Verification of Low Latitude Ionosphere Effects on WAAS During October 2003 Geomagnetic Storm

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ABSTRACT

The Federal Aviation Administration's Wide Area Augmentation System (WAAS) provides high integrity GPS-based precision navigation service to users in the conterminous United States. In October 2003, only four months after WAAS was commissioned, a series of coronal mass ejections from the sun triggered one of the strongest geomagnetic and ionospheric storms of the solar cycle. WAAS user integrity was maintained during this entire time by reducing precision navigation service availability.

Toward the end of this storm period a localized region of enhanced TEC that persisted for several hours was observed over Florida. GPS measurements of TEC made from the WAAS sites near the Gulf of Mexico indicate that the high density region was as much as 60 TECU (about 10 m delay at L1) higher than the surrounding ionosphere. The feature was observed in the Florida region from local evening on October 30, 2003, through midnight on the 31st. It is conjectured that this feature is not in reality so localized as to have the spatial area of roughly Florida, but may be part of a larger ionospheric structure in that longitude sector, spanning many degrees of latitude south of the sampling area of the WAAS GPS reference network. It is also thought to be the case that this larger structure may exist due to the effects of the geomagnetic storm in the South Atlantic Anomaly.

We examine this hypothesis by augmenting the WAAS network with GPS dual-frequency ionospheric data over a broader geographic region including Central America and the Caribbean. These data include a network of twelve sites situated in the Caribbean islands, a network of sixteen International GPS Service (IGS) sites in Mexico and Central America, and the Continuously Operating Reference Stations (CORS) in the United States. The measurements extending south toward the geomagnetic equator allow us to trace the feature back in time to come to a better understanding of the storm-time dynamics. We show that the feature observed with the WAAS network is indeed part of a larger previously existing ionospheric structure. In addition we use JASON sea surface satellite data to demonstrate that, while other studies have shown TEC uplift above 400 km, the feature does not appear to have been lifted up beyond 1300 km altitude.

The apparent extreme localization of this ionospheric anomaly poses a challenge to WAAS integrity maintenance. The WAAS reference GPS receiver network of twenty-five stations is spread over the entire U.S. including Alaska and Hawaii. Although sparse sampling is always accounted for in the error bounds that determine WAAS user integrity, prior to the October 2003 storm, a feature so localized and dense had not been observed. Such an observation may imply that undersampling error bounds be revised upward, reducing precision navigation availability even during nominal conditions unless the storm behavior is well enough understood to demonstrate with high confidence that such a localized region of high density could not exist without the detection of a storm in real-time by WAAS.

MOTIVATION

On October 29 and 30, 2003, a series of coronal mass ejections (CMEs) from the sun arrived at earth, severely disturbing the magnetosphere and ionosphere. A general summary of observations made by SOHO, ACE, and the GOES satellites is found at [9] and reviewed below. Such energetic input to the earth's space environment is known to have an impact on power systems, HF radio communications, satellite operations, and navigation. As a GPS navigation aide, the FAA's Wide Area Augmentation System (WAAS) was no exception.

WAAS provides single-frequency GPS users with error corrections and bounds on those corrections to maintain the integrity of applications in which safety is critical, such as landing aircraft. The ionosphere causes the largest and most variable source of GPS error, and WAAS provides sigma bounds on its estimates of this error over the conterminous United States (CONUS). The GPS range delay is proportional to the amount of ionization along the signal path, and during disturbed conditions such as the October 2003, or "Halloween" storm, extremely high spatial and temporal variation may be observed.

The 25-station WAAS network made observations of the delay at L1, or total electron content (TEC), during the October storm as it affected CONUS, and one ionospheric feature, illustrated in Figure 1, was detected that may in general pose a particularly troublesome threat to WAAS user integrity.

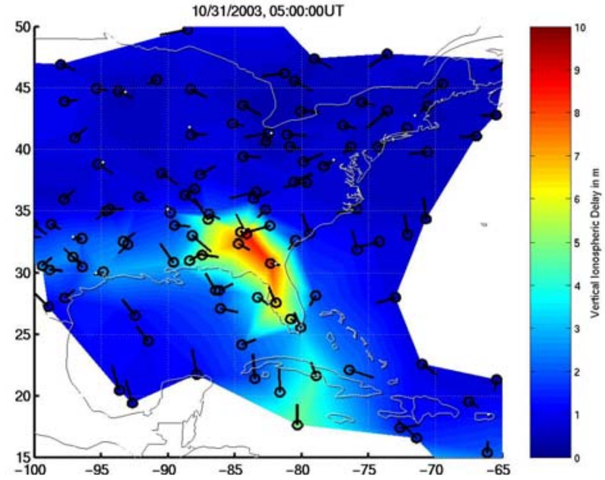

Figure 1: Contour map of ionospheric error in meters at L1 over the eastern U.S. on 10/31/03 05:00 UT, (local midnight) as measured by WAAS. Black circles indicate measurement locations and lines point to associated ground station. Color scale is 0 (blue) to 10 m (red).

Figure 1 is a contour plot of the equivalent vertical GPS range delay, in meters at L1 frequency, due to the ionosphere, from 0 (blue) to 10 m (red). The measurement locations, shown as black circles, are taken to occur at the intersection of each line of sight (LOS) with a surface that lies at 350 km altitude above the earth. Each of these ionospheric pierce points (IPPs) is drawn with a line segment pointing back to the ground station at which the measurement is made, with segment length inversely proportional to the satellite elevation.

The map shows a region of high total electron content (TEC) that is apparently localized over Florida at local midnight. The GPS delay at L1 frequency in that region is about 10 m, an order of magnitude higher than the background ionization. This feature is of interest for WAAS and other Satellite-Based Augmentation System (SBAS) developers. Its limited spatial extent leaves open the possibility that, were such a feature to occur again, the WAAS network might fail to sample it. Without knowledge of this feature's existence the WAAS broadcast error bounds might not be wide enough to protect against such a feature.

WAAS user integrity is ensured in such a case by implementation of an Extreme Storm Detector. The cost of maintaining integrity with this ESD is reduced availability of vertical guidance service, known as LPV.

The purpose of this paper is to investigate whether the high density region, which we will refer to as the "Florida feature" is truly that localized in space, to ask whether such a feature can happen anywhere in CONUS at any time, and to start to understand what caused it.

