Assessment of Nominal Ionosphere Spatial Decorrelation for LAAS

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***Abstract*—The Local Area Augmentation System (LAAS) is a ground-based differential GPS system being developed to support aircraft precision approach and landing navigation with guaranteed integrity. To quantitatively evaluate navigation integrity, an aircraft computes vertical and lateral protection levels as position-error bounds using integrity parameters broadcast by a nearby LAAS Ground Facility (LGF). These parameters include a standard deviation of ionosphere spatial decorrelation because the range errors introduced by the ionosphere vary between LGF receivers and LAAS users. Thus, it is necessary to estimate typical ionosphere gradients for nominal days and to determine an appropriate upper bound to sufficiently cover the differential error due to the ionosphere spatial decorrelation.**

In this paper, both Station-Pair and Time-Step methods are used to assess the standard deviation of vertical (or zenith) ionosphere gradients (σ_{vig}). The Station-Pair method compares the simultaneous zenith delays from two different reference stations to a single satellite and observes the difference in delay across the known ionosphere pierce point (IPP) separation. Because most of these IPP separations are larger than 100 km, the Time-Step method is also used to better understand ionosphere gradients at LAAS-applicable distance scales (10 – 40 km). The Time-Step method compares the ionospheric delay of a single line-of-sight (LOS) at one epoch with the delay for the same LOS at the other epoch a short time (seconds or minutes) later. This method has the advantage of removing inter-frequency bias (IFB) calibration errors on different satellites and receivers while possibly introducing an estimation error due to temporal ionosphere gradients.

This paper shows results from analyzing the post-processed ionosphere database for the Wide Area Augmentation System (WAAS), known as "supertruth", as well as JPL post-processed data from the Continuously Operating Reference Stations (CORS) database. CORS data is adequate for the Station-Pair method because of the relatively dense CORS receiver network. However, WAAS data is of higher quality since each reference station has three high-quality receivers that aid in removing measurement outliers and reducing noise. The results of this study demonstrate that typical values of σ_{vig} are on the order of 1 – 3 mm/km for non-stormy ionosphere conditions. As a result, a broadcast σ_{vig} of 4 mm/km is conservative enough to bound ionosphere spatial decorrelation for nominal days with margin for more active days and for non-Gaussian tail behavior. Future work will attempt to better resolve the details of nominal ionosphere behavior over short distances as well as determine if the broadcast "bounding value" of σ_{vig} can be reduced prior to LAAS commissioning.

I. Introduction

The ionosphere, a region of charged particles in Earth's upper atmosphere (roughly from 200 to 1500 km altitude), produces the largest range measurement errors for standalone GPS Standard Positioning Service (SPS) users. Under normal or "quiet" conditions, the ionosphere delays L1 pseudorange measurements by several meters and advances L1 carrier-phase measurements by an equal amount. However, under active ionosphere conditions, such as daytime during the peak of the 11-year solar cycle that governs ionosphere activity, ionosphere delays can reach 30 – 50 meters or more. Ionosphere activity and the resulting GPS impacts vary with location, time of day, and time of season in addition to the 11-year solar cycle, which last peaked in 2000-1 and will reach another peak in 2011-12 [1].

Because LAAS users apply differential corrections from nearby reference stations, almost all user ionosphere error is removed when differential corrections are applied because the reference station "sees" almost the same ionosphere delay. The residual error that remains is due to spatial and temporal decorrelation between reference and user. While spatial decorrelation, the larger of the two, is almost always very small (less than 10 cm), it can become significant under active ionosphere corrections; thus it is taken into account in the user calculation of Vertical Protection Level (VPL) via the broadcast of a $\sigma_{vertical\_ionosphere\_gradient}$ or σ_{vig} parameter that expresses the typical one-sigma variation in ionosphere delay per kilometer of user-to-reference separation (the units of σ_{vig} in the LAAS ICD [2] are m/m, but the number is most easily expressed in terms of mm/km). Because ionosphere delay varies according to the ionosphere obliquity factor, which varies with satellite elevation from 1.0 at 90^o to just over 3.0 at 5^o, σ_{vig} must be broadcast in terms of "vertical" or "zenith" ionosphere delay gradient, which allows each user to multiply by the obliquity factor to find the actual "slant" delay gradient for each approved satellite in view [3].

The goal of this research is to identify the value of σ_{vig} that should be broadcast by Conterminous United States (CONUS) LAAS stations. Previous work by Stanford using early WAAS data suggests that a typical value of σ_{vig} in

CONUS is about 1 mm/km. Separately, recent work by Peter Kolb also produces an estimate of 1 mm/km for σ_{vig} [4]. Thus, the "typical" one-sigma gradient is already well established, but LAAS must broadcast a larger number because it needs to bound ionosphere error under all but the most severe, stormy ionosphere conditions. Because LAAS cannot distinguish typical "quiet" conditions from "active" (but not stormy) conditions in real time, it needs to broadcast a value for σ_{vig} that bounds all such ionosphere states as opposed to only "quiet" conditions.

This paper fills the gap between the known sigma for quiet conditions and the extensive research that has been conducted to model extreme or anomalous conditions that cannot easily be bounded by VPL (e.g., see [5]). Section II describes the post-processed reference-station data that was used. Section III explains both the "Station-Pair" and "Time-Step" methods used to analyze this data. Section IV presents results for both methods using WAAS "supertruth" data. Section V explains how excess noise and bias errors in post-processed CORS station measurements are removed to the extent possible, and Section VI presents results using CORS data after noise and bias correction. Section VII concludes the paper with the recommendation that σ_{vig} = 4 mm/km (or 4 times the value for "quiet" conditions) be broadcast by LAAS stations when initially fielded. Additional short-baseline data collected from multiple LAAS stations will hopefully allow us to reduce this value in the future.

