

Observations of the Ionospheric Total Electron Contents During the Solar Eclipse of October 24, 1995 by Using the GPS Beacon

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ABSTRACT

The ionospheric total electron contents (TEC) during the total eclipse of October 24, 1995 were observed by means of the Global Positioning System (GPS) receivers located at Wuchang and Guangzhou. The observations showed that there were obvious effects of the eclipse on the ionosphere. The eclipse gave rise to decreases in the TEC in comparison with an established TEC reference level, referred to as the negative deviations of the TEC. The deeper the obscuration degree was, the larger was the negative deviation. Furthermore, the restoration of the negative deviations was delayed by about 2 hours after the last contact of the eclipse.

(Key words: Solar eclipse, Ionosphere, GPS satellite beacon, TEC measurement)

1. INTRODUCTION

Observers have been recording solar eclipses on earth for more than 2500 years, the earliest records being those of the Chinese. More specifically, investigations on the ionospheric effects of eclipses have been carried out since the end of the 1920's by using various radio wave measurements. In the early stage, ionosonde was one of main tools for monitoring the effects of an eclipse on the ionosphere (Ts'en *et al.*, 1936; Beynon and Brown, 1956). Since the 1960's, however, beacon satellites have been used to observe ionospheric changes during eclipses (Hunter *et al.*, 1974; Maitra *et al.*, 1982; Cohen, 1984; He and Long, 1990). Such observations have provided a great deal of fruitful information about ionospheric photochemistry and the dynamic processes during eclipses. Radio beacons transmitted from the Global Positioning System (GPS) satellites are now commonly used to determine the total electron content (TEC) of the ionosphere by measuring differential group delays and carrier-phase advances with a ground-based dual-frequency receiver (Blewitt, 1990; Mannucci *et al.*, 1993; Klobuchar *et al.*, 1993).

To observe the ionospheric effects during the solar eclipse of October 24, 1995, two sets of Turbo Rogue dual-frequency receivers were placed at Wuchang (30°32'N, 114°20'E) and Guangzhou (23°08'N, 113°21'E) to obtain radio beacon signals from GPS satellites. Observation results at these two stations during the eclipse are presented in this paper. First, the data processing method is described; then, some results and a brief discussion are presented.

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2. DATA PROCESSING METHOD

Producing ionospheric TEC data requires a conversion of the raw GPS range data to the TEC along the line of sight, i.e. the slant TEC. Once the slant TEC is formed, original delay observables are no longer required. The first step in data processing is the application of a data conversion and editing program similar to one of those described by Blewitt (1990) to produce a text file in which all required observables, such as pseudorange delays (P_1 and P_2), carrier-phases (L_1 and L_2) and satellite coordinates etc., are recorded. This program can correct cycle slips in phase data and identify carrier phase breaks. In this study, two types of delay observables are available from each station-to-satellite line of sight measurement, namely, the pseudorange delay and carrier-phase. Each observable was acquired at frequencies of f_1 (1.2276 GHz) and f_2 (1.57542 GHz) with a 30-second time interval.

For the pseudorange observables, the difference in the group delays at the two frequencies is directly proportional to the slant TEC expressed as the number of electrons per unit area:

$$\text{differential group delay } (P_1 - P_2) \text{ in nanoseconds} = 2.85 \times 10^{16} \text{ el/m}^2. \quad (1)$$

Receiver and satellite clock errors in the pseudorange were removed in the differencing. However, receiver and satellite biases still remained. It is well known, in fact, that they significantly affect the value of the slant TEC (see Wilson *et al.*, 1992; Sardon *et al.*, 1994). The differential carrier phase ($L_1 - L_2$) is negative and, although inherently more precise than the pseudorange, is biased by an integer cycle ambiguity. This bias is constant for each phase-connected arc of data, such as between a given satellite and receiver, but it differs from one arc to another. The slant TEC was formed using the pseudorange and carrier phase data in accordance with the following procedure (Mannucci *et al.*, 1993). All the phase data were adjusted by a constant to match the absolute level of the pseudorange. The carrier phase was used because it was much more precise than the pseudorange. The constant was then computed so as to minimize the root-sum-square difference between pseudorange and phase differential delay calculated over the arc, such that :