We will do this by augmenting WAAS observations of the ionosphere with additional measurements over the U.S., Mexico, Central America, and the Caribbean to constrain the horizontal position of the high density TEC. We will also compare some of these ground observations with JASON satellite measurements of vertical TEC taken over oceanic regions to constrain the altitude of the high density TEC.

INTRODUCTION

A coronal mass ejection (CME) released from the sun at 20:49 UT on 29 October impacted the geomagnetic field at around 16:00 UT on 30 October. The geostationary satellites GOES 10,11, and 12 observed the magnetopause boundary for several hours. The Bz component of the interplanetary magnetic field (IMF) as measured by ACE turned and remained southward at 15-30 nT for several hours subsequently.

It is well-known that geomagnetic activity is associated with periods of southward Bz. However, the direct relationship, due to magnetic reconnection, is not completely understood. In any case, as Bz turns southward, the magnetic field lines of the solar wind connect with the field lines of the earth's geomagnetic field, resulting in particle and energy input to the near-earth environment. One effect of southward Bz is an increase in the ring current, which effectively reduces the strength of the geomagnetic field. This field strength reduction is measured by ground-based magnetometers and recorded as a drop in hourly measure Dst of the disturbance, storm-time. The Dst measurements for the Halloween storm are shown in Figure 2. The Florida feature begins to come into view of the WAAS network around 23:00 UT, or 18:00 Eastern Standard Time (EST) on the 30th. This is during the main phase of the storm, following the second sudden storm commencement at the end of UT October 30th.

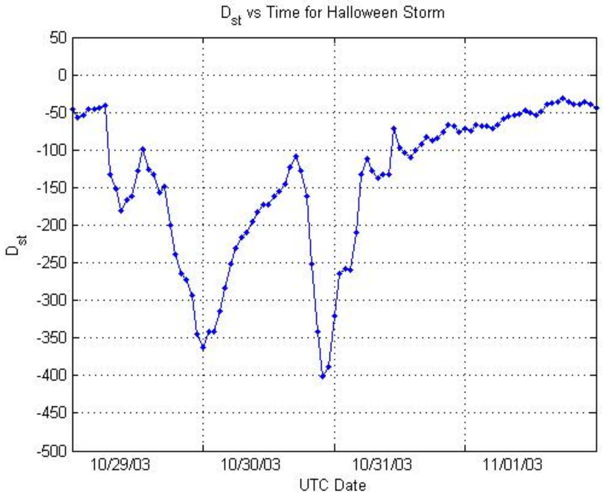

Figure 2: D_{st} vs Universal Time. The feature of interest first appears over Florida around 23:00 UT on 30 October.

HORIZONTAL AND TEMPORAL EXTENT

In order to view the extent and evolution of the Florida feature, we augment the WAAS network data with dual frequency GPS data from several other sources. These include about 400 CORS and IGS stations in CONUS and Mexico and a set of 12 stations in the Caribbean. The CORS and IGS stations were processed to level the interfrequency biases using the JPL Global Ionospheric Mapping (GIM) tool. Details on this processing tool can be found in [5].

The Caribbean data are provided by Dr. Glen Mattioli at the University of Arkansas, from the Caribbean-North American Plate Boundary Experiment (CANAPE) effort. The code-leveled carrier phase measurement of the ionosphere is computed from the dual frequency rinex data. The interfrequency and inter-data-set biases are removed by leveling each line of sight (LOS) to the nearest CORS/IGS station, also located in the Caribbean. LOSs with data at 19:00-07:00 EST (nighttime) are leveled to nighttime values first, and any LOSs without data at this time are leveled using their tracks from 07:00-19:00 EST (daytime). This method disregards the fact that the receiver bias must be the same for LOSs to a single receiver and that the satellite bias must be the same for LOSs to a single satellite. An alternate method of leveling interfrequency biases, taking this coupling of biases into account, was attempted as described by Hanson [3]. However, it did not show sufficient consistency with the separately processed CORS, WAAS, and IGS data to yield realistic contour maps. Our main goal in leveling the biases is to be able to combine this data set with the data of CONUS, Mexico, and Central America. Therefore, leveling LOS by LOS was chosen because it was effective though simplistic.

A sequence of contour maps combining all these dual frequency GPS measurements is shown in Figures 3-11. These maps are snapshots of the equivalent vertical ionospheric delay in meters at L1 in the eastern U.S. and the Caribbean. The color scale varies from blue (0 m) to red (10 m). IPPs, assuming a 500 km shell height, are marked with small black dots, and line segments point from the dots in the direction of the ground station making the measurement. The higher shell height was chosen based on results by Mannucci et al. [7] demonstrating that most of the storm enhanced density observed during the Halloween storm existed above about 400 km altitude, based on CHAMP satellite GPS data.

The contour maps are generated by determining a plane at each set of three nearest IPPs and shading the triangle corresponding to the values of that plane. If the nearest IPPs are more than 5 degrees away, however, the region is left blank, as there is insufficient data to indicate what may be occurring in the ionosphere at that region. For this reason, as the satellites and the associated IPPs move, the shaded regions of the map will change shape from figure to figure.

At 22:00 UT (17:00 EST), the primary storm enhanced density (SED) has already passed by eastern CONUS, as seen in red on the lower left of Figure 3. To the immediate east of the boundary of the SED, at 25° N, 85° W, is a region of lower TEC of about 4 m. The delay over Florida is lower than the SED at about 5-6 m, but to the east are observations of a higher 8-9 m delay. These are probably related to the higher TEC measurements in the Caribbean, but there are not enough IPPs to fill in the region between 20-25 N and 70-75 W.

At 23:00 UT (18:00 EST), shown in Figure 4, the region of high TEC has spread from the Caribbean northwest to Florida and the states bordering the Gulf of Mexico. It is still a distinct feature from the SED, because a region of low TEC stretching from east of the Yucatan up to Texas separates the Florida feature from the SED seen in the lower left part of the map.

By 00:00 UT on 31 October (19:00 EST), the SED has moved west almost completely off the map of Figure 5, but the edges of the ionospheric feature of interest are still sampled and still located in the Caribbean. The feature continues to have the same orientation northwest-southeast as before. Also visible in this and the previous plot is evidence of the auroral region of higher TEC stretching from the Great Lakes east to New England, though the auroral delays are only a couple meters higher than the background ionization.