II. Data

The data used to estimate nominal ionosphere spatial gradients are of two types: WAAS post-processed network data (known as "supertruth") and data from the Continuously Operating Reference Stations (CORS) post-processed by JPL.

A. WAAS "Supertruth" Data

The WAAS network consists of 75 WAAS Reference Element (WRE) receivers located at 25 reference stations (i.e., each station has three nearly co-located dual-frequency receivers). To generate high precision ionospheric TEC data, the carrier phase measurements collected from the 75 receivers are first cleaned by identifying cycle slips. Carrier-phase-based ionospheric delay measurements (generated from carrier-phase measurements on both the L1 and L2 frequencies) are then leveled by computing the average of code-minus-carrier ionospheric observables. Using the very-precise leveled ionospheric measurements, a Kalman filter solves for instrument biases. Satellite and receiver inter-frequency biases are removed from the leveled carrier-phase ionospheric observables to obtain (almost) unbiased phase-leveled ionospheric TEC observables. The corrected data sets are then passed through a voting algorithm to select one of three measurements (from three co-located receivers) as the ground "truth". The final output of this process is the "supertruth" data: high-precision estimates of ionospheric delay.

The WAAS "supertruth" data is less noisy than the JPL post-processed CORS data because of the high-quality receivers and antennas with the same firmware versions and the voting scheme explained above. However, the limited number of stations results in larger separations between stations (typically at least several hundred kilometers), which makes it difficult to observe ionospheric behavior at LAAS-applicable distance scales (several tens of kilometers or less).

B. JPL Post-Processed CORS Data

GPS measurements collected from a network of Continuously Operating Reference Stations (CORS) (more than 400 stations over CONUS) are made available to the public via the U.S National Geodetic Survey website [6]. Using CORS data, high-precision ionospheric measurements were generated at JPL using "truth processing" methods similar to those described in Section A. The detailed algorithm was described by Komjathy, Sparks and Mannucci [7], and the processing summary is as follows. Raw data from RINEX files was processed using the NASA's GPS-Inferred Positioning System (GIPSY) module Sanity Edit (SanEdit) to detect cycle slips [8]. The cycle-slip criterion was set at 18 cm, which requires the assumption that ionospheric variation is not rapid during nominal days. A tighter slip parameter may degrade data accuracy because the accuracy of leveling depends highly on the length of continuous arcs of data [7]. The carrier-phase-based ionospheric measurements were then leveled using the code ionospheric observables and an elevation-dependent weighting function [7]. The satellite and receiver inter-frequency biases were then estimated using GIPSY and the JPL's Global Ionosphere Mapping (GIM) software and corrected to the degree possible to provide high precision ionospheric measurements.

The noise level of JPL CORS data is about one order of magnitude higher than that of WAAS "Supertruth" data. This is mainly due to the fact that CORS receivers and antennas coming in all shapes, forms and levels of quality. However, the dense CORS network, with more than 400 stations in CONUS, allows the examination of ionosphere characteristics at smaller scales. Therefore, if the higher noise of CORS measurements can be reduced effectively (as will be discussed in Section IV), CORS data may be more useful for this study than WAAS data

C. Data Sets

The analysis described in this paper was carried out using data from eight days listed in Table 1. The data of ionospheric nominal days was chosen from the WAAS "supertruth" archive to include all nominal and ionosphere active days that were not classified as "ionosphere storm" days. Table 1 shows the geomagnetic storm class, Kp index, Dst index, and WAAS coverage of each day. The Kp and Dst (direct) indices are measures of the magnetic perturbation of the Earth's atmosphere. For example, the absolute value of the Dst index was larger than 400 during the 20 November 2003 ionosphere storm, whereas absolute values of the Dst index on nominal days are almost always below 40. Geomagnetic storm class has been defined based on Kp indices. By design, the days listed in Table 1 cover all storm classes except those which produce ionosphere gradients within the ionosphere anomaly threat model (i.e., spatial gradients greater than 30mm/km [5]).

WAAS coverage indicates the percentage of the WAAS coverage volume in which the WAAS LPV service was available at least 95 percent of the time. This study was initially conducted on six days for which the WAAS coverage was better than 90 percent. Two more days (shaded in Table 1) were added later to examine the sensitivity of ionosphere gradients to WAAS LPV availability (the details will be discussed in Section VI.B).

TABLE I
DATA SET

	Geomagnetic Storm Class	K_P	D_{ST}	WAAS Coverage
2 July 2000	N/A ("quiet" day)	1.7	2	Nominal (≥ 99%)
11 Sept. 2002	Moderate	5.0	– 78	~ 95%
25 July 2004	Strong	8.0	– 148	~ 73.7%
26 July 2004	Strong	7.3	– 94	~ 96.4%
27 July 2004	Severe	8.7	– 197	~ 96.4%
22 Aug. 2004	N/A ("quiet" day)	3.3	– 37	~ 24.7%
9 Nov. 2004	Severe	8.7	– 223	~ 96%
10 Nov. 2004	Severe	8.7	– 289	~ 96.4%

III. Estimation Method

Ionosphere spatial gradients were estimated using the following three methods based on different configurations of stations and satellites.