$$\mathbf{B}^{rs} = \frac{1}{N} \sum_{i=1}^N \{ (\mathbf{P}_{1i}^{rs} - \mathbf{P}_{2i}^{rs}) - (\mathbf{L}_{2i}^{rs} - \mathbf{L}_{1i}^{rs}) \} \quad (2)$$

where N is the number of measurements in a phase-connected arc of data for a given receiver r and satellite s . For each datum i , the pseudorange delays are denoted by \mathbf{P}_{1i}^{rs} and \mathbf{P}_{2i}^{rs} for the f_1 and f_2 frequencies, respectively; the corresponding phase delays are \mathbf{L}_{1i}^{rs} and \mathbf{L}_{2i}^{rs} . The slant TEC for measurement i becomes:

$$\text{TEC}_i = \mathbf{K} [\mathbf{B}^{rs} + (\mathbf{L}_{rs_{2i}} - \mathbf{L}_{rs_{1i}})] \quad (3)$$

where $\mathbf{K} = 2.85$. The left side of Equation (3) is the slant TEC expressed in the TEC unit of 10^{16} el/m².

The receiver can record differential group delays and differential Doppler phases of dual-

frequency beacons from 4-8 satellites simultaneously. By using the above method, the ionospheric total electron contents along 4-8 propagation paths, can be deduced. Then, the vertical TEC can be obtained by computing the zenith angle of the line of sight at the sub-ionospheric point which is defined as the intersection of the the line of sight and the ionosphere at 400 km height, namely,

$$N_T = \text{TEC}_i \cos \chi \quad (4)$$

where N_T is the vertical column electron content per unit area, and χ is the zenith angle of the line of sight at the sub-ionospheric point. The sub-ionospheric point is important in determining the locations of the vertical TEC. In the present paper, the height of 400 km was taken as the height of the sub-ionospheric point on the basis of the results from simulation for the Chapman layer.

3. RESULTS

On October 24, 1995, a total solar eclipse took place. Its path of totality started in Iran during sunrise and swept across northern India and a good part of Southeast Asia, and then passed between Borneo and the Philippines in the Pacific before finally disappearing at sunset. To monitor the ionospheric changes during this solar eclipse, two sets of Turbo Rogue dual-frequency GPS receivers were placed at Wuchang and Guangzhou, one set at each station, to measure the ionospheric TEC. The geographic coordinates and obscuration conditions at the two observation stations were listed in Table 1. At Guangzhou, the maximum area of coverage of this eclipse (i.e. the Middle of the Eclipse) was about 64%, occurring at 4:14 UT, while at Wuchang it was about 45% at 4:10 UT.

Table 1. Geographic coordinates and obscuration conditions.

Station Name	Latitude (N)	Longitude (E)	First Contact (UT)	Middle of the Eclipse (UT)	Last Contact (UT)	Totality (%)
Guangzhou	23°08'	113°21'	2:45	4:14	5:45	64
Wuchang	30°32'	114°20'	2:53	4:10	5:28	45

During this solar eclipse, four satellites numbered as 9, 17, 21 and 26 were coincidentally tracked by the two receivers. The traces of the sub-ionospheric points of the 4 satellites are illustrated in Figure 1. All of the 8 traces fall within the eclipse belt in the region of longitude 110 °E-120 °E and latitude 15 °N-35 °N.