Two hours later at 02:00 UT (21:00 EST) on Figure 6, the aurora has all but disappeared, the background level of

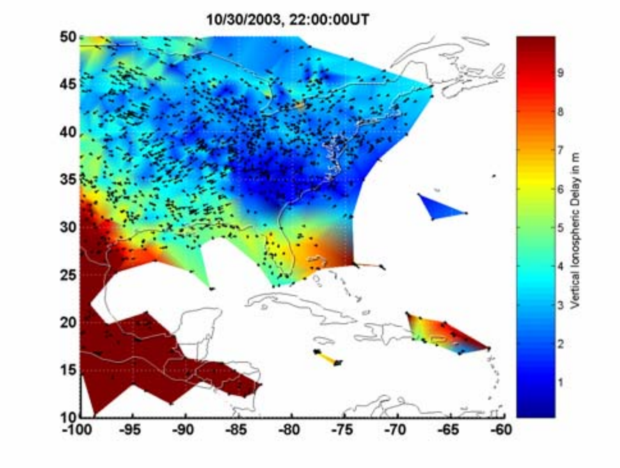

Figure 3: October 30, 22:00 UT (17:00 EST).

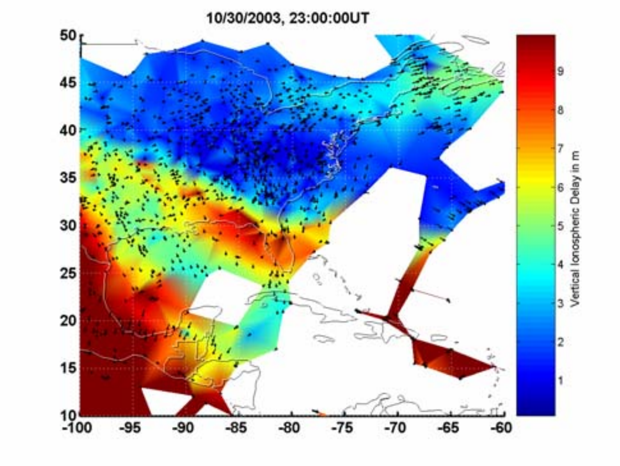

Figure 4: 23:00 UT (18:00 EST).

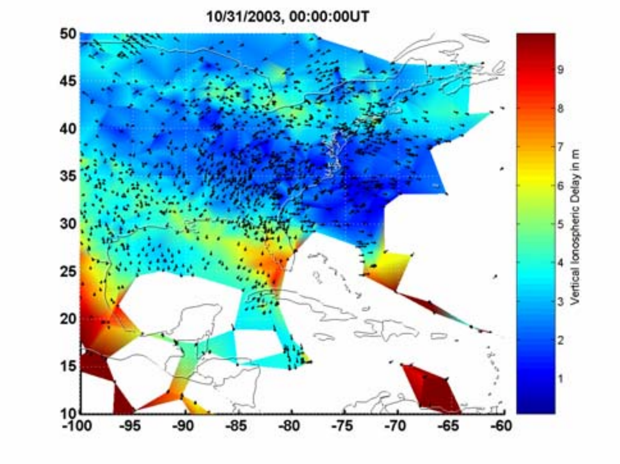

Figure 5: October 31, 00:00 UT (October 30, 19:00 EST).

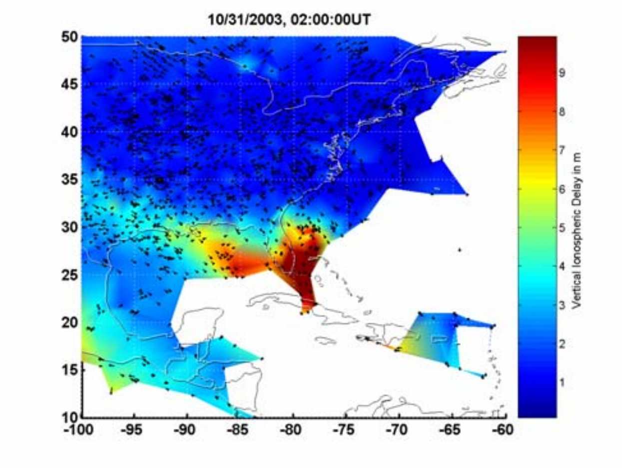

Figure 6: October 31, 02:00 UT (October 30, 21:00 EST).

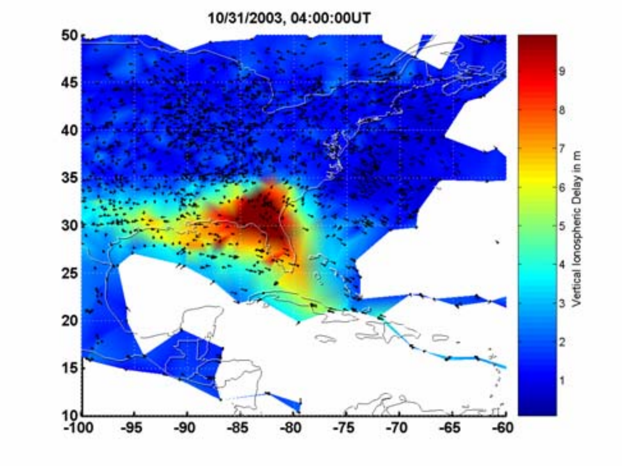

Figure 7: October 31, 04:00 UT (October 30, 23:00 EST).

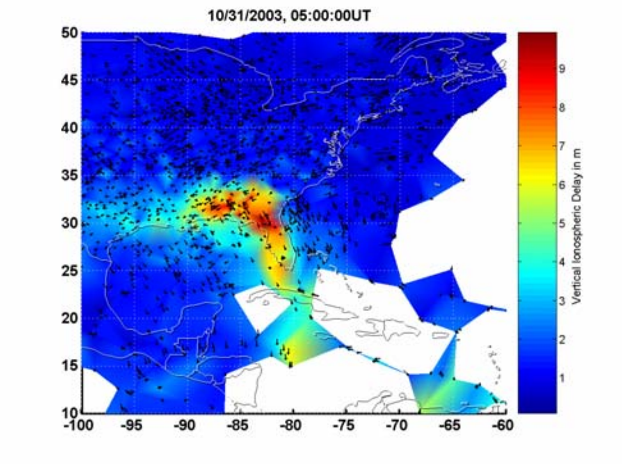

Figure 8: October 31, 05:00 UT (00:00 EST).

