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Magnetic effects during the solar eclipse of July 11, 1991

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RESUMEN

Durante el eclipse total de Sol del 11 de julio de 1991 se realizaron observaciones magnéticas en tres estaciones en México. Los resultados muestran la presencia de un efecto magnético claro del eclipse, tanto en la componente horizontal H, como en la intensidad total F. La declinación D y la componente vertical Z muestran un pequeño efecto, mientras que la inclinación no muestra nada. Las observaciones de F en las tres estaciones son muy similares. El efecto del eclipse es parecido a los cambios en FoE y N(h) reportados varias veces en la literatura, por lo que se sugiere la existencia de una posible relación lineal entre los efectos ionosféricos y magnéticos. Se propone que en próximos eclipses se realicen observaciones simultáneas de fuentes de Rayos-X en el Sol, parámetros ionosféricos y campo magnético superficial para determinar más claramente estas relaciones. Se debe realizar además una revisión a fondo de los modelos teóricos existentes a fin de poder explicar las observaciones.

PALABRAS CLAVE: Efectos magnéticos de eclipses, variaciones magnéticas, eclipses solares.

ABSTRACT

During the total solar eclipse of July 11, 1991 magnetic observations were conducted at three stations in Mexico. A very clear signature of the eclipse effect is present in the horizontal component H, as well as in total intensity F. Declination and vertical component show a small effect and nothing is noted in magnetic inclination I. The F observations from all stations are very similar. The eclipse effect profile resembles the foE and N(h) changes reported several times in the literature. A possible linear relation between the ionospheric and magnetic effects is suggested. It is also proposed that simultaneous observations of X-Ray sources on the Sun, ionospheric parameters and surface magnetic field changes must be conducted during next eclipses to establish more clearly its relationships. Furthermore, a revision of the theoretical basis of the generation of the magnetic effect must be made in order to explain the observations.

KEY WORDS: Magnetic eclipses effect, magnetic variations, solar eclipses.

INTRODUCTION

The effects of a solar eclipse on the values of the geomagnetic field observed at ground level have been studied since the early days of this century (see Table 1). However these eclipses are often visible only in remote areas where scientific observations are difficult or impossible. Normal daily variations could mask the small eclipse-induced changes, especially if classical fiber-suspended variographs are used. Chapman (1933), and Chapman and Bartels (1940) expressed some doubts about the feasibility of recording small geomagnetic variations due to ionospheric changes occurring in short periods of time.

However, technical advances in ionospheric studies and the consequent improvement in the determination of the physical parameters at the E-ionospheric layer give the opportunity to detect small variations of electron content due to an almost sudden, short-duration change of the solar ionizing radiation. The measurements at the levels where S and S_q variations originate, produced an increased interest in the subject. When ground level and ionospheric measurements are simultaneous, a more accurate study is possible, and the results could show more clearly the different processes that occur in the ionosphere and their connection with the magnetic field variations. A good example of this kind of studies was made during the November 12, 1966 solar eclipse (Bomke *et al.*, 1967). In this eclipse, the totality band crossed the equatorial electrojet and included some geomagnetic stations in Peru, specifically Huancayo. Ionospheric sounding observations were made at the same time at Ñaña, Peru. Clear simultaneous changes on the horizontal component H, measured at ground level and on some ionospheric parameters were observed (Bomke *et al.* 1970). Also, Nagata *et al.* (1955) obtained clear effects during the May 9, 1948 eclipse, on the ionospheric layers and the geomagnetic field. Later Kato (1960, 1965), and Bomke *et al.* (1967, 1970) obtained clearer evidence of simultaneous effects on the ionosphere and on the geomagnetic field. Also, it was observed that the instants of mid-totality and the maxima of the geomagnetic and ionospheric effects were not simultaneous. Some authors [i.e. Bomke *et al.* (1970), Rishbeth (1970), and Rowe *et al.* (1970)] have noted that covering and uncovering by the Moon of the localized sources of intensified X-rays and Extreme Ultra-violet (EUV) radiation from solar flares or solar active regions could explain the irregularities in the solar eclipse effects on the ionosphere or the ground level magnetic field.