Simultaneous observations of the TEC at the stations in Wuchang and Guangzhou started on October 20, 1995 and lasted for 7 days. Figure 2 shows an example of the TEC observed at

Guangzhou for Satellite 26. The solid and dotted lines indicate TEC's obtained from the differential carrier-phases and differential pseudorange delays, respectively. It is very obvious that, compared with the control days, there was a depletion of TEC during the solar eclipse of October 24, 1995. To extract the eclipse effects, the average value of the diurnal TEC on both pre-eclipse day (October 23) and post-eclipse day (October 25) was taken as the reference level, and the deviations of the diurnal TEC on October 24 (eclipse day) from the reference level were then calculated. On these adjacent three days, the orbits for the same satellite changed little because rotation period of the GPS satellites were about 12 hours. Figure 3 showed the deviations of the TEC during the eclipse observed at Guangzhou and Wuchang, respectively, for each satellite. The percentages of obscuration along the sub-ionospheric point traces were also shown in the same figure. It can be seen from this Figure that: (1) the eclipse led to decreases in the TEC, thereby causing three- to four- hour negative deviations in comparison with the reference level; (2) with movement of satellite, the deeper the obscuration degree was, the larger was the negative deviation except for Satellite 23 for which a deeper obscuration was shown in Wuchang whereas a negative deviation was noted in Guangzhou. In fact,

