Verification of ionospheric sensors

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Abstract. Ionospheric products from sensors and models were compared to investigate strengths and limitations of each. Total electron content data from computerized ionospheric tomography (CIT) and TOPEX sensors in the Caribbean region in 1997 were compared to estimates produced by models Parameterized Ionospheric Model (PIM) and Raytrace/ICED-Bent-Gallagher (RIBG) and global maps from GPS. A 5 total electron content unit (TECU) bias was observed in TOPEX. CIT and TOPEX confirmed the location and structure of the equatorial anomaly. A GPS map confirmed the location of the anomaly but did not reproduce structure less than 1000 km in latitude and 1500 km in longitude and underestimated TEC by at least 11 TECU or 25%. PIM positioned the anomaly 13° equatorward of its observed location and greatly underestimated (~50%) the rise in content over 5°-25°N range. RIBG overestimated the latitudinal extent of the anomaly and underestimated TEC at the peak by 40%. Additional comparisons were made using CIT and ionosonde sensors at midlatitude during the summer of 1998. Fourteen days of TEC, \( h_m F_2 \), \( N_m F_2 \), and half-thickness comparisons showed reasonable agreement between CIT and ionosonde for TEC and \( N_m F_2 \). The \( h_m F_2 \) and half-thickness comparisons were contaminated by noise, which accounted for a significant portion of the ionospheric variation. Daytime cases where CIT overestimated maximum density were attributed to underestimating layer thickness. Finally, TOPEX and multiple GPS sensors were compared to verify regional ionospheric conditions associated with occurrence of nighttime ionospheric depletions in the Caribbean during Combined Ionospheric Campaigns in June of 1998. From 0300 to 0800 UT on June 26, GPS and TOPEX showed elevated nighttime content over the entire Caribbean region. Vertical TEC approached 25 TECU in some places with interspersed depletions, which in some cases evacuated nearly the entire ionospheric content.

1. Introduction

Whether the objective is to properly ingest sensor data into a model, assimilate multiple sensors into a four-dimensional tomographic solution, validate a model, or simply verify the scientific conclusion made from another sensor, the relative accuracies and limitations of ionospheric sensors and models must be understood. Multiple-sensor campaigns are a good vehicle for exploring this concept.

This paper presents a few results from multisensor campaigns. First, total electron content (TEC) from the Caribbean region is compared between three sensors, computerized ionospheric tomography (CIT), TOPEX, and GPS, and two models, Parameterized Ionospheric Model (PIM) and Raytrace/ICED-Bent-Gallagher (RIBG) [Daniell et al., 1995, 1996; Reilly, 1993]. Second, four ionospheric parameters are compared between CIT and an ionosonde at midlatitude: TEC; \( h_m F_2 \), height of the main ionospheric layer; \( N_m F_2 \), maximum density of the main ionospheric layer; and half-thickness of the bottomside of the main ionospheric layer. Third, TOPEX and multiple GPS sensors are used in the Caribbean to verify the extent and magnitude of nighttime enhancements and associated...
depletions during the Combined Ionospheric Campaign in June of 1998 [Bust and Coco, 1999].

Some important caveats should be pointed out before the results are given. The GPS data, used in the 1997 Caribbean TEC analysis, were obtained from global maps of TEC produced by Jet Propulsion Laboratory (JPL) [Mannucci et al., 1993]. These maps use GPS data from multiple longitudes rotated in solar time to specify the ionosphere in places where sampling is poor. So the results obtained from comparisons using these data are reflective of the mapping process in addition to sensor errors. The CIT processing used in this study is the “operational version” of CIT developed at Applied Research Laboratories, University of Texas at Austin around 1994 [Vaisicek and Kronschnabl, 1995] and does not necessarily reflect the performance of current research algorithms.