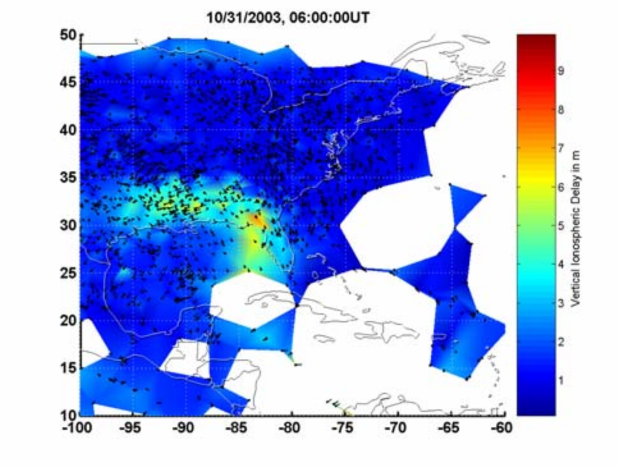

Figure 9: October 31, 06:00 UT (01:00 EST).

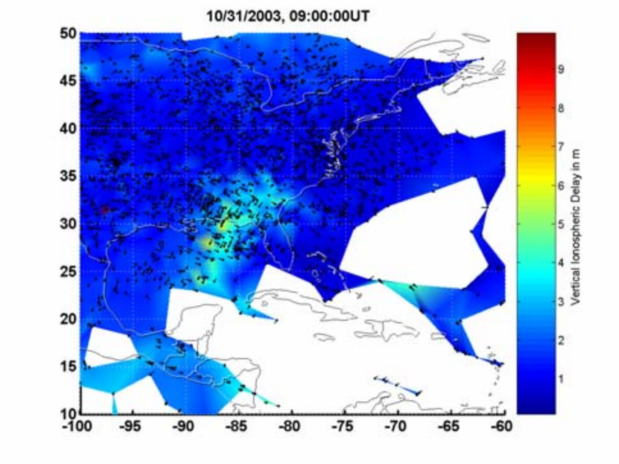

Figure 10: October 31, 09:00 UT (04:00 EST).

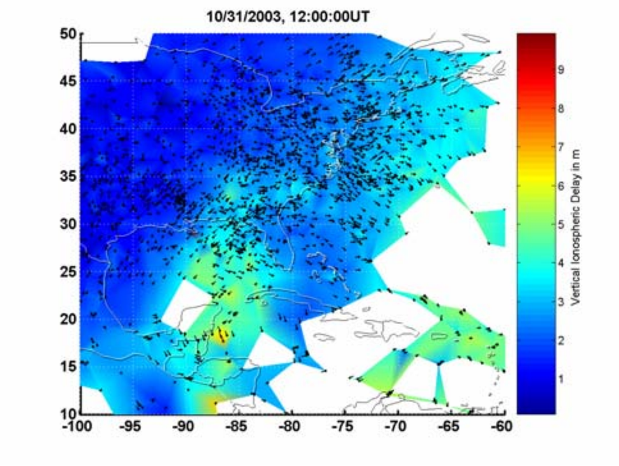

Figure 11: October 31, 12:00 UT (07:00 EST).

nighttime ionization has dropped slightly to about 1 m, and the SED has moved west off the map. However, the feature (red) remains around the tip of Florida. Due to a lack of data over Cuba, how far south and east it extends is not clear, but for the first time, measurements over Puerto Rico and Haiti are only around 3-5 m, indicating that the feature is no longer in that area.

Figure 7 is a map at 04:00 UT (23:00 EST). The sampling near Cuba seems to indicate that the high density "blob" is confined to the Florida-Georgia region. The measurements in the Caribbean are all around 3 m, lending support to the idea that the feature is now localized to a few degrees of latitude and longitude. However, none of the measurements plotted at Cuba are actually taken overhead at Cuba. Instead these measurements are from other sites viewing low elevation satellites. For this reason it is possible that the feature still extends southward but is not being sampled because the available lines of sight pass under the high-TEC region.

Figure 8 corresponds to 05:00 UT (local midnight) and is a more complete version of the map shown in Figure 1. The feature is fading, as the delays associated with it are declining. It is smaller in apparent extent, confined to Florida and the southern parts of Mississippi, Alabama, and Georgia. As with the previous plot, this may be due in part to a lack of GPS ground stations in Cuba. Between Figures 7 and 8, the feature appears to have changed apparent shape a bit, but has not moved noticeably.

In Figure 9, a snapshot of 06:00 UT (01:00 EST), the feature has continued to fade to about 5 m maximum vertical delay compared to the background 1m. It has similar apparent shape to an hour before (Figure 8), but has moved slightly to west of the Florida peninsula. Over the next few hours, the density changes shape a bit more and continues to fade, as seen in Figure 10. However, it does not move out of the Gulf of Mexico area and never fades completely into the background ionization level. In Figure 11, by noon UT (7:00 EST), the feature is still about 5 m in delay and better sampling gives it the appearance of being somewhat larger in spatial extent, stretching south to the Yucatan. It is also distinct spatially from the diurnal rise in TEC due to solar ionizing radiation that is just starting to be detectable in the Atlantic.

In summary, the major observations to be made about the Florida feature, based on the data throughout CONUS, Mexico, and the Caribbean are that: 1) the high density region convects north and west from equatorial latitudes to southeast CONUS (Figures 3-6); 2) the Florida feature is part of a larger structure, at least initially, as seen in the Caribbean data; 3) the earth initially rotates under the high density ionosphere, as seen by the apparent westward motion of the SED; 4) the feature is relatively stationary after reaching southeast CONUS, implying it co-rotates with the earth (Figures 7-11); and 5) the feature persists from 17:00 EST through local midnight to the next day. The TEC gradually decreases throughout the night but does not appear to reach background ionosphere level completely. After it is overtaken by the diurnal TEC rise of the next morning, it is less clear if it is superposed on the diurnal rise or is subsumed by it.