A remarkable eclipse took place on July 11th, 1991. The totality band crossed a large part of the planet (Bangerth *et al.*, 1989), from Hawaii to the Brazilian

Table 1

Selected references on geomagnetic and ionospheric effects of solar eclipses.

Eclipse	References	Studies
1900, May 28th	Bauer (1900)	1
1901, May 18th	Bauer (1902)	1
1905, Aug 30th	Nordmann (1907)	1
1912, Apr 17th	Chree (1913)	1
1919, May 29th	Bauer (1920)	1
1932, Aug 31st	Henderson (1933), Chapman (1933)	1,2
1948, May 9th	Nagata et al. (1955)	1
1954, Jun 30th	Egedal and Ambolt (1955)	1
1954, Dec 25th	Van Wijk (1955)	1
1955, Jun 20th	Kato (1956), Datta (1972)	1,2
1958, Oct 12th	Kato (1960), Matsushita (1966), Van Zandt et al. (1960)	1,2
1962, Feb 5th	Kato (1965)	2,3
1966, Nov 12th	Bomke et al. (1967), Bomke et al. (1970)	1,2
1970, Mar 7th	Rishbeth (1970), Bienstock et al. (1970), Klobuchar and Malik (1970), Almeida and da Rosa (1970), Rowe et al. (1970), Flaherty et al. (1970), Carson et al. (1970), Lanzerotti et al. (1971), D'Costa et al. (1981).	1,2,3
1972, Aug 10th		
1973, Dec 24th		
1974, Dec 13th	D'Costa et al. (1981)	1,2,3
1977, Oct 12th		
1991, Jul 11th	Brenes et al. (1992)	1

1 Geomagnetic effects

2 Ionospheric effects

3 Magnetic pulsations

Amazonic Region. Many populated areas were covered by the Moon shadow and, by coincidence, two Latin-American magnetic observatories were inside the umbra (Teoloyucan, Mexico and Chiripa, Costa Rica). A program on geomagnetic observations was scheduled (Muniz Barreto, 1992) and the main observing activities were concentrated in Mexico for the following reasons: (a) Teoloyucan Magnetic Observatory was very near the central line of the totality band, (b) The duration of the totality phase (2nd. and 3rd. contacts) at Teoloyucan was 6.39 minutes for the longest eclipse of this century observed at any magnetic observatory.

At Teoloyucan the Suns elevation was high (about 80°) during the totality. Two favorable consequences could be obtained from this: A high daily amplitude could be expected and as the incidence of the ionizing solar radiation was almost vertical, the rate of electron-ion pair production before and after the eclipse is at its maximum. Therefore the fall of the rate of ion production was expected to be greater than in other cases.

Four observing stations were placed in Mexico; their locations as well as the eclipse parameters are presented in Table 2. The characteristics of the instruments utilized in each station are described in Table 3. This paper describes the magnetic observations obtained and presents some results from the analysis of variations and the corresponding possible relations with different eclipse related phenomena and ionospheric processes. Also some comments about the magnetic observations at Chiripa (Costa Rica), Fúquene (Colombia), Huancayo and Ancón (Peru), and Tatuoca and Vassouras (Brazil) magnetic observatories are made.

MAGNETIC OBSERVATIONS DURING THE ECLIPSE

In order to measure possible changes in magnetic elements during the 11th July, 1991 solar eclipse, an international team was formed, including personnel from Mexico, Brazil and Germany. Four places were selected: Teoloyucan Magnetic Observatory and two other places in the center of totality, one up-shadow and the other down-shadow (Tuxpan, Nay.; and Tehuacán, Pue. respectively). The fourth point (Actopan, Edo. de México) was at the border of totality (see Figure 1). The geographic positions of the four stations are listed in Table 2 together with the local times of the four contacts of the optical eclipse. Total magnetic intensity was measured at the four stations in a specific routine (see Table 4), designed to follow the main eclipse phases. Station 2 data had problems and was not considered for final results.