2. Caribbean Total Electron Content

Beacon data from Navy Ionospheric Measuring System (NIMS) satellites (formerly Navy Navigation Satellite System, also known as “Transit”) were recorded in 1997 from nine ground stations in two chains spanning the Caribbean region. CIT processing of the recorded relative TEC data from multiple receivers along the trajectory of the satellite produces high-accuracy TEC data [Leitinger et al., 1975; Raymund, 1995]. These were compared with TEC data from coincident TOPEX dual-frequency altimeter passes over the Caribbean. Two cases of coincident passes are presented: a nighttime case and an afternoon case.

Figure 1 describes the geometry of two nearby passes of NIMS and TOPEX during the night of August 20 (day 232) and compares the TEC from CIT and TOPEX along with TEC from models PIM and RIBG and global maps of TEC using GPS (source JPL). The passes are within 10 min of each other with minimal longitudinal separation. This nighttime case is especially useful for examining relative TEC biases in the sensors and models. CIT shows a relatively flat and low-content ionosphere with latitude, 3-4 TECU. TOPEX-derived TEC (noisy gray data with circles representing 10 s averages) is ~5 TECU higher than CIT and shows high-frequency variations attributed to noise on the altimeters [Imel, 1994]. The 5 TECU bias has been observed previously [Coker et al., 1996] and is attributed to instrument calibration errors on TOPEX. This is supported by the relative magnitude of the data taken from a longitudinal slice of a global GPS map of TEC (source JPL). GPS measures TEC out to 20,000 km and TOPEX only out to 1300 km. GPS data should generally be larger than TOPEX. In the nighttime case, GPS is a few TECU (1-2) larger than CIT as might be expected, so no bias between the two is evident.

Figure 1. Nighttime case: comparison of TOPEX, CIT, and GPS total electron content with models PIM and RIBG.
The modeled TEC from PIM agrees nicely with CIT in this case. Similarly, the modeled TEC from RIBG, which includes the plasmasphere, agrees reasonably well with GPS. However, with the protonosphere included, PIM shows a more latitude-dependent protonosphere than is observed in the GPS data.

Figure 2 describes the afternoon case, also on August 20 (day 232). The NIMS and TOPEX passes are within 30 min of each other and separated in longitude by 15° at the equatorward end of the passes. After visually adjusting the TOPEX data down by 5 TECU, TOPEX and CIT agree remarkably well in the northern latitudes (15°-30°N geographic latitudes). The ionospheric anomaly is observed by both sensors from 0° to 15°N, with peak TEC occurring at roughly 8°N. The secondary peak in the CIT data around 0°-5°N is an artifact of the CIT processing reverting back to a priori model estimates outside the viewing area of the ground stations. Differences in peak TEC of the anomaly from CIT and TOPEX are attributed to the longitudinal separation of the sensors. A slice of the GPS map (source JPL) along the CIT longitude (295°E) confirmed the general location of the anomaly but did not capture its peak structure (8° in latitude and >15° in longitude). The peak TEC is underestimated by 11 TECU or 25%, even more when protonospheric content is considered.

PIM estimates the peak of the anomaly in this case to be located 13° to the south at -5°N and as a result greatly underestimates the rise in the ionosphere from 25° to 5°N. PIM underestimates the peak TEC at 8°N by 20 TECU or 45%. RIBG shows a much broader anomaly structure with generally less content than other sensors/models. RIBG underestimates the peak TEC by 17 TECU or 39%, even more when protonospheric content is considered. The protonospheric portion of PIM shows a strong dependence with latitude, estimating the protonospheric content at the anomaly peak to be ~5 TECU. Yet the GPS map data do not show this dependence, when compared with CIT at this longitude.