SUPER-FOUNTAIN EFFECT AND L-SHELL

The fact that the feature persists for so long implies that it is recombining extremely slowly. Lower recombination rates occur at higher altitudes of several hundred kilometers, which would require ionospheric uplift of the Florida feature. Based on its initial similarity in orientation and convection to the main daytime SED, we suspect that the Florida feature was initially produced by a similar mechanism to that of the daytime enhancement.

Mannucci et al. showed that the dayside ionospheric response of the Halloween Storm at mid-latitudes was not only enhanced total electron content, but an overall uplift of the bulk of ionization to altitudes above 400 km [7]. In their study of the SED region shown in the lower left of Figures 3-5, Mannucci et al. use the CHAMP satellite's onboard GPS receiver to measure the electron content between CHAMP orbiting at 400 km and the GPS constellation at 20,000 km. As CHAMP passes through the main SED of the storm, most of the TEC seen from a nearby ground station is seen from CHAMP as well. This implies that almost all of the TEC is above CHAMP orbit, beyond about 400 km at magnetic mid-latitudes. Mannucci ascribes this to the "super-fountain effect" explained by Tsurutani [10].

The fountain effect is a well-known daily occurrence in which the existence of an electric field in the daytime equatorial region superposed with the northward-pointing geomagnetic field yields an upward plasma ExB drift to higher altitudes on the day side. After uplift, the plasma then drifts down along field lines to lower altitudes, usually peaking in density at +/-20 degrees magnetic latitude as the equatorial anomaly.

Tsurutani explains the "super-fountain" as uplift caused by an unusually large electric field, induced by interactions of the IMF with the earth's magnetic field, possibly through magnetic reconnection. Even higher uplift will take plasma to a higher L-shell such that recombination happens very slowly and the plasma drifts north and south along field lines to produce TEC enhancements at mid-latitudes.

For an idea of the order of magnitude of the uplift required at the equator to place plasma at 400 km altitude at Florida's magnetic latitude of 40 degrees, we do a very simple L-shell calculation. The L-shell is the distance in earth radii to which the plasma was uplifted at the magnetic equator; all points along a single magnetic field line will have the same L value. The equation for an earth centered dipole magnetic field line is:

$$r = LR_E \cos^2 \lambda_m \qquad \textbf{Equation 1}$$

where r is the distance from the center of the earth to any point along a single field line, R_E is the radius of the earth, λ_m is the magnetic latitude of the point on the field line, and L is the distance to the field line at the equator, in units of earth radii. Using the fact that Florida is at magnetic latitude $\lambda_m = 40$ degrees, where plasma is at least as high as $r = R_E + 400$ km from the center of the earth and $R_E = 6370$ km, we solve for L to find L = 1.83. This implies that the plasma, if it were simply drifting along field lines, would have needed to be lifted up to an altitude of $0.83R_E = 5300$ km at the equator in order to arrive at an altitude of 400 km at magnetic latitude 40 degrees!

This is an extremely high altitude and is meant to be an order of magnitude calculation. In such dynamic conditions a steady-state dipole field is of course unrealistic. Even an off-centered dipole field that better models the South Atlantic Anomaly would not yield an L value sufficiently low. Before using data to demonstrate that plasma is not in fact lifted up this high, we consider briefly the feasibility of such uplift. The ionized region occurring at greater than 1000 km altitude is known as the plasmasphere and is typically dominated by hydrogen ions, unlike the topside ionosphere where oxygen ionization plays a major role in recombination rates. One possible way of inferring the altitude of the Florida feature and additionally computing recombination rates (beyond the scope of this paper) would be to find the hydrogen and oxygen concentrations at this time and compare them to the rate of "fading" or recombination observed in Figures 3-11. We choose an alternate method, using JASON satellite data, in the next section.

A paper written by Hanson and Moffett in the early stages of ionospheric research demonstrated that uplift need not be so high if there exists an electric field at midlatitudes [4]. E x B drift again plays a role after the initial uplift in transporting plasma further away from the equator than simple drift along field lines. The Florida feature may be evidence of an E field existing at mid-latitudes but further investigation of an electric field is also beyond the scope of this paper.

ALTITUDE CONSTRAINT WITH JASON DATA

In previous sections we used a large number of dual-frequency GPS receivers to illustrate the horizontal extent and motion of the Florida feature. In this section we will use JASON satellite data to provide an upper bound on the altitude of the Florida feature. This will demonstrate that ionospheric uplift was not several thousand kilometers, but several hundred.

Previous work [7] showed uplift of the daytime TEC enhancement to higher than 400 km. Based on the initial similarity of the Florida feature's source (equatorial) and motion (northwest) to the daytime TEC enhancement, we suspect it is also above 400 km at least initially. JASON data will demonstrate that it is located under 1300 km.

JASON is a satellite designed to use an altimeter (at C- and Ku- bands) to measure sea surface height. It orbits at an altitude of about 1330 km, repeating its ground track every 10 days. One of the sources of error corrected for in this sea surface measurement is the delay due to the ionosphere as the radar signal makes its way roundtrip from 1300 km to the ground. Data provided by Patricia Doherty and Bonnie Delay at the Boston College Institute for Scientific Research includes the latitude and longitude of the satellite, and the ionospheric correction, in TEC units (TECU). About 6.13 TECU correspond to 1 m of delay at L1 frequency.

Figure 12 shows the JASON satellite ground track in black, from about 20:10-20:50 UT on 30 October. The satellite traverses from high latitude to low latitude, and the gap in the track occurs at a period when there is no TEC data available. Though this track is nowhere near Florida, it is close in geography and time to the CHAMP data tracks analyzed in [7], and both together give the tightest altitude constraints on the location of the enhanced TEC.

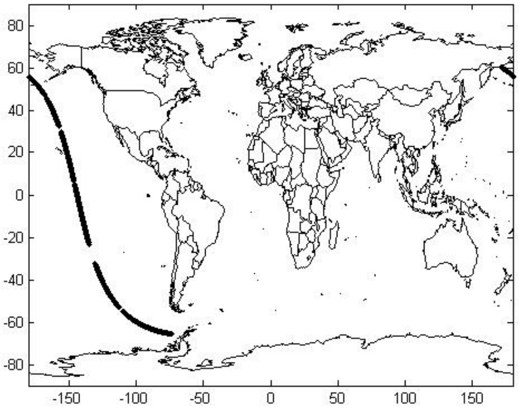

Figure 12: Ground track of JASON satellite from 20:05-20:55 UT on 30 October 2003.