A. Station Pair Method

The Station-Pair method considers each pair of stations as the LGF-aircraft receiver pair. Each pairs are configured to view the same satellite. For each epoch the ionosphere vertical delays at each of two stations are differenced. The ionosphere can be approximated with the thin shell model, where the entire ionosphere is assumed as a shell of finite thickness with the condensed TEC and to be located at an altitude of approximately 350 km as shown in Figure 1. The point where a LOS and this thin shell ionosphere intersect is defined as the Ionospheric Pierce Point (IPP). The differential delays are then divided by the IPP distance between the stations to compute the vertical ionosphere gradient. Because two stations viewing the same satellite is paired, the satellite Inter-Frequency Bias (IFB) calibration error is canceled out when differencing the vertical delays. However, the receiver IFB calibration error may still be remaining. The IPP distance of the Station-Pair method depends on the physical separation of stations. Therefore the CORS data collected from the dense stations is adequate to measure the gradients at the short distance when used with this method.

B. Mixed Pair Method

The Mixed-Pair method considers all possible configurations including the two station pairs viewing the same satellite, one station viewing the two satellite pairs, and the two station pairs viewing the two different satellites. This method allows estimating the ionosphere gradients at both short and long baselines. However, the estimates would not be free from both satellite and receiver IFB calibration errors.

C. Time Step Method

The Time-Step method was introduced to gain sufficient sampling at distances less than the physical separation of stations [9]. This method configures a single satellite and a single receiver as a pair. The ionosphere delay between the satellite and receiver at one epoch (T_1) is compared with the delay for the same pair at a later epoch (T_2). The gradient is then computed by dividing the differential delay with the distance between the IPP at T_1 and the IPP at T_2. With this configuration, therefore, the spatial separation of interest (i.e. short distances for the LAAS application) can be obtained by adjusting the time interval (Δt).

This approach shows less architectural resemblance to the LAAS LGF-aircraft scenario than the "Station-Pair" configuration, and thus it may not be intuitive to connect this method to the LAAS application. Nonetheless, this configuration captures the same ionospheric effect as an LGF receiver and an aircraft receiver whose Line-of-Sights (LOS) to a satellite penetrate neighboring regions of the ionosphere.

When differentiating the delays of the same satellite and receiver pair, both the satellite and receiver IFB calibration errors are eliminated. However, the Time-Step method introduces another error source: the temporal decorrelation error. Since the delays of different epochs are used to estimate the ionosphere spatial decorrelation, the estimated gradients would be a mixture of the spatial gradient and the temporal gradient (which cannot be extracted easily from the total gradient estimates).

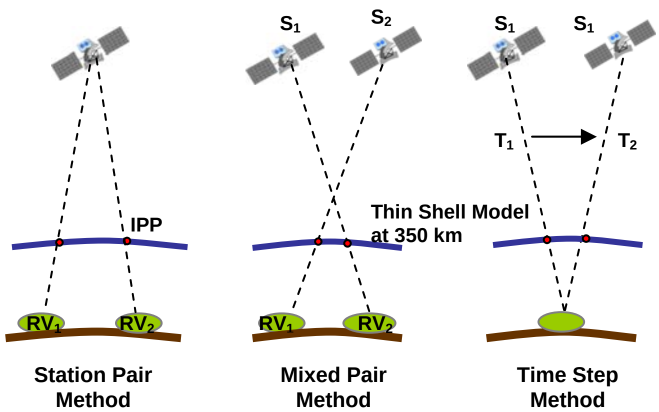

Fig. 1. Satellite and Receiver Configuration for Station-Pair Method, Mixed-Pair Method and Time-Step Method.

IV. ESTIMATION RESULTS

A. *Results from Station Pair Method*

Figure 2 shows the result for a "Quiet" day (July 2, 2000), which exhibited nominal ionospheric behavior, using the Station-Pair method and the WAAS "Supertruth" data. The two-dimensional histogram of the number of observations is shown as a function of both the IPP separation distance and the difference in the vertical ionosphere delay ($dI_{vertical}$). The horizontal axis divides the IPP separation distances into bins, the vertical axis divides observations of the difference in vertical delay into bins, and the color of each pixel indicates the number of measurements counted. Although there was no data for distances less than 50 km, the fairly smooth and linear behavior was observed at distances between 100 km to 1000 km. The differential delays were divided by the corresponding separation distances to obtain the vertical ionosphere gradients.

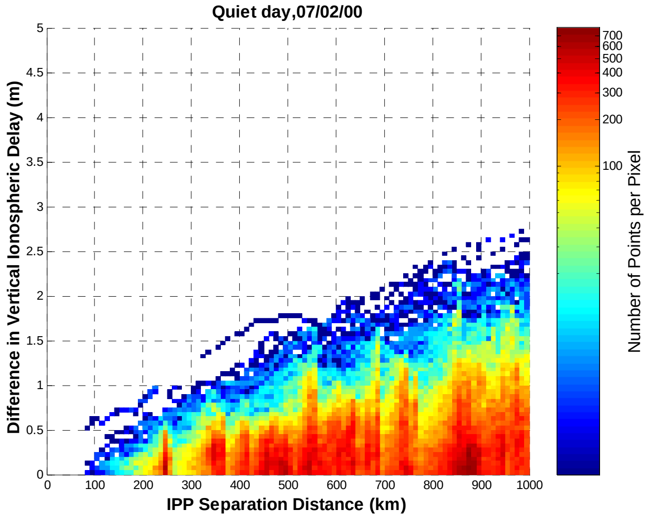

Fig. 2. Differential Vertical Ionosphere Delays Results on a "Quiet" day from Station Pair Method and WAAS "Supertruth" Data.

