and Ganguly et al. [9] showed that the anticorrelation is an inherent property of the steady state ionosphere, essentially saying there is little vertical drift. We observe the expected anticorrelation for most of the time and the turn-around points, particularly for lower heights coincide with the local *E* region build up. The response curves (*Vpa*) for several heights below the *F* region peak also indicate the distributed nature of the dynamo region.

The qualitative arguments presented here are mostly based on the temporal signatures of the relevant parameters and the time resolution is extremely important. Because the Arecibo beam swinging technique takes about 15 to 30 minutes for the entire revolution and consequent formation of vector components, the time resolution of the derived components cannot be any better. To pin down the times more precisely, we have analyzed a few days of more recent data when two simultaneous beams (using two independent feed systems) were used. In one of these experiments, one beam was pointed vertical and the other was rotated in the usual manner. Figure 8 shows the such a data for 19 January, 2010. No attempts to form vector components are made here and both the data sets (for vertical and rotating) indicate transitions around 04:00 and 06:00 LT, consistent with the earlier observations (adjusted for shifts in SR times and within the uncertainties in time for vector formation).

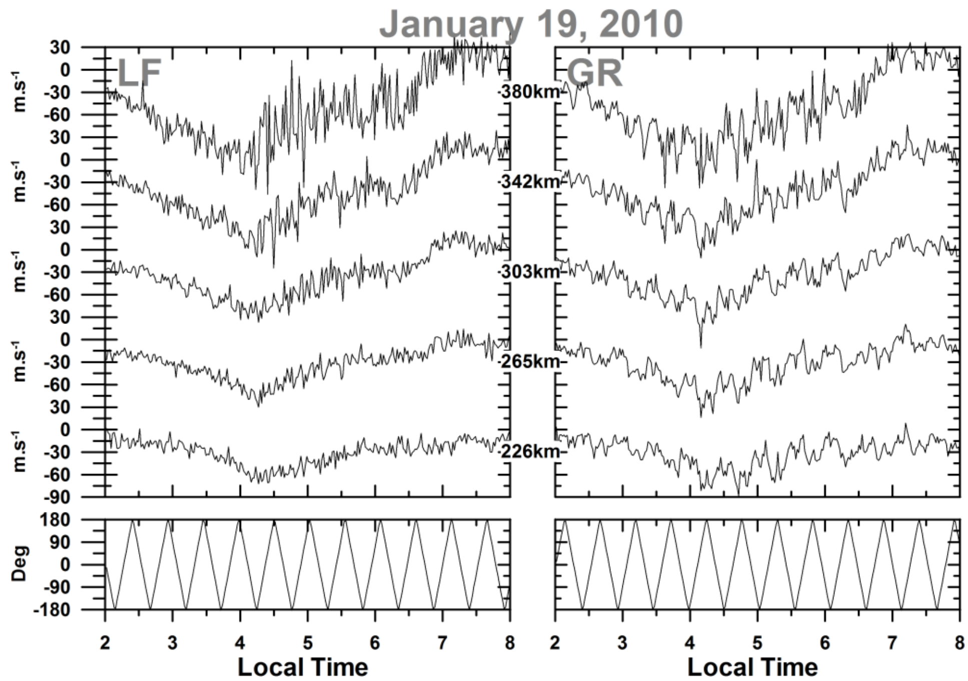

Figure 8. Direct Line of sight (LOS) velocities (with finer time resolution) measured using two simultaneous beams plotted for selected heights (temporal smearing due to vector component formation is not involved). The two panels show the results for two beams, one pointing vertical and the other at 15 degrees and rotating. The rotation angles (azimuth angle is shown in the bottom panels). The results show clear transitions around 04:00 and 06:00 LT (corresponding to conjugate and local sunrises). Date: January 19, 2013.

2.2. Sunset Observations

Some preliminary observations regarding the sunset situations at Arecibo are worth reporting. The panels (similar to what has been shown earlier for SR) are shown in Figures 5 to 7.

1) The large *PRE* increase in vertical drift well described for equatorial ionosphere is much subdued or almost non-existent at Arecibo. There are small increases in vertical drifts as seen in *Vpn* around 20:00 LT. This is followed by a dip in *Vpn* around 22:00 LT after which the vertical drift becomes upward.
2) Eastward drift (*Vpe*) becomes positive after 20-21:00 LT (local dynamo region sunset). It remains positive briefly, and turns around 22-23:00 LT (conjugate region sunset).
3) Field aligned drift (*Vap*) shows considerable departures from the anti-correlation patterns with *Vpn*. Departure appears to be larger at higher altitudes.

