

## **Ionospheric Response to the Total Solar Eclipse of 22 July 2009 as Deduced from VLBI and GPS Data**

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### **Abstract**

A total solar eclipse occurred over China at latitudes of about 30°N on the morning of 22 July 2009, providing a unique opportunity to investigate the influence of the sun on the earth's upper ionosphere. GPS observations from Shanghai GPS Local Network and VLBI observations from stations Shanghai, Urumqi, and Kashima were used to observe the response of TEC to the total solar eclipse. From the GPS data reduction, the sudden decrease of TEC at the time of the eclipse, amounting to 2–8 TECU, and gradual increase of TEC after the eclipse were found by analyzing the diurnal variations. More distinctly, the variations of TEC were studied along individual satellite passes. The delay in reaching the minimum level of TEC with the maximum phase of eclipse was 5–10 min. Besides, we also compared the ionospheric activity derived from different VLBI stations with the GPS results and found a strong correlation between them.

### **1. Introduction**

The ionosphere undergoes substantial changes during a solar eclipse. The eclipse causes a change of ionization in the E-region and F-region of the ionosphere where dynamic processes play an important role. During the eclipse, the Total Electron Content (TEC) is a good indicator of the state and dynamics of the F-region of the ionosphere. Consequently, experimental observations of the ionosphere at such time provide a unique opportunity to investigate the ionospheric response to the change in the solar flux emission towards the earth.

Different techniques have been used to study the eclipse-induced ionospheric changes including the earlier beacon satellite, then predominantly ionosonde measurements, and today the widely used Global Positioning System (GPS)-based TEC measurements. The response of GPS-based TEC variations to the solar eclipse under low solar activity was studied by several authors [1][2][3][4]. Baran et al. (2003) [3] detected the effect of the eclipse on 11 August 1999 over Europe in diurnal variations and found trough-like variations with gradual decrease, followed by increase of TEC at all European stations. The depression of TEC of this eclipse amounted to 2–8 TECU (TEC Unit, 1 TECU=1 × 10<sup>16</sup> electron/m<sup>2</sup>) and the delay in reaching the minimum TEC with respect to the maximum phase of the eclipse was 10–20 min. Observations by Afraimovich and Lesyuta 2002 [4] for the total eclipse of 21 June 2001 using data from three African GPS stations showed a low level of geomagnetic disturbance and a clearly pronounced effect of a depression of TEC for all GPS stations during the eclipse period. The delay between the smallest TEC with respect to eclipse totality was 9–37 min, and the depth and duration of the TEC decrease were 0.5–0.9 TECU and 30–67 min, respectively. Using data from a GPS network in Antarctica on 23

November 2003, Zainol et al. 2006 [5] analyzed in detail the signature of a Traveling Ionospheric Disturbance (TID) event and the different values of sudden TEC depressions at different stations. A linear relationship between the eclipse magnitude and TEC depletion was also detected. And before and after the eclipse day the observation of the TID waves suggested that the TID event on the eclipse period did not result from the solar eclipse but had tropospheric origin. Observation results by Jakowski et al. 2008 [6] showed the response of TEC to the total solar eclipse on 3 October 2005 with European GPS network. They also detected the depression of TEC of 3–4 TECU and the delay of a minimum level of TEC with respect to the maximum phase of the eclipse at 20–30 min by diurnal variation analysis. The two-dimensional TEC maps with 5-min interval temporal resolution showed that the eclipse produced remarkable changes in the structure of the ionosphere. Such response of TEC to the solar eclipse depends on the latitude as well as the longitude.

In addition, Very Long Baseline Interferometry (VLBI) can measure the difference of TEC in the ray path to the radio source between two stations of a baseline due to the nature of the dual frequency observations. By comparing VLBI with GPS-based TEC values, we can get the difference between the two techniques, and such comparisons have been used by many researchers [8][9][10]. From the published results, ionospheric parameters derived by VLBI and GPS show similar trends and differ by a few TECU or by a large system constant. And such systematic difference is due to the S/X VLBI receiver offsets.