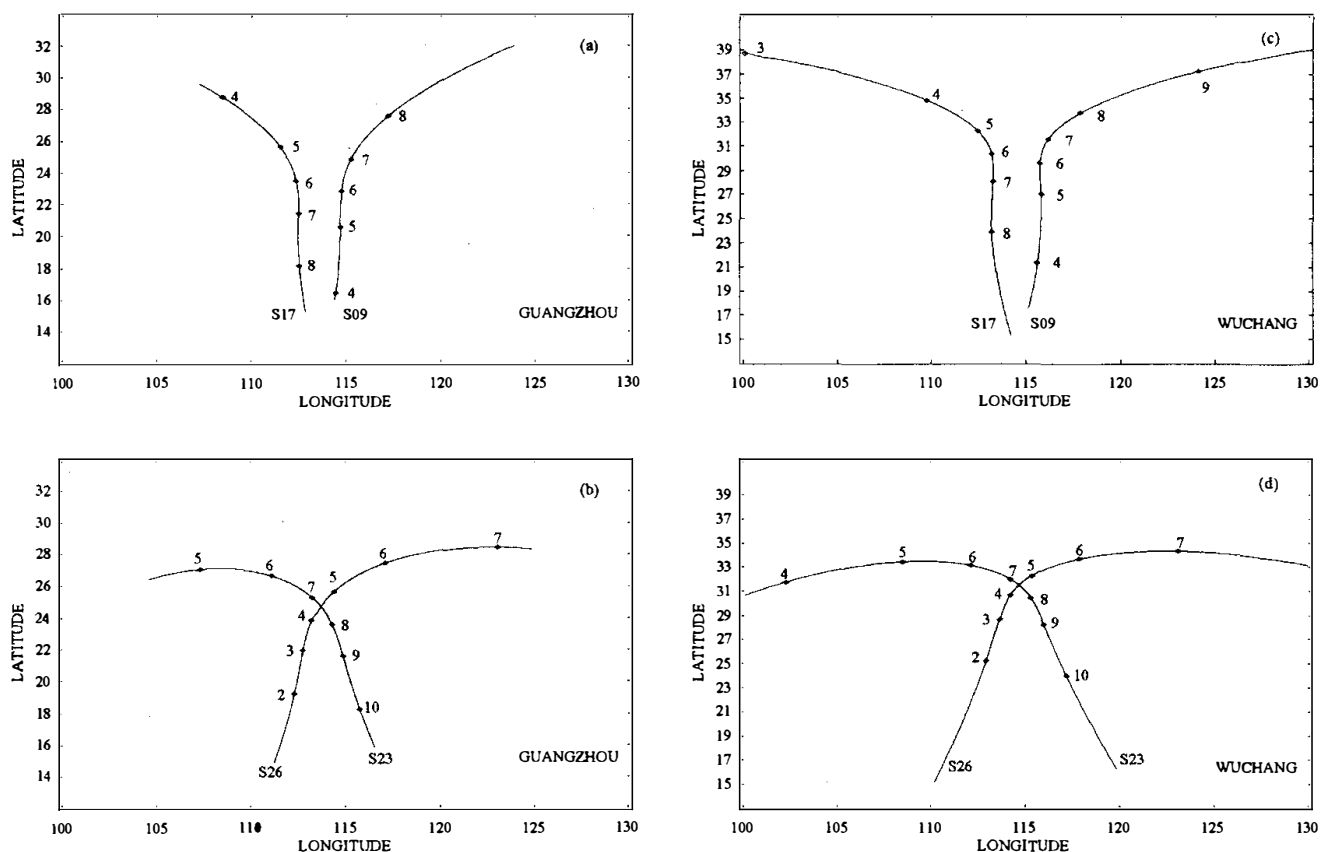


Fig. 1. Traces of the sub-satellite points for the stations of Guangzhou and Wuchang. (a) for satellites with PRN numbers of 9 and 17 at Guangzhou; (b) for satellites with PRN numbers of 23 and 26 at Guangzhou; (c) for satellites with PRN numbers of 9 and 17 at Wuchang; and (d) for satellites with PRN numbers of 23 and 26 at Wuchang.