The vertical total electron content measured in TECU by JASON along this ground track is plotted against dipole magnetic latitude in Figure 13. Since the satellite is passing from high latitude to low, time increases from right to left on this plot. The peaks at 20 degrees magnetic latitude correspond to the equatorial anomaly. The asymmetry and enhancement of the southern peak is evidence of the disturbed ionospheric activity at this time.

This JASON track passes within a few hundred kilometers of Hawaii. At 20:20 UT, JASON reaches its point of closest approach, at 570 km away. At that time, the WAAS network station at Honolulu measured 102.3 TECU slant along a line of sight at 80 degrees elevation. The JASON measurement at this time is about 117 TECU, and occurs north of the northern anomaly peak shown in Figure 13. A JASON measurement of TEC must be less than or equal to that of a colocated ground station. In this case the JASON measurement exceeds the ground measurement by 15 TECU. This may be due to a bias between the JASON data and GPS data. Even if there were no biases though and the difference were due only to the spatial variation of the ionosphere, the difference in delay over that distance would correspond to a gradient of 4 mm/km, which is nominal in the ionosphere. The fact that the GPS measurement is along a slant path introduces an error of only a couple TECU because the GPS satellite it is very nearly overhead in Honolulu.

If the ground station measurement of TEC were much greater than the JASON measurement, it would indicate that some of the TEC was above the JASON orbital altitude. The fact that the measurements are within a few percent of each other indicates that nearly all of the TEC is accounted for under 1300 km. Together with the constraint shown in [7], we conclude that the TEC is located between 400 and 1300 km.

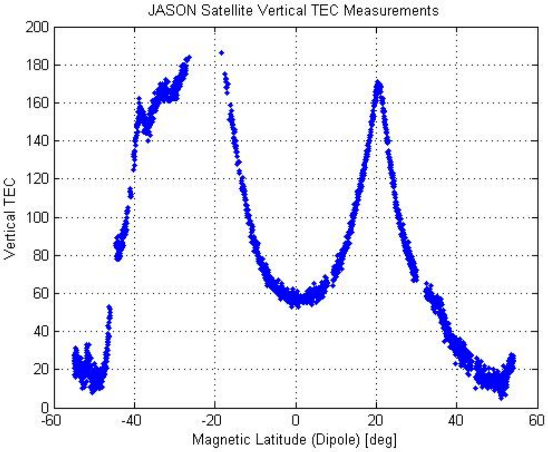

Figure 13: JASON satellite vertical TEC measurements in TECU as a function of dipole magnetic latitude. Time increases from right to left.

JASON later passes over the Gulf of Mexico at local midnight, when the Florida feature is as illustrated in Figure 8. The ground track is shown in Figure 14; the satellite passes from south to north. The TECU measurements during this time are shown in Figure 15. The multiple gaps in the data occur when the satellite passes over land, where its radar altimeter measurements are not reflected. For most of the pass through the northern magnetic latitudes, the TEC is under 30 TECU, or 5 m. However, a spike occurs around 30-35 degrees magnetic north. The peak value of 71 TECU, or 11.6 m, recorded by JASON occurs at geographic latitude and longitude (25 N, 82 W). On the map in Figure 14 and Figure 8, this location is in the Gulf of Mexico west of Miami. Again, this is a meter or two higher than the ground station delay measurements shown in Figure 8, but may be accounted for by differences in measurement location and biases between the data sets. The fact that the measurements rise consistently indicate that the JASON data is not providing spurious data, but is tracing a real TEC enhancement. The measurements end abruptly as the satellite passes over Florida.

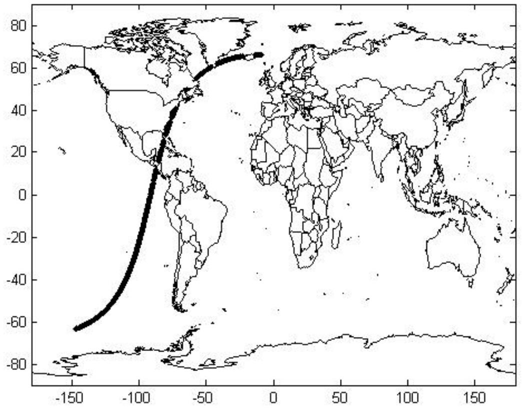

Figure 14: Ground track of JASON satellite from 04:30 – 05:20 UT on 31 October 2003.

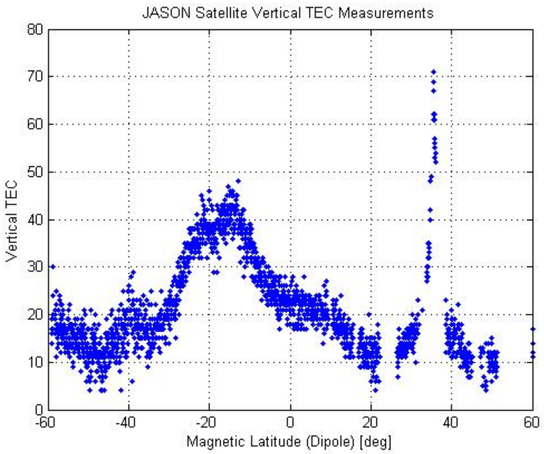

Figure 15: JASON satellite vertical TEC measurements in TECU as a function of dipole magnetic latitude. Time increases from left to right.

From the JASON vertical measurements of ionosphere, we conclude that the Florida feature at local midnight is below 1300 km, as was the daytime TEC enhancement. This is consistent with other findings that the daytime TEC enhancement is above 400 km [7]. It is also consistent with a “super-fountain effect” if there are additional E-field mechanisms that push plasma poleward more than simple drift along field lines can do. However, the super-fountain does not predict the co-rotation of the Florida feature that was observed in Figures 7-11.

OBSERVATIONS DURING OTHER STORMS

In this section we show GPS dual-frequency data of the ionospheric delay over CONUS from CORS and IGS stations in order to provide a preliminary answer to the question of whether such an event can happen at any place at any time.