At Teoloyucan we obtained a clear continuous record only for the horizontal component H; also large time-spaced control observations of declination (D), and inclination (I) were obtained. In a separate experiment, ionospheric vertical sounding was realized at the "El Cerrillo" Mexican ionospheric sounding station. This station was also in the path of totality (Pérez de Tejada, 1992).

Data was collected also from the Brazilian observatories of Tatuoca and Vassouras and the Peruvian stations of Huancayo and Ancon. The observations at the Costa Rica magnetic observatory of Chiripa were reported by Brenes *et al.* (1992).

RESULTS

Figure 2 shows the variation of the horizontal component H, for the geomagnetic field recorded at Teoloyucan on July 11th, 1991. According to the primary visual characterization the day was magnetically quiet with characteristic index C = 0 and a very clear eclipse signature is present. H magnetogram was digitized and reproduced using a cubic spline technique to obtain one-minute samples. It is fortunate that the eclipse started just after the time of H maximum daily value. The H digitized data was plotted in the same scale for F at all the stations.

In Figures 3a, 3b, and 3c are shown the total intensity F observations at Teoloyucan, Tehuacan and Actopan respectively. The plotted values are the result of smoothing the raw data in order to reduce field fluctuations, as well as to take into account the accuracy of the instruments, and to reduce possible effects of magnetic pulsations present during the event. After smoothing, a cubic spline routine was used to obtain one-minute samples. Mainly at the beginning and the end of the eclipse some fluctuations could be caused by possible pulsations, as reported often in the literature [see for example: Kato (1965), Lanzerotti *et al.* (1971), D'Costa (1981)]. However, this aspect of the event is beyond the scope of this paper.

Owing to the difficulty to forecast or represent S or S_q variation for a specific day, when no regular record for the previous or following days are available, we used the approach of Van Wijk (1955) and Bomke *et al.* (1967) to analyse eclipse magnetic and ionospheric data.

Thus the observed data for the horizontal component at Teoloyucan and total intensity at the three stations were smoothed and sampled at one minute intervals as explained before. Next a virtual S_q daily variation curve was traced between the instants of the first and fourth contacts, in such a way that the recorded undisturbed parts of the daily variation fit smoothly the virtual segment (see Figure 2).

As the duration of the eclipse main phase was relatively short with respect to the daily variation changes, the procedure permits to follow the S variation relatively safely. The errors expected with this method, as can be seen from the curves, would be about 1 to 2 nt, in the same order of instrumental precision. From this expected undisturbed solar variation H_o or F_o we obtain the eclipse effect (H_e, or F_e) substracting the observed values [equations (1) and (2)].

$$H_e = H_{obs} - H_o \qquad 1$$

$$F_e = F_{obs} - F_o \qquad 2$$

Table 2

Geographic positions and eclipse times at the observing points

Station	Geog. Pos. Lat. (N)	Long. (W)	Contact times 1st	2nd	3rd	4th
Teoloyucan	19°44'48"	99°10'53"	11:52:51	13:19:44	13:26:23	14:46:33
Tuxpan	21°56'52"	105°17'30"	11:36:00	13:02:16	13:09:08	14:32:18
Tehuacán	18°27'51"	97°23'20"	11:59:22	13:26:15	13:32:54	14:53:04
Actopan	20°15'40"	98°45'10"	11:54:41	13:21:39	13:28:18	14:48:28

1st contact: beginning of partial eclipse
2nd contact: beginning of total eclipse
3rd contact: end of total eclipse
4th contact: end of partial eclipse

Table 3

Magnetic equipment utilized at the different observing points

No.	Station	Equipment
1	Teoloyucan	Traditional Variometer Set (H, D, Z) Askania, 40 mm/hr (only H record available).
		Declination and Inclination Magnetometer DIM-100
		Proton Precesion Magnetometer (Geometrics) Total Magnetic Intensity
		Quartz Horizontal Magnetometer (QHM) Horizontal and Declination measurements
2	Tuxpan, Nay.	Fluxgate Magnetometer (EDA) Three component (X, Y, Z)
		Proton Precesion Magnetometer (Geometrics) Total Magnetic Intensity
3	Tehuacán, Pue.	Proton Precesion Magnetometer (Scintrex) Total Magnetic Intensity
4	Actopan, Hgo.	Proton Precesion Magnetometer (Geometrics) Total Magnetic Intensity