The distribution of normalized vertical ionosphere gradients is shown in Figure 3 on a logarithmic scale. It is clear that the distribution (the dotted curve), derived from the observations shown in Figure 2, has non-Gaussian tails. Since the LAAS users assume a zero-mean normally distributed error model in the computation of protection levels, the nominal sigma (1σ) of a zero-mean Gaussian distribution – shown as the dashed curve – should be inflated to cover the non-Gaussian tails of the actual distribution. The inflation factor needed for July 2, 2000 was 1.42. The 1.42σ Gaussian distribution (the solid curve) well overbounds the empirical distribution (the dotted curve).

Figure 4 shows the "σ_{vig} overbound" result for a quiet day (July 2, 2000). The overbounding method is as follows. First, the vertical ionosphere gradients were divided into bins of the IPP separation distance. Second, the mean (μ_{vig}) and standard deviation (σ_{vig}) of vertical ionosphere gradients in each bin were computed, interpolated at each distance corresponding to each gradient, and used to normalize the gradients. Based on the distribution of normalized ionosphere gradients, the inflation factor (f) was then determined as shown in Figure 3. Lastly, the "σ_{vig} overbound" was computed as $|\mu_{vig}| + f\sigma_{vig}$ for each bin. The estimated "σ_{vig} overbounds" (the pink curve) are less than 2mm/km and the one sigma values (the red curve) are just below 1mm/km at distances greater than 200 km. The estimates at distances less than 200 km cannot be trusted because the number of samples is not sufficient to obtain reliable statistics of vertical ionosphere gradients.

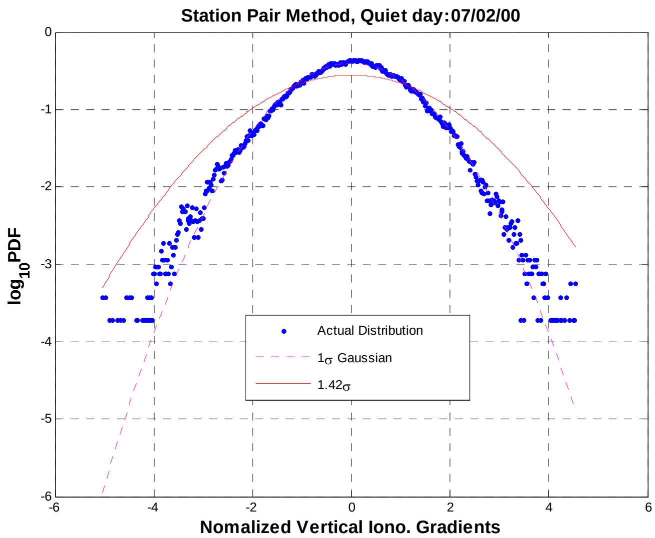

Fig. 3. Probability Density Function of Normalized Vertical Ionosphere Gradients on a "Quiet" Day.

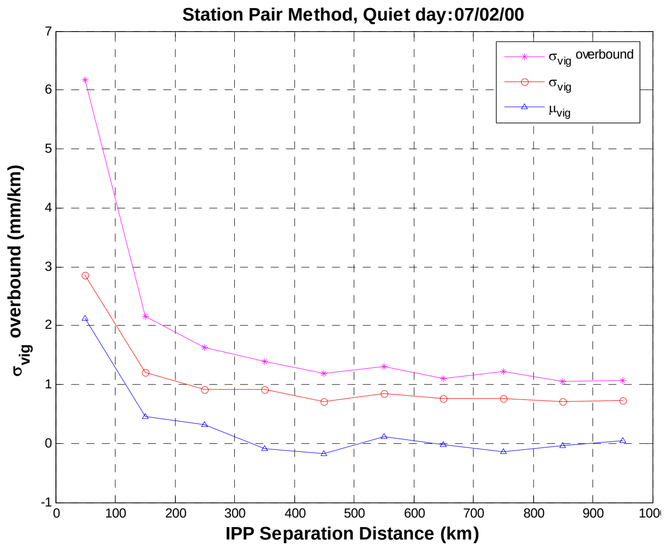

Fig. 4. σ_{vig} Overbound Results from Station Pair Method and WAAS "Supertruth" Data for a "Quiet" Day.

The "σ_{vig} overbounds" were estimated for all six days listed in Table 1 using the Station-Pair method and the WAAS "Supertruth" data. The results are shown in Figure 5. The different colors indicate the different days. The red curve shows the result for the "quiet" day (also shown in Figure 4). The solid curve shows the one sigma plus the absolute value of the mean of vertical ionosphere gradients. The solid line with circles shows the "σ_{vig} overbound" (i.e., the inflated sigma to overbound the non-Gaussian tails of the actual distribution). The inflation factors applied for each day are in the range of 1.3 to 2.6. The results show that the sigmas including those of severe days can be bounded by 4mm/km. However, the Station-Pair method combined with the WAAS "Supertruth" data has certain limitations when applied to the LAAS scenario. First, a reliable statistic is not available at the IPP separation distances below 100km due to the sparse network of the WAAS stations. Second, the estimates increase as the distances decrease because of the remaining bias (ex., the receiver IFB calibration error or the carrier-phase leveling error due to the multipath and receiver noise). The same amount of a bias divided by a shorter distance would magnify the bias effect.