Qualitative explanations of these observations can be obtained following conventional *F* region dynamo and *E* region circuits. The small increase in vertical drift at the local sunset could be due to causes similar to *PRE*, but subdued due to the shorting of the circuit through conjugate *E* region, which could be acting both as a driver (dynamo) and a sink (motor). At the conjugate sunset around 22:00 LT, we observe the vertical drift to attain a dip (downwards). From then on, it is only *F* region polarization field. Similar turn-around is also evidenced in *Vpe*, establishing the temporal coincidences with the local sunset and conjugate sunset times.

The break points for the Vertical drift components can be correlated with the decrease of *E* region conductivities after sunset (19:00 LT), when the *F* region polarization field creates some charge build up in the *E* region, creating the upward drift all along the ionosphere. Remembering that the conjugate region at Arecibo is still sunlit, the field in the *F* region cannot develop to the extent what is observed in the equatorial ionosphere. It is partially shorted by the conjugate region preventing the full development of *PRE* like phenomenon.

Because the Arecibo *F* region is connected with the *E* region for extended periods (starting from conjugate region sunrise to conjugate region sunset), the charge separation at the conjugate *E* region can also affect the observed *F* region drifts. Evidences of conjugate region sunset affecting the vertical drift in the entire ionosphere is seen at prominent dip in *Vpn* at around 22:00 LT, corresponding to the opening of the *F* region field lines from the conjugate *E* region. The behavior is almost textbook example of Farley [4] mechanism describing the *F* region wind driven vertical *E* field being carried to the *E* region and then mapped back again to the *F* region as EW Electric field. The transformation from vertical *E* field to the EW *E* field taking place through Hall conductivity and charge separation in the *E* region (See [6]). This would produce "first an increase in upward drift followed by a decrease: as the sunset terminator passes though the *E* region. The intriguing feature at Arecibo is that this is exactly what is seen, except caused by the conjugate sunset at around 22:00 hrs.

It is apparent that the detailed behavior of the plasma drifts and *E* fields in the ionosphere over Arecibo, will demand modeling using the entire path length along the field lines and including both the local and conjugate regions. Layers of ionization, particularly *E-F* valley's can produce strong effects on integrated conductivities and reasonably detailed models of the electron density distributions over the entire path, in conjunction with reasonable neutral wind representations with height is necessary. Gravity waves would always create perturbations in the wind models and the external factors such as those occurring in the magnetosphere and/or atmospheric sources could also be significant. While, these are formidable tasks, we have developed a simple lumped parameter model for the Electric circuit and coupled it with another simple ionospheric model to provide more quantitative estimates.

3. Conclusions

Sunrise and sunset conditions at Arecibo offers interesting situation as allowing intuitive arguments in describing the measured plasma drift components and other ionospheric parameters. Depending largely on the temporal signatures of transitions, we infer:

1. The existence of downward drift during sunrise, when the downward velocity shows a dip as the sunrise terminator crosses the local *E* region. The combined roles of *F* region dynamo and *E* region circuit (dynamo and sink) are evidenced in the sunrise observations of Eastward (*Vpe*) and *Vpn* components. The pre-sunrise velocity dip is started around the conjugate region sunrise, indicating the dip is started/created by the conjugate region. The combined actions of the conjugate *E* region and the *F* region, creates a westward electric field and drives a downward drift. Just before ground sunrise, local *E* layer starts operating its own dynamo and thus the downward drift reaches its maximum near the ground sunrise. Near the local ground sunrise, *F* region field builds up for a little while and then *E* region conductivity adds up resulting in rapid buildup of the vertical drift.

2. We observe analogous interplay of *F* region dynamo and *E* region circuits during the sunset. The upward drift shows increase around the local sunset and shows a decrease at the conjugate region sunset. *Vpe* observations also corroborate the effects of conjugate region effects causing the dip.
3. Using some recent Arecibo data we have demonstrated the existence of a downward velocity started around the conjugate sunrise and reaching minimum around the local sunrise, when it turns around and merges with normal daytime behavior, controlled by the dynamo region. During sunset, the upward drift increase at local sunset and shows a dip at the conjugate sunset, when it turns around. Afterwards, the *F* region is isolated and behaves in regular night time fashion.
4. Qualitative explanations are being bolstered by using a combined lumped circuit model and a simplified ionospheric model. The need for implementing the complete circuit including the conjugate region is emphasized.

4. Acknowledgments

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