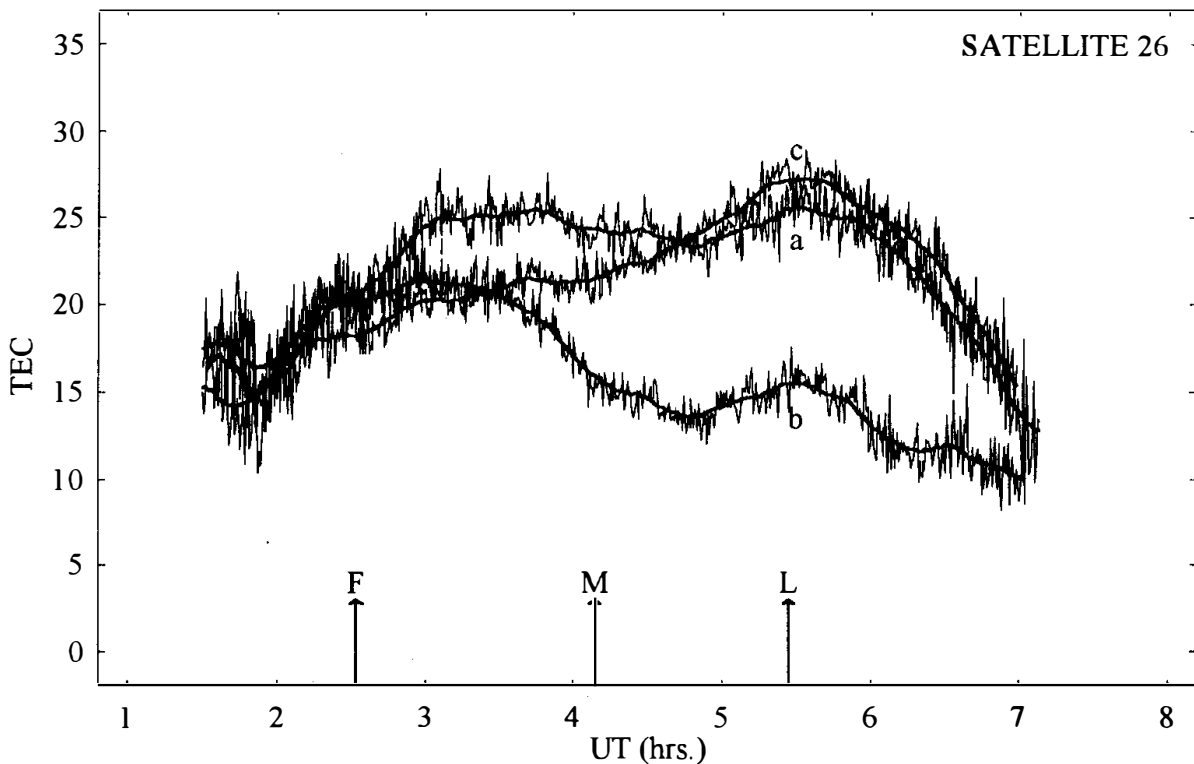


Fig. 2. An example of TEC records. The TEC unit is 10^{16} el/m². The thick and thin lines indicate the TEC obtained from differential time delays and differential carrier-phases, respectively. The letters of a, b and c in the Figure indicate October 23, 24 and 25, respectively. The arrows above the x-axis indicate the time of the first contact (F), the middle of the eclipse (M), and the last contact (L).

the percentages of obscuration before 12:30 LT for Guangzhou are not shown in Figure 3 because the signal of Satellite 23 was not locked before that time, and at the same time the obscuration for Guangzhou was still deeper than that for Wuhan. (3) the maximum negative deviation occurred on average one to two hours later than the appearance of the maximum percentage of obscuration, and restoration of the negative deviations was delayed by about 2 hours after the last contact of the eclipse; (4) the observed maximum decrement in the TEC from the reference level was about 20% to 50%; and (5) on the whole, the eclipse effects at Guangzhou were greater than those at Wuchang. The absolute maximum of the deviations was up to 1.0×10^{17} el/m² at Wuchang, while the maximum negative deviation at Guangzhou was more than 2.0×10^{17} el/m². This may be attributed to the fact that Guangzhou is closer to the center of the totality belt than Wuchang is.

Figure 4 shows relative fluctuations of the ionospheric TEC observed at Wuchang and Guangzhou during the solar eclipse. The fluctuations which were obtained by passing data through a band-pass filter with a lower cut-off period of 20 min and an upper cut-off period of 60 min., they look like traveling waves. These wavelike fluctuations have a main period of about 40 min. with amplitudes of about 2% (Satellite 17) to 4% (Satellite 26) for records at Guangzhou and of 4% (Satellite 9) to 12% (Satellite 26) for records at Wuchang. It can also be