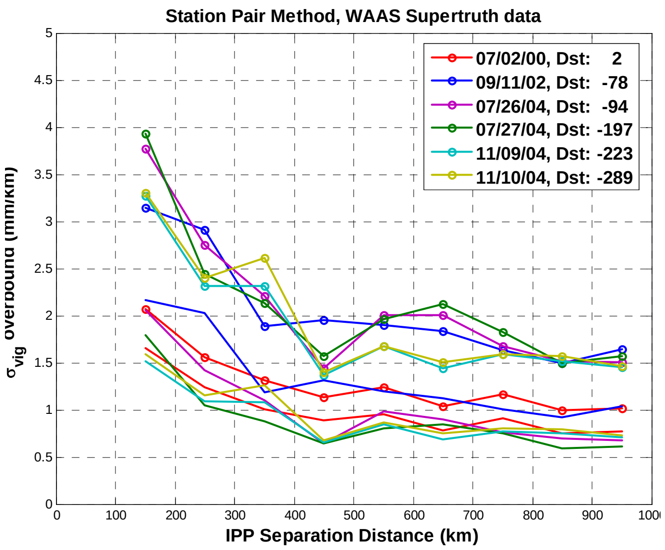

Fig. 5. σ_{vig} Overbound Results from Station Pair Method and WAAS "Supertruth" Data for All Six Days.

B. Results from Mixed Pair Method

Figure 6 shows a two dimensional histogram of measurements as a function of the IPP separation distance and the differential ionosphere delay for the "Quiet" day (July 2, 2000), obtained using the Mixed-Pair method and the WAAS "Supertruth" data. By considering all possible pairs of satellites and receivers, many observations of gradients become available at shorter distances. However, the σ_{vig} estimates are still not accurate enough and even get worse than those with the Station-Pair method at short baselines as shown in Figure 7. This is due to the fact that the Mixed-Pair method is not free from both the satellite and receiver IFB calibration errors, while the Station-Pair method is susceptible to the receiver IFB calibration error only. At baselines greater than 200 km, the results from the Mixed-Pair method and Station-Pair method agree well with each others, because the bias effects are relatively small for both methods.

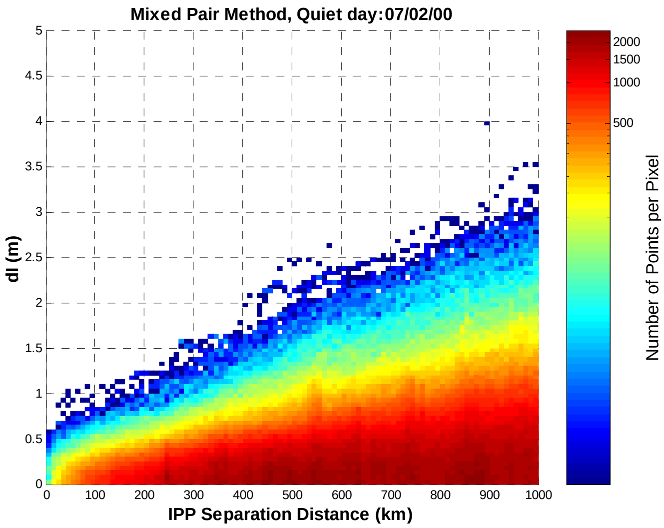

Fig. 6. Differential Vertical Ionosphere Delays Results on a "Quiet" day from Mixed Pair Method and WAAS "Supertruth" Data.

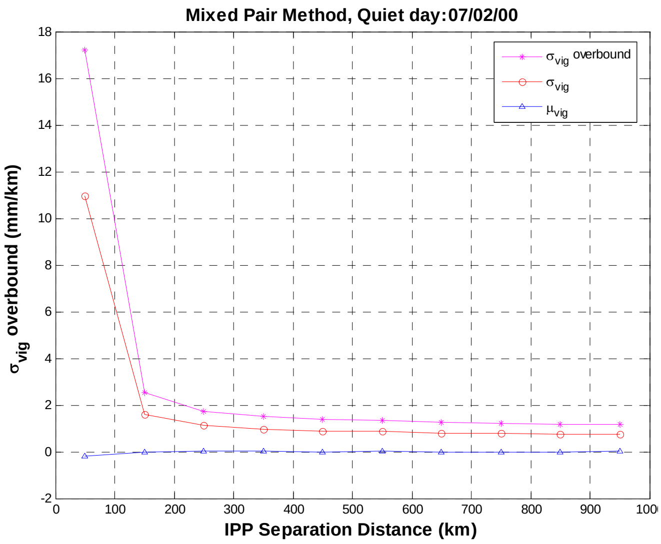

Fig. 7. σ_{vig} Overbound Results from Mixed Pair Method and WAAS "Supertruth" Data for a "Quiet" Day.

C. Results from Time Step Method

The results for all six days using the Time-Step method and the WAAS "Supertruth" data are shown in Figure 8. One sigma plus the absolute value of mean ($\sigma_{vig} + |\mu_{vig}|$) of vertical ionosphere gradients is presented in the left plot with different colors for each days. The different markers indicate the different time intervals (Δt) used to configure the pairs for the Time-Step method. By adjusting the time interval, the ionosphere gradients can be estimated at the targeted separation distances.