3. Midlatitude Comparison of CIT and Ionosonde

Beacon data from NIMS satellites were recorded in 1998 from four ground stations in a single chain along the west coast of the United States (along 237°E). Processed CIT data were compared with ionosonde data at Point Arguello, California (35.6°N 239.4°E). Fourteen days of TEC, \( h_mF_2 \), \( N_mF_2 \), and half-thickness data from the August-September time frame were included in the comparisons. The CIT data were shifted in solar time (<25 min) to compensate for longitudinal differences between the CIT reconstruction and the ionosonde, and ionosonde data were interpolated using 30 min samples to match sampling times with CIT. For the purposes of this comparison the half-thickness was defined as the

![Figure 2](image-url)
distance from the height of the maximum density for the $F_2$ layer, $h_mF_2$, to the height on the bottomside where the density is one-half the maximum density. Table 1 summarizes the results of differencing CIT- and ionosonde-derived parameters at 35.6°N. The number of samples $N$ is 83. Since CIT is an accurate estimator of TEC, it was used as truth for the purpose of the relative error calculations, but only for the TEC parameter. For all other parameters ($h_mF_2$, $N_mF_2$, and half-thickness) the ionosonde estimate was used as truth for the purposes of relative error calculations.

The comparisons reveal that the ionosonde-derived TEC correlates reasonably well with CIT-derived TEC over the 0-25 TECU range (see Figure 3a). The ionosonde-derived TEC is slightly lower on average

**Table 1. Midlatitude CIT and Ionosonde Parameter Differences**

<table>
<thead>
<tr>
<th>CIT-Ionosonde Parameter</th>
<th>Mean</th>
<th>Sigma</th>
<th>Units</th>
<th>Percent Error Mean</th>
<th>Percent Error Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEC</td>
<td>1.6</td>
<td>2.7</td>
<td>$10^{16}$ el/m$^2$</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>$h_mF_2$</td>
<td>10</td>
<td>25</td>
<td>km</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>$N_mF_2$</td>
<td>0.8</td>
<td>1.1</td>
<td>$10^{11}$ el/m$^3$</td>
<td>16</td>
<td>28</td>
</tr>
<tr>
<td>Half-thickness</td>
<td>-10</td>
<td>20</td>
<td>km</td>
<td>-2</td>
<td>53</td>
</tr>
</tbody>
</table>

**Figure 3.** Comparison of CIT- and ionosonde-derived ionospheric parameters: (a) TEC, (b) $h_mF_2$, (c) $N_mF_2$, and (d) half-thickness, for Point Arguello, California (35.6°N), late summer, 1998.
than CIT-derived TEC with a standard deviation of less than 3 TECU. This bias and noise produce some large relative errors at night when the content is low. Other than the bias, no other trend is observed in the comparison.

Comparison of the height of the main ionospheric layer, $h_mF_2$, shows a weak correlation between CIT and the ionosonde (see Figure 3b). Most of the ionosonde heights are in the 260-320 km range with only a few larger heights during the late evening or night. The CIT heights are generally confined to the 280-340 km altitude range. The resolution in the CIT-derived height is on the order of 20 km, and the precision of the ionosonde-derived height is probably on the order of 15 km during the day and 25 km at night. Thus it is easy to see why the two sensors show very little correlation over a 60 km altitude range, where most of the samples occur. On average, CIT heights were 10 km higher than the ionosonde heights with a standard deviation of 25 km. When differences are analyzed with the time of day, no trend is observed for most of the day. There is a suggestion in the data that during the nighttime, CIT underestimates the height when compared to the ionosonde, but there are too few samples during the nighttime to firmly draw this conclusion.

Comparison of the maximum density $N_mF_2$ from both sensors shows a reasonable correlation, similar to the correlation for TEC (see Figure 3c). On average, CIT overestimates the maximum density by $0.8 \times 10^{11}$ el/m$^3$ with a standard deviation of $1.1 \times 10^{11}$ el/m$^3$. In contrast to the TEC and height data, however, the density differences show a trend with time of day during the morning and late afternoon. In general, CIT appears to increasingly overestimate the maximum density with increasing daylight. There were no CIT samples in the 1100-1500 LT time frame, preventing this trend from becoming evident in the correlation. No trend is observed after sunset and before sunrise.