Using the CORS/IGS stations in CONUS and Mexico, the WAAS network, and the Caribbean CANAPE network, we generate contour maps of the delay at L1 for the night of 29-30 October. This is the local night before the night that the Florida feature occurs. These plots are shown in Figures 16-19, at UT 02:00, 04:00, 06:00, and 08:00, respectively, on the 30th.

At 02:00 UT (October 29, 20:00 Central Standard Time CST) as shown in Figure 16, there appear to be two high-density 10 m delay regions oriented WNW-ESE, separated by a lower 7 m region. The northern one, over Texas and the Gulf of Mexico, will persist for several more hours, much as the Florida feature does the subsequent night. The southern enhanced region continues to move west out of view, similar to the primary daytime TEC enhancement that the earth rotates out from underneath from.

Two hours later at 04:00 UT (October 29, 22:00 CST), on Figure 17, the low-delay region between the storm’s main TEC enhancement and the localized feature has become even more pronounced by decreasing to only 4 m. By 06:00 UT (midnight CST) the feature of interest extends from the Gulf to southern California, but is narrow, confined to only a few degrees latitude (Figure 18). The main daytime TEC enhancement by this point has moved west out of CONUS view, except for the few southernmost measurements.

The “filament” extending WNW from the Gulf of Mexico gradually fades over the next couple of hours such that by 08:00 UT (02:00 CST), it causes a delay of only 4 m, compared to a background of 1 m, as seen in Figure 19. Later maps (not shown) indicate that by the time the daytime TEC rise occurs at this region, this feature has faded completely into background, unlike the subsequent night’s Florida enhancement (as in Figure 11).

The night of the 29th-30th shows a feature similar in magnitude of delay, at a location several degrees west of, geographically larger, occurring later in the local day, and of shorter duration than the Florida feature. On the other hand, the feature is still near the Gulf of Mexico, occurs at

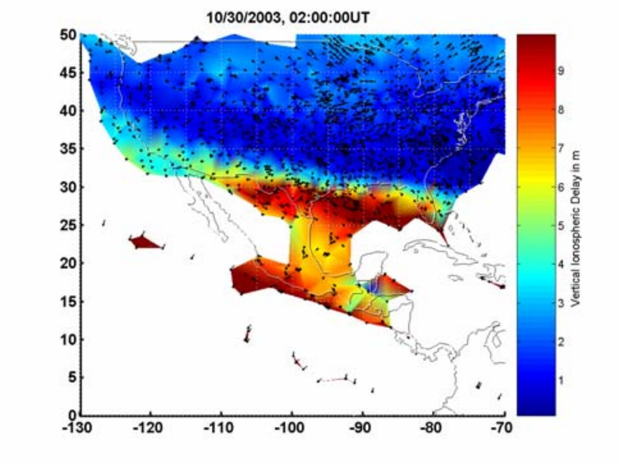

Figure 16: October 30, 2003, 02:00 UT (October 29, 20:00 CST).

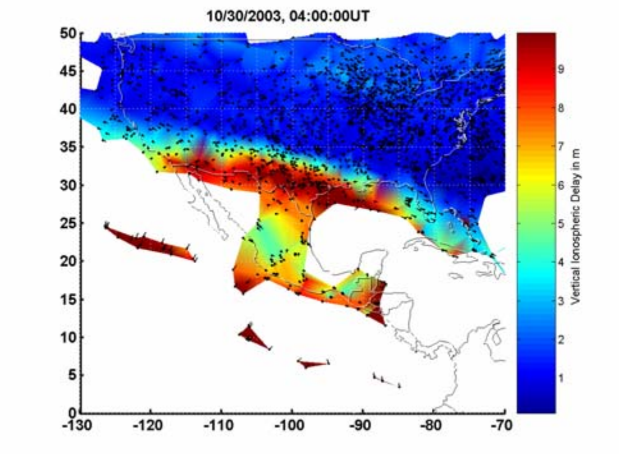

Figure 17: October 30, 2003, 04:00 UT (October 29, 22:00 CST).

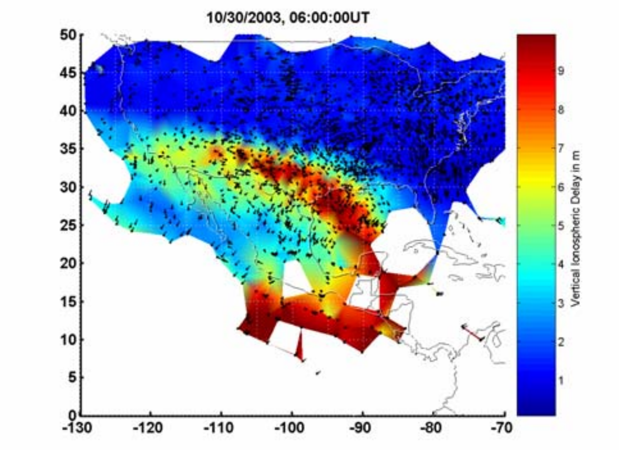

Figure 18: October 30, 2003, 06:00 UT (00:00 CST).

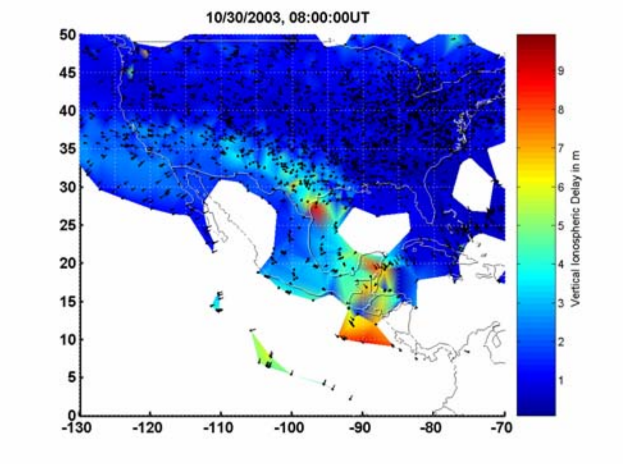

Figure 19: October 30, 2003, 08:00 UT (02:00 CST).

the same time as the Florida feature to within a couple hours, and lasts significantly longer than the time for the mid-latitude ionosphere as a whole to recombine at nighttime. It is not exactly the same as, but similar to the Florida feature.