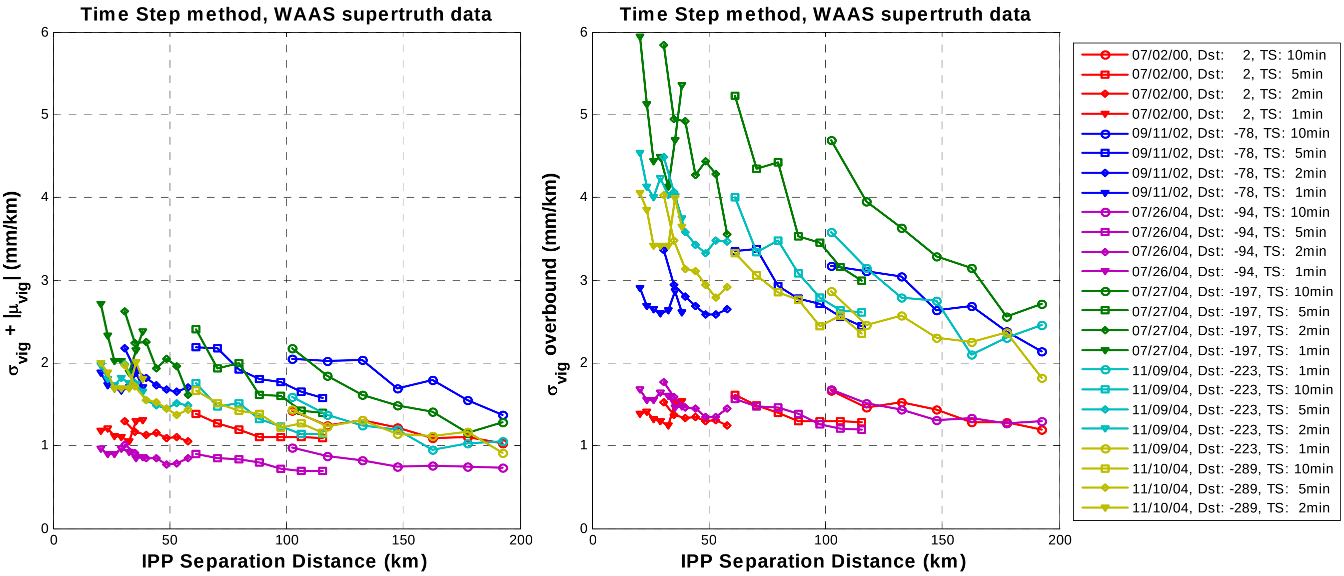

Fig. 8. σ_{vig} Overbound Results from Time Step Method and WAAS "Supertruth" Data for All Six Days.

As an example, Δt of ten minutes was used to get estimates at baselines longer than 100 km, and Δt of one minute is chosen to observe ionosphere gradients at separation distances shorter than 40 km. The sigmas were then inflated by a factor of approximately 1.2 ~ 2.3 to overbound the thick tails of the true distribution. The right plot in Figure 8 shows those "σ_{vig} overbound" results for all six days.

It is clear that the estimates of ionosphere gradients are obtainable at the LAAS applicable distances, 10 to 40 km, using the Time-Step method. However, several curves in the right plot exceed a "σ_{vig} overbound" of 4 mm/km, which is the maximum limit derived using the Station-Pair method (see Figure 5). This is caused by the fact that the ionosphere temporal gradients along with other remaining biases degrade the results especially at shorter distances. Although the Time-Step method provides a fairly good estimate of the ionosphere spatial gradient, we cannot fully rely on this method given that the temporal gradient is difficult to be estimated and extracted from the total gradients. To obtain a reliable σ_{vig} estimate, the two problems should be solved at the same time: observability at short distances and the removal of remaining biases. This subject will be discussed with the use of CORS data in the following section.

V. Noise Reduction And Bias Removal

Although the dense network of the CORS stations enables us to measure the ionosphere spatial decorrelation at distances less than 100 km, the noise level of the JPL post-processed CORS data is much higher than that of WAAS "Supertruth" data. Therefore, some degrees of noise reduction and bias removal are necessary to estimate ionosphere spatial gradients. To reduce the noise of CORS data, the residuals between the computed TEC from JPL's GIM software and the measured TEC were utilized. A threshold of 20 sigma of residuals (which corresponds to about 50 TECU) was applied to eliminate the extreme outliers. An elevation cut-off angle of 30 degrees was also applied to exclude noisy measurements (due to multipaths and noises), because GIM is not doing such a good job modeling the ionosphere at low elevation angles. The remaining biases are also large at low elevation compared to those at high elevation, because the length of continuous arc is typically shorter due to frequent cycle slips at low elevation. For short arcs, the elevation weighting has almost no effect on averaging code minus carrier measurements and this introduces large leveling errors and large biases [7].

To remove remaining biases, we leveled differential ionosphere delays by computing the mean of differential ionosphere delays of continuous arcs. The continuous arcs were determined by applying the slip detection parameters of 5~30 cm depending on the IPP separation distances and the ionosphere activities of the day. Figure 9 shows one example of the bias removal from CORS data. A pair of CORS stations (the station numbers of 25 and 118) looking at the same satellite (SV39) was chosen on a quiet day (July 2, 2000). The blue and green curves on the top plot show ionosphere slant delays of the pair, and the blue and green curves on the lower plot are the IPP distance and the satellite elevation angle respectively. The differential ionosphere delays (shown as the blue dotted line) are corrupted by the different levels of biases at each continuous arc. As an example, a bias of about 90 cm exists on the third arc for which the corresponding IPP distance is approximately 30 km, and thus the bias is converted to an equivalent ionosphere gradient of 30mm/km. Knowing that a good estimate of σ_{vig} is about 4mm/km, this bias cannot be ignored in the estimation process. The red dotted line shows the leveled differential slant delays obtained after removing the biases.