Comparison of the half-thickness from both sensors shows even less correlation than the height data (see Figure 3d). This is not completely unexpected since errors in the height estimation propagate into the half-thickness estimate for both sensors to varying degrees. Most of the ionosonde half-thickness estimates are in the 40-100 km range. In contrast, most of the CIT estimates are in the 40-70 km range, possibly indicating a response limitation of the CIT estimation of layer thickness. On average, CIT underestimates the layer half-thickness by 10 km with a standard deviation of 20 km. Comparing differences between the two sensors with time of day reveals a reciprocal relationship to maximum density results for the morning and late afternoon time frames. CIT appears to increasingly underestimate the half-thickness with increasing daylight. Again, no trend is observed after sunset and before sunrise. An underestimation of the layer thickness would cause the CIT density to increase in

![Map of Caribbean](image1.png)

**Figure 4.** Caribbean nighttime enhancement June 26, 1998: comparison of TOPEX pass at 0550 UT and nearby GPS total electron content.
order to maintain the observed TEC. This seems the most likely explanation of why CIT is overestimating the maximum density during certain times of the day.

4. Caribbean Nighttime Depletions

GPS data, available in the Caribbean region during the 1998 Combined Instrument Campaign, were used to define the regional extent and magnitude of nighttime depletions observed on June 26 [Bust and Coco, 2000]. A TOPEX pass over the region at 0550 UT (see Figure 4) gave a snapshot of the regional conditions. The gaps in the TOPEX data are attributed to periods, when the altimeters were passing over islands in the Caribbean. While no evidence of deep depletions was observed along the pass, TOPEX indicated that ionospheric content was enhanced above typical nighttime levels over the entire Caribbean (10°-30°N) by 5-15 TECU. Comparing TOPEX with individual GPS data samples within 100 km and 30 min of the TOPEX pass shows reasonable agreement once the 5 TECU bias in TOPEX is considered.

This comparison verifies the TEC values reported by GPS to within a couple TECU and verifies that some of the observed depletions evacuated 90% or more of the surrounding ionosphere. Figure 5 shows an example of such a depletion. One GPS satellite observed from Bogota, Columbia, shows as many as four depletions in a 4 hour time span. The background vertical content is estimated between 12 and 18 TECU during this time: enhanced late evening/nighttime condition. A large depletion (18 TECU), evacuating essentially all of the background content, was observed at 0400 UT.

5. Conclusions

Ionospheric products from sensors and models were compared to investigate strengths and limitations of each. CIT and TOPEX were able to capture the detailed TEC structure of the anomaly. TOPEX has limited sensitivity to structures smaller than 200 km in latitude and 2 TECU in magnitude, because of noise observed on the data with a standard deviation of 2-3 TECU. A 5 TECU bias was also observed in TOPEX data. The GPS map confirmed the location of the anomaly but did not reproduce structure less than 1000 km in latitude and 1500 km in longitude, underestimating the peak TEC by at least 25%: more if protonospheric content is considered. This result is most likely dependent upon the available GPS coverage in the region and the influence of samples outside the region or time.
frame. No bias was observed in the GPS map data. No latitudinal dependence of the nighttime protonospheric content was observed, when comparing GPS map with CIT. PIM positioned the anomaly 13° to the south of its observed location and, as a result, greatly underestimated (~50%) the rise in the content over the 5°-25°N range. RIBG overestimated the latitudinal extent of the anomaly and underestimated the TEC at the peak by 40%.

Comparisons of CIT and ionosonde sensors at midlatitude indicated that the ionosonde estimated TEC about as well as CIT estimated maximum density, NmF2. Both showed a small overall bias with a variance that was relatively constant with magnitude of the ionosphere. As a result, relative errors were dominated by time periods of low ionospheric densities. The hmF2 and half-thickness comparisons were contaminated by noise on both sensors, similar in magnitude to the observed ionospheric variation. Cases in the daytime where CIT overestimated the maximum density were attributed to CIT underestimating the layer thickness.

TOPEX verified the vertical TEC estimates produced by GPS sensors in the Caribbean region during the Combined Ionospheric Campaign in June of 1998. On the night of June 26 the ionosphere over the entire Caribbean region was enhanced 10-20 TECU above typical nighttime conditions and interspersed with depletions. In some cases, depletions were observed which evacuated all of the background content to within the limits of the sensor.

References


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