In this paper we present the ionospheric response to the total solar eclipse on 22 July 2009 using three VLBI stations at Shanghai, Urumqi, and Kashima, GPS co-located receivers, and the Shanghai GPS Local Network to study the TEC diurnal variations during the eclipse day. The event took place under low solar activity.

## 2. The Geometry and General Information about the Total Solar Eclipse

The total solar eclipse took place on 22 July 2009. The three curved lines with bars in Figure 1 show the central path of the total eclipse by the central line and zones of partial eclipse by the outer lines. Shanghai and Wuhan are located very near to the central path of the total eclipse. Besides, two other VLBI stations (Urumqi and Kashima) carried out observation experiments during the event. At Shanghai station, the partial eclipse began at Universal Time (UT) 00:23:26 (first contact) and ended at UT 03:01:38 (fourth contact) with the maximum eclipse occurring at UT 01:36:48 [11].

Different methods were used for the analysis of the TEC behavior during the eclipse. A single technique was employed for diurnal TEC variations by averaging GPS measurements for satellites in different directions. The comparison of VLBI- and GPS-based TEC was also presented. VLBI measures the difference of TEC in the ray path to a radio source between two stations, whereas GPS measures the TEC along the ray path from a GPS satellite to the stations. To compare results between them, firstly the vertical TEC value at the VLBI station is calculated. Then slant TEC is obtained from vertical TEC by applying an ionosphere mapping function according to the VLBI observation elevation at the two stations. Lastly the difference of the slant TEC is easily computed [8].

### 3. The Eclipse Effect on TEC by GPS Measurements

For GPS-based TEC reduction, we used the widely-used local ionosphere model as a single, infinitesimally thin layer at a fixed height of 375 km and a simple mapping function to convert the slant TEC along the ray path into vertical TEC. Figure 2 shows the diurnal variations of TEC from the phase measurement along satellite passes at four different stations on eclipse day and reference quiet days. In Figure 2 we can clearly see an obvious depression of TEC, amounting to 2–6 TECU, at eclipse day compared with that on the reference day. The time of the maximum phase of the eclipse varied in Universal Time (UT) from 01:30 to UT 01:35, so the delay of the minimum TEC with respect to such maximum phase of the eclipse was in the range of 5–10 min combined with the minimum TEC value shown in Figure 2. As the stations were close, the levels of TEC depression observed by the same satellite and different stations were similar to each other.

Figure 3 shows the diurnal variations of the vertical TEC over a single station (SHAO) for the eclipse day (22 July 2009) and a reference quiet day (21 July 2009). By comparing the TEC on the eclipse day with that of the reference quiet day, we can study the eclipse effect on the TEC variations. It is shown in Figure 3 that the obviously sudden depression of the TEC value occurred for the eclipse day. The time for the minimum TEC value was close to the maximum phase of the eclipse, and its depression reached 6–8 TECU. In the following approximately 2 hours, the TEC value gradually reached the regular level.

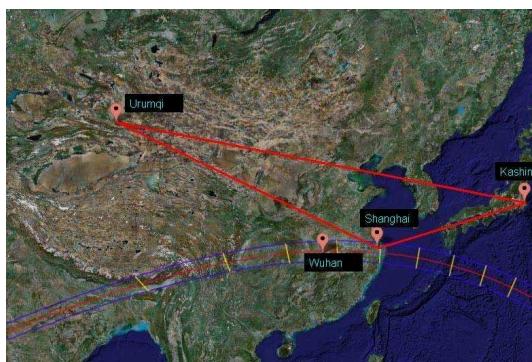


Figure 1. Map of the total solar eclipse path on 22 July 2009, and distributions of VLBI and GPS sites. Shanghai and Wuhan are located very near the central path of the total eclipse.