After removing biases and noises as discussed above, the cleaned JPL CORS data was used to estimate the vertical ionosphere gradients. Figure 10 shows a two dimensional histogram of observations as a function of the IPP separation distance and the differential ionosphere delay in vertical domain for the "Quiet" day (July 2, 2000), obtained using the Station-Pair method. Note that not only the smooth linear behavior but large numbers of samples are available at the short separation distances (less then 40km).

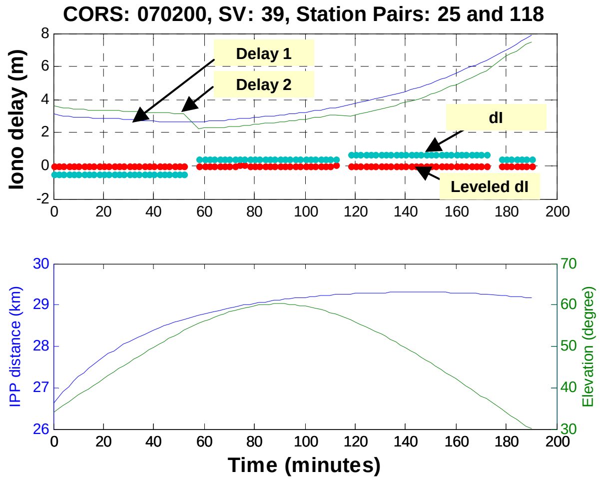

Fig. 9. Bias Removed Differential Ionosphere Slant Delays from JPL Post-Processed CORS Data.

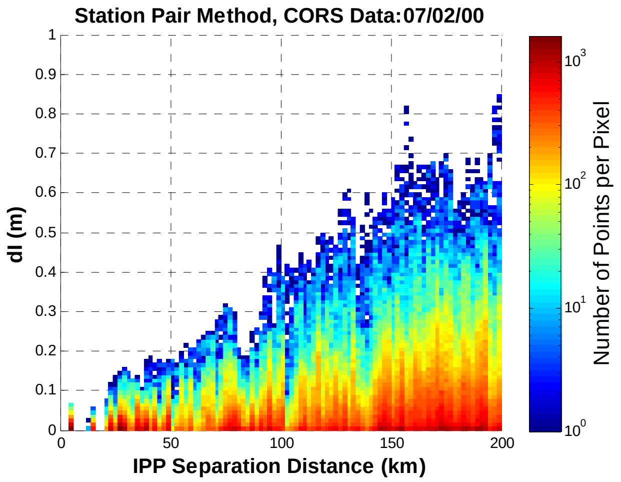

Fig. 10. Differential Vertical Ionosphere Delays Results on a "Quiet" day from Station Pair Method and JPL CORS Data (with Noise Reduction and Bias Removal).

The JPL CORS data of all six days listed in Table 1 as white were processed to estimate the "σ_{vig} overbounds". The results are shown as the solid curves with circles in Figure 11. The same approach described in Section 4.1 was taken to determine the inflation factor covering the non-Gaussian tails of distributions. Again the different colors represent the different days, and the solid curves (located below sigma-overbound curves inflated by a factor of 2.2 ~ 4.1) shows the one sigma plus the absolute value of the mean of vertical ionosphere gradients. Note that the inversely proportional trend (noticed in Figures 5 and 8) has been almost suppressed by removing the bias effect. The "σ_{vig} overbounds" are almost consistent at distances above 40 km except for one "severe" day (July 27, 2004). The inverse linear trend appears again in the region below 40km because the bias cannot be removed perfectly and whatever remaining biases divided by very short distances must degrade the results. Knowing the fact, it is reasonable to extend the flat lines to the region of short separation distances. Therefore, the result supports that σ_{vig} is conservatively bounded by 4mm/km on nominal days.

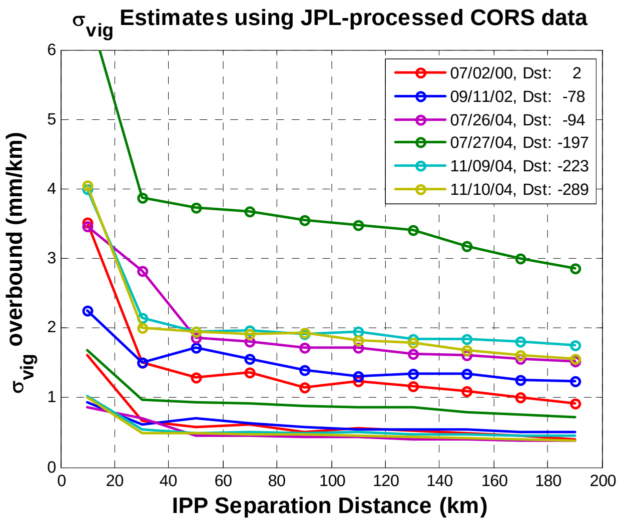

Fig. 11. σ_{vig} Overbound Results from Station Pair Method and JPL CORS Data for All Six Days (with Noise Reduction and Bias Removal).

VI. SENSITIVITY ANALYSIS

This section addresses some concerns about whether the σ_{vig} of 4mm/km is truly sufficient enough to cover ionosphere spatial deccorelation for nominal days. First of all, since the southern sites are closer to the geomagnetic equator, those stations may not be covered by the numbers derived from all of CONUS stations combined. The geographic trend of ionosphere gradients was thus examined in Section VI.A. Second concern is whether LAAS could operate "nominally" as well on days in which WAAS LPV availability was affected by ionosphere storms but which were not severe enough to be threathing to LAAS. Section VI.B discusses σ_{vig} dependency on WAAS availability.