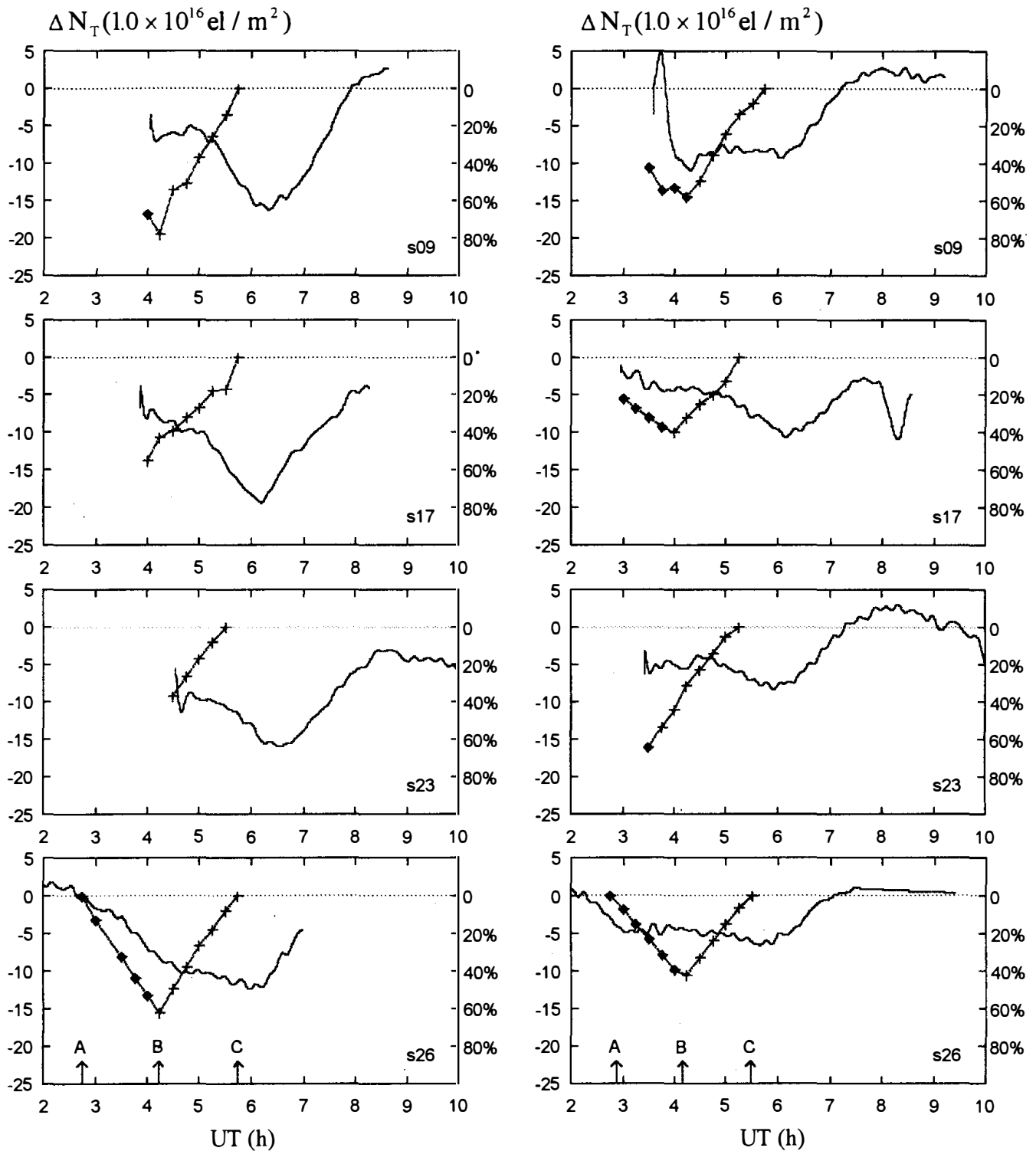


Fig. 3. Deviations of the TEC (ΔN_T) (solid line) during the eclipse observed at Guangzhou and Wuchang by means of the GPS receiver. The dashed lines show the degrees of obscuration (%) along the sub-ionospheric point traces for each satellite. The square signs and cross signs on the dashed lines indicate the time before and after the middle of the eclipse at corresponding sub-satellite points, respectively. The sign (s09 etc.) at the right cornal of each picture indicates the satellite number.