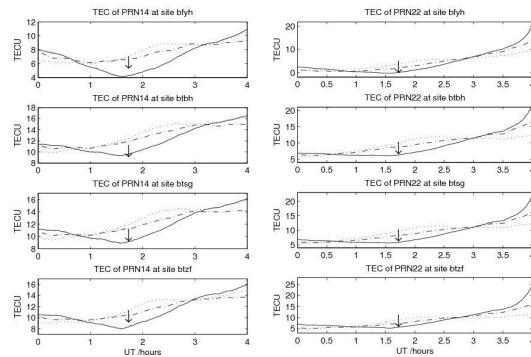


Figure 2. Temporal TEC variations along individual satellite passes for PRN 14 (left) and 22 (right) observed at BFYH, BTBH, BTSG, and BTZF stations on 22 July (black solid line—the eclipse day), 21 July (dashed line—quiet day) and 23 July (dotted line—quiet day). The arrows show the time of TEC minima.

### 4. Comparison of VLBI- and GPS-based TEC

To detect the TEC variations by VLBI, a 9-hour VLBI experiment for ionospheric TEC measurement during the eclipse was carried out in S/X dual-band with participation of Shanghai, Urumqi, and Kashima stations. The observation target was a strong extragalactic source, 4C39.25, at the solar angle of 25°. The difference of TEC in the ray path to the source was determined

by VLBI group delay measurements. The method for comparing the differences of TEC by the VLBI- and GPS-based measurements was described in section 2. The differences between them on eclipse day are shown in Figure 4. The jump in VLBI-based TEC differences at about UT 02:40 needs further analysis.

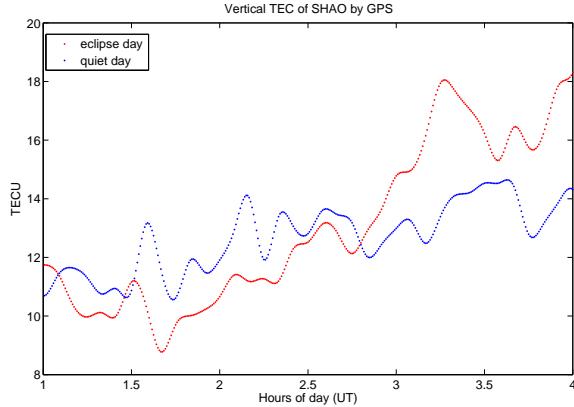


Figure 3. Diurnal VTEC variations observed at SHAO station on 22 July (the eclipse day) and 21 July (the quiet day). The line with the larger initial value is the eclipse day line.

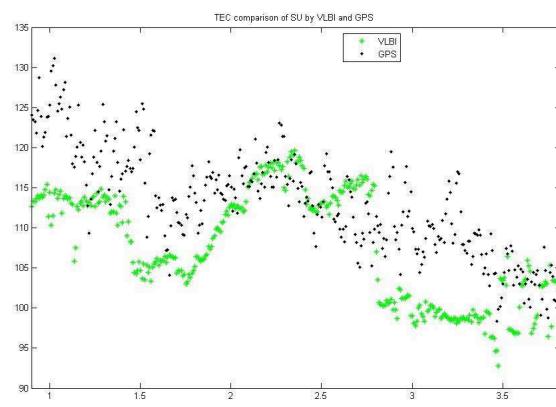


Figure 4. Correlation between GPS and VLBI data: Shanghai-Urumqi baseline on eclipse day 22 July 2009. The RMS of the difference was 4 TECU. The offset was caused by S/X VLBI receiver offset.

## 5. Conclusions

We presented the TEC variations' response to the eclipse over the Shanghai GPS Local Network and a comparison of VLBI- and GPS-based TEC. By analysis of the diurnal TEC variations, the sudden TEC depression amounted to 2–8 TECU for the eclipse day, and the delay of minimum TEC with respect to the time of maximum phase of the eclipse was in the range of 5–10 min.

The comparison of VLBI- and GPS- based TEC variations was also presented. The offsets between them were caused by S/X VLBI receiver offsets. We also found a jump in the VLBI-based TEC differences at UT 02:40; this jump needs further analysis.

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