The Halloween Storm of 2003 is also not the only storm to display a localized TEC enhancement over the southeastern U.S. Figure 20 is a plot of the equivalent vertical delay at L1 on the night of April 6-7, 2000, during which another of the most severe storms of the same solar cycle occurred. At 08:00 UT (03:00 EST) on 7 April 2000, a localized region of enhanced TEC of about 8-9 m is visible above, south, and west of Florida. The background ionization of this feature is different however. While the northern CONUS ionization level is around 1 m of delay, the southern region of CONUS is in the 4-6 m range. This feature is not so prominent against the background because the background level is higher. In addition, the evolution prior to this configuration of the ionosphere may be different, based on maps generated at 10-minute intervals throughout the night (not shown).

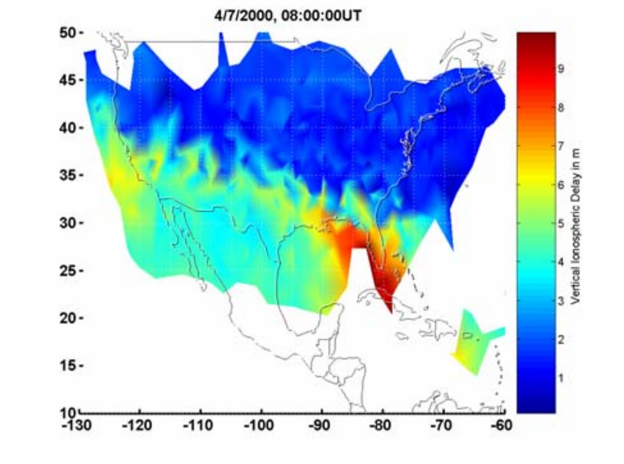

Figure 20: April 7, 2000, 08:00 UT (04:00 EDT).

As another illustration, a map of equivalent vertical TEC during the night of 15-16 July 2000, also known as the "Bastille Day Storm," is shown for 03:30 UT on the 16th. In a similar location and orientation – west of Florida, aligned northwest-southeast – another TEC enhancement of about 10 m is visible. Finally, Dehel [2] shows a plot by Makela for 03:00 UT on 17 July 2004, that looks generally similar to Figure 4, although smaller in overall magnitude. During this period a minor geomagnetic storm occurred that had minimal effect on WAAS performance, unlike all of the days shown in this paper, for which LPV service availability was 0. On July 17th, 2004, there was a 7-m enhancement extending southeast and northwest from Georgia that was separated from the main daytime TEC enhancement by a small region of 1-2 m delay to the west.

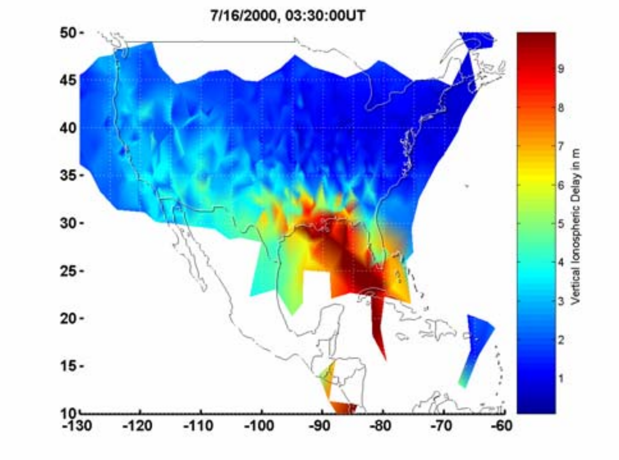

Figure 21: July 16, 2000, 03:30 UT (July 15, 2000, 23:30 EDT).

CONCLUSIONS

The FAA Wide Area Augmentation System (WAAS) network sampled a highly localized enhancement in TEC over Florida on the night of 30-31 October 2003. This paper was an investigation into the spatial and temporal extent of the feature, and a preliminary look at its frequency of occurrence. Combining CORS/IGS, WAAS, and CANAPE dual-frequency GPS network data in the southeastern U.S., Mexico, and the Caribbean, this "Florida feature" is observed to begin as part of a larger structure coming north and west from the equatorial region at local dusk. After convecting separately from the main daytime TEC enhancement, the feature then appears to be confined to a geographic region about the size of Florida, although this may be due to a lack of sampling in Cuba. During this time it co-rotates over Florida and the eastern Gulf of Mexico and gradually dissipates. However, it does not appear to recombine to background ionization levels by the time of the daily TEC rise next day.

Using JASON satellite data measurements of the electron content between the sea surface and 1300 km altitude, we constrained the altitude of the majority of the electrons of the Florida feature to be lie below 1300 km. Taken together with other research [7], the Florida feature, if generated by the same mechanism as the main daytime TEC enhancement, also lies above 400 km altitude, at least initially. Even though plasmaspheric processes involving hydrogen ions occur as low as 1000 km, the bound of the JASON satellite data may be evidence that oxygen is likely the dominant ion in the Florida feature's evolution.

The "super-fountain effect" is a plausible mechanism for this amount of uplift if there are mid-latitude electric fields and/or compression of the geomagnetic field to allow plasma to reach mid-latitudes without being uplifted to L=1.83. However, the super-fountain effect does not explain the late night co-rotation of the Florida feature. Additional sources [1, 6] indicate that the region may be a medium-scale traveling ionospheric disturbance (MSTID), initially at least, but again, this description does not include co-rotation.

Evidence from the previous night of the Halloween storm and from other storms exists to suggest that the Florida feature is not an isolated incident or statistical fluke. We showed GPS dual-frequency data early on UT dates 30 October 2003, 7 April 2000, and 16 July 2000 that indicate that the feature may occur on other active dates during local evening in the southeastern U.S. Moreover, the evidence of [2] suggests that such a feature may occur on less severely disturbed nights. However, the exact time, location, and evolution of each of these cases varies. The consistency of geographic location suggests that the feature may be causally linked to the South Atlantic Anomaly.

Future work in both data analysis and modeling will help further illuminate this phenomenon. Airglow measurements may be used to test the MSTID concept. Ion flux measurements may be used to compare O^+ and H^+ concentrations at this time to identify whether the plasmasphere plays a role or whether the topside ionosphere is the main source of enhancement. Modeling of the mid-latitude E and B fields in a manner similar to Hanson and Moffett [4] would provide insight into the TEC uplift and drift if the super-fountain effect is the driving process.

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