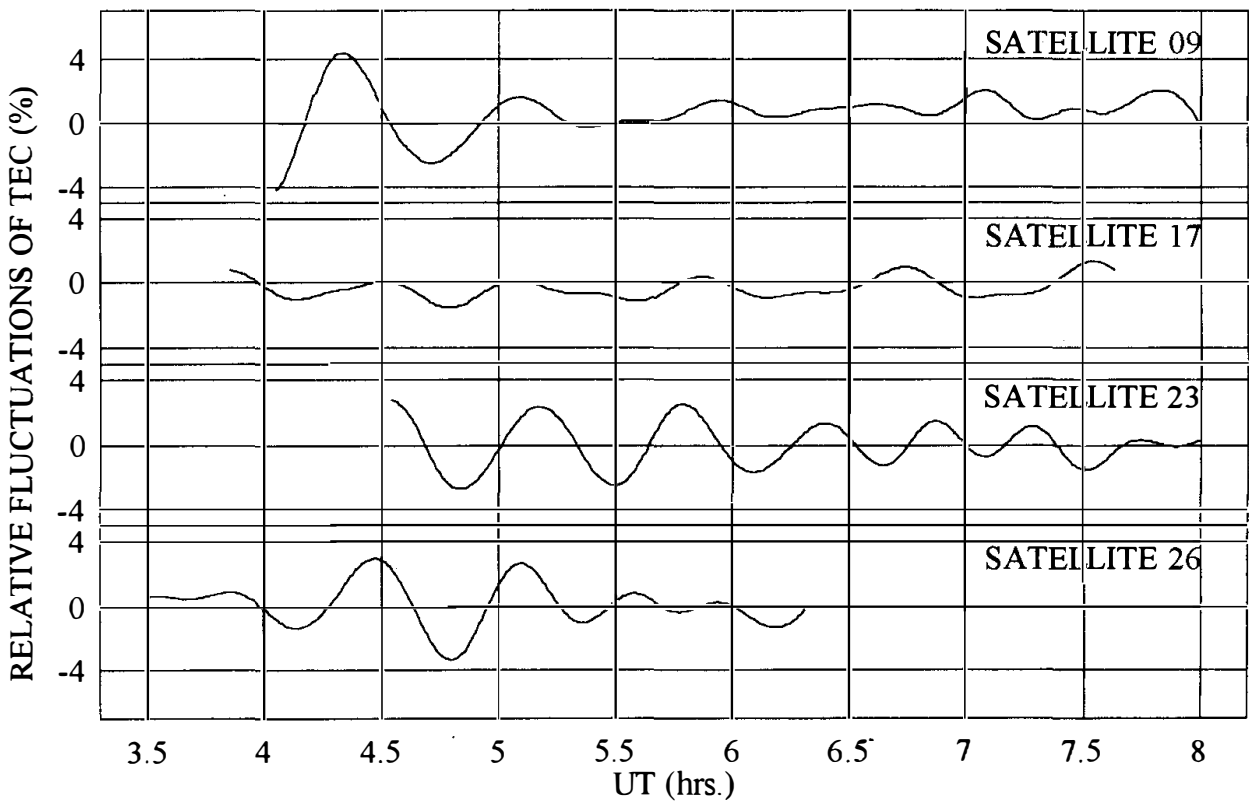
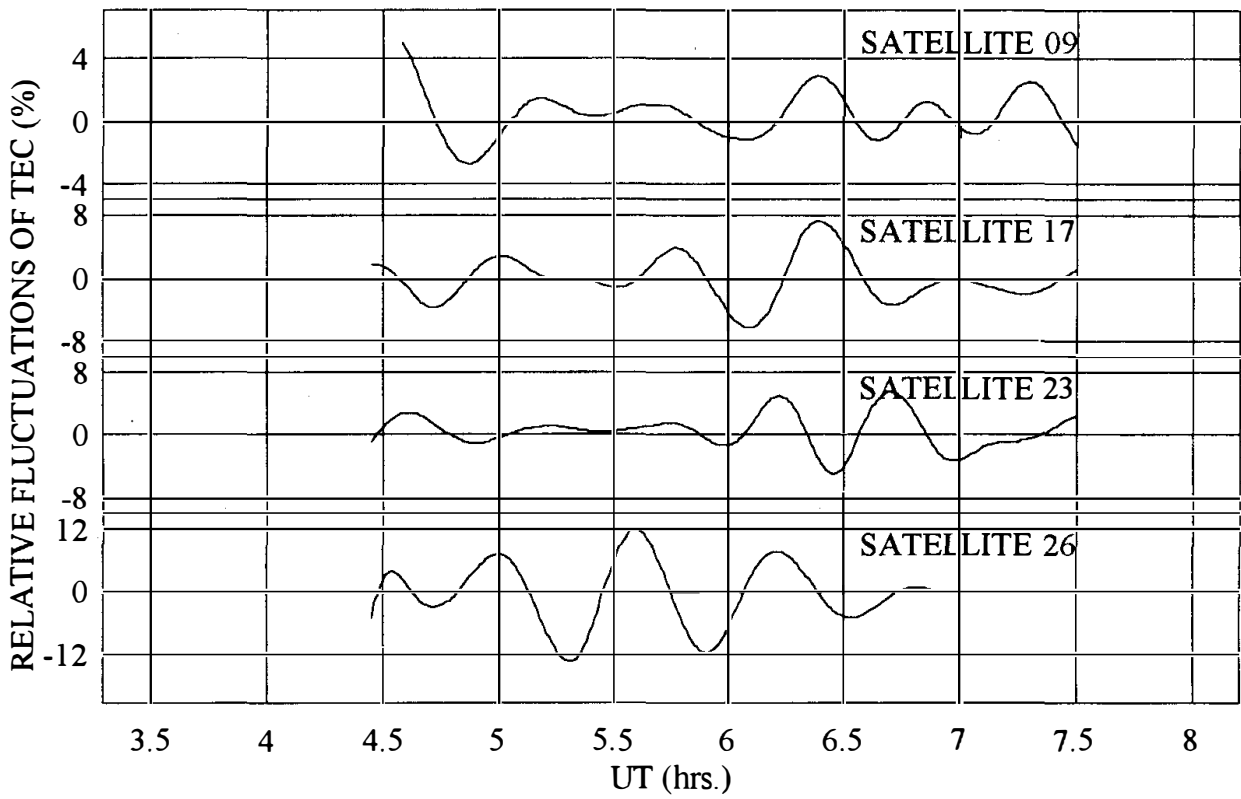