A. Geographic Trend

To investigate if any significant geographic trend exists, the CONUS stations were subdivided into three groups: "Northern" for latitudes of 40 ~50 degrees, "Central" for latitudes of 33 ~ 40 degrees, and "Southern" for latitudes of 23 ~ 33 degrees. The data from those sub-regions were then used to compute statistics for each separately. Figure 12 shows the estimates of σ_{vig} for a "Moderate" day (September 11, 2002). The estimates of each group (shown as blue for "Southern", magenta for "Middle", and green for

“Northern”) were derived using the Station-Pair method and bias-removed JPL-CORS data, and were compared to the σ_{vig} estimated with all CONUS stations (shown as the red curve). On this “Moderate” day and other days examined, no significant geographic trend was observed. In fact, by dividing CONUS into sub-regions, we were able to reduce the inflation factor (from 2.5 to about 1.8) which may have been increased additionally due to the mixing of all three regions.

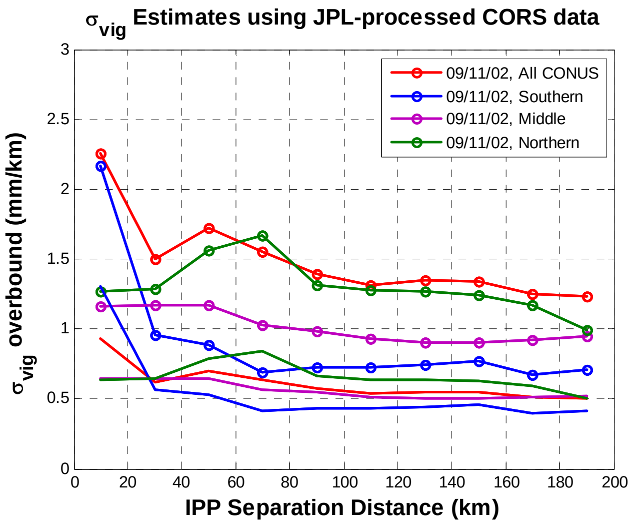

Fig. 12. σ_{vig} Overbound Results of All Sub-Regions from Station Pair Method and JPL CORS Data for a “Moderate” Day.

B. Dependency on WAAS LPV Availability Coverage

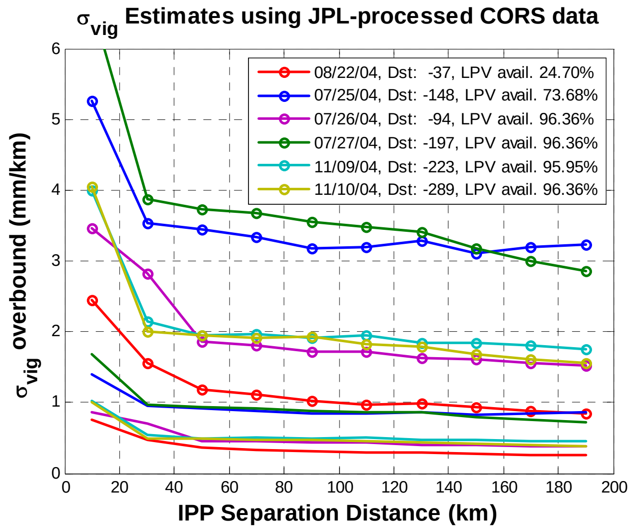

Fig. 13. σ_{vig} Overbound Results of WAAS-Affected days from Station Pair Method and JPL CORS Data.

Two more days (shaded in orange in Table 1) in which WAAS LPV coverage was poor (24.70 and 73.68 percents respectively) were examined. The σ_{vig} estimates of those two days (the blue and red curves) are compared to those of days with nominal WAAS coverage (greater than 95 percents). Again the solid curve shows the one sigma plus the absolute value of the mean of vertical ionosphere gradients, and the line with circles shows the “σ_{vig} overbound” result. The “σ_{vig} overbounds” of the days with poor WAAS coverage are still bounded by 4mm/km (the relatively flat lines shown at longer separation distances can be extended for the estimates at IPP distances less than 40km, by applying the same logic explained in Section V). Therefore σ_{vig} of 4mm/km does not need to be changed to cover any WAAS-affected days.

VII. Summary

This study has demonstrated with both WAAS supertruth data and post-processed CORS data that, while typical ionosphere spatial decorrelation in CONUS is approximately 1 mm/km at a one-sigma level, a significantly higher value should be broadcast for σ_{vig} by LAAS stations to bound active (but not stormy) ionosphere conditions as well as quiet conditions. The results in this paper suggest that σ_{vig} = 4 mm/km is sufficient to cover almost all ionosphere conditions in CONUS. However, a precise assessment of the bounding value of σ_{vig} cannot be made from post-processed WAAS and CORS data because of the relatively large baselines between WAAS and CORS reference stations (compared to typical LAAS reference-to-user baselines) and because L1-L2 inter-frequency biases cannot be completely removed from this data.

Once several LAAS sites are fielded in different parts of CONUS, additional analysis should be done on the apparent ionosphere spatial gradients between LGF reference station antennas or, better yet, between the LGF reference point and a fixed “pseudo-user” antenna several kilometers away. A combination of single-frequency code-minus-carrier data and L1-L2 data with carefully-calibrated inter-frequency biases could help in reducing the conservatism that we believe is present in the 4 mm/km one-sigma bound. In the meantime, or absent additional data, 4 mm/km appears sufficient to cover all non-anomaly ionosphere conditions in CONUS with adequate safety margin.

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