Fig. 4. Relative fluctuations of the ionospheric TEC during the eclipse observed at Wuchang (the upper panel) and Guangzhou (the lower panel) for four GPS satellites.

seen that wave-like fluctuations were enhanced after the middle of the eclipse.

4. DISCUSSION

A solar eclipse is a seldom-seen natural phenomenon. The eclipse process is analogous to a rapid process occurring from sunset to sunrise from which there is a great change in the intensity of sunshine and radiation entering into the ionosphere in a short time interval, bring about an obvious variation in the ionization rate. In the D, E and F_1 regions where the electron densities are controlled by the balance between photoionization and chemical recombination, observing the effects of the eclipse provides a means to determine the loss rate. However, the ionospheric TEC is an integration of electron density along the propagation path, its main part is attributed to the ionizations in the F_2 region and the higher topside ionosphere. The effect of the transport term in the continuity equation for the ionizations is very significant in the ionospheric F_2 region. During the eclipse, the ionization may recombine around the F_2 peak due to cooling. The negative deviations on the TEC from the reference level probably reflected these changes in the F_2 region during the eclipse.

Because of the large variability in the ionosphere from day to day, changes in the ionospheric TEC caused by solar eclipses are very difficult to quantitatively measure. Generally, TEC temporal measurements taken using geostationary satellites are more easily normalized to reference day measurements than spatial measurements taken using orbiting satellites (Cohen, 1984). However, the orbits for GPS satellites change very little within several consecutive days, thereby making it reasonable to use TEC deviations during the eclipse from a reference level obtained on the basis of TEC measurements one day before and one day after the eclipse to measure the effect of a solar eclipse on the ionosphere.

It is difficult to explain the reason for the TEC wave-like disturbances as shown in Figure 4. One possibility is that they may be attributed to the eclipse-produced irregularities in the upper F_2 region. Another possible cause could be the presence of eclipse-produced atmospheric gravity waves. Chimonas and Hines (1970) and Chimonas (1970) suggested that atmospheric gravity waves could be generated by the supersonic passage of the Moon's shadow through the Earth's atmosphere during a solar eclipse. Observations of the TIDs produced by solar eclipses have been reported by some authors (e.g., Davis and da Rosa, 1970; Arendt, 1971, Singh et al., 1989). However, because of the regular daily occurrence of the TIDs in the ionosphere and the amplitude of the eclipse-produced TIDs being of the same order as or smaller than those generated from the other sources, it is very difficult to identify the cause of the TIDs observed during the solar eclipses. It is a fact that there are somewhat wave-like disturbances of the TEC on reference days. Consequently, in further observations combining various measurements are required in order to establish whether or not TIDs are actually generated subsequent to a total eclipse.

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