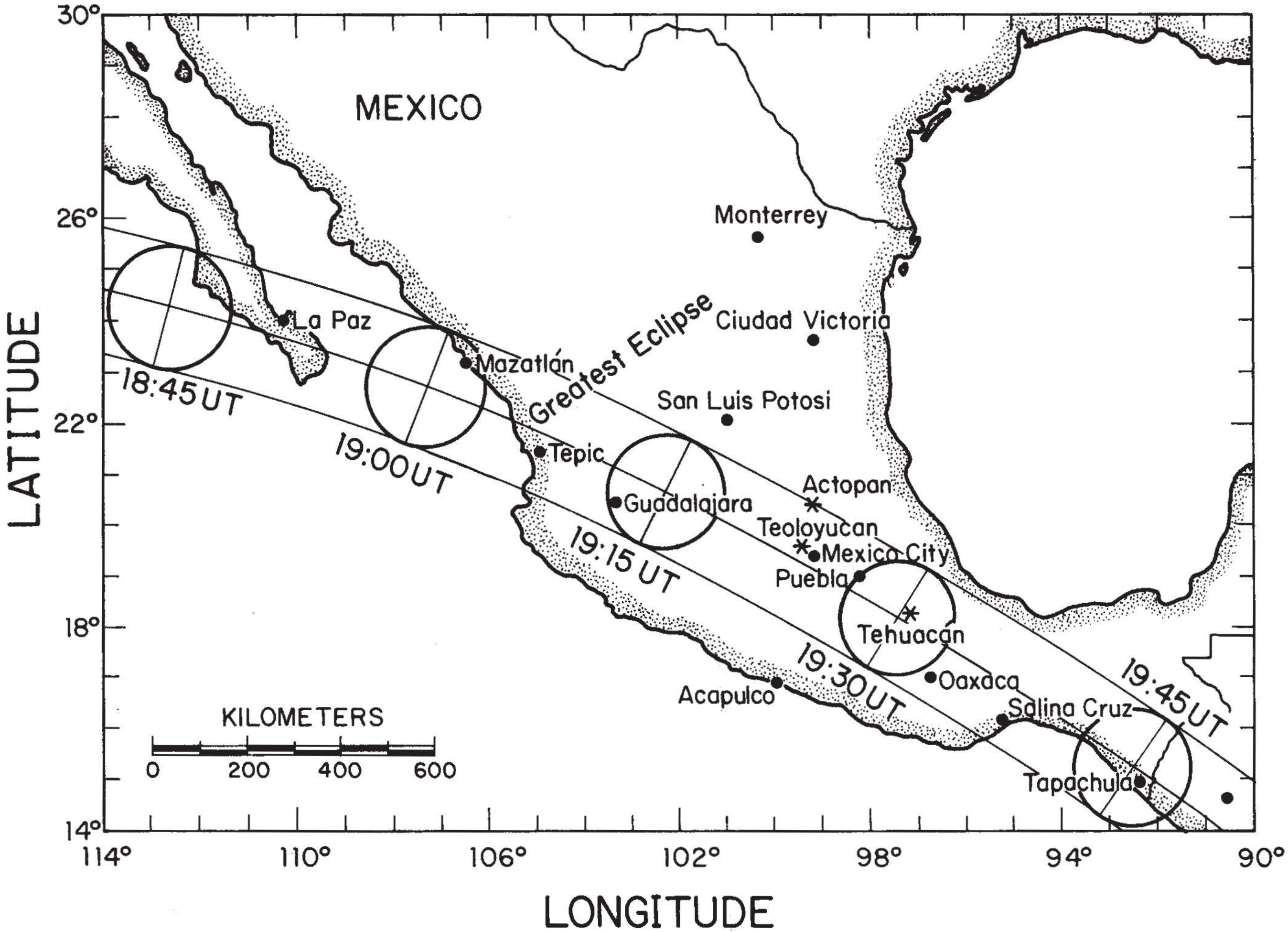


Fig. 1. Solar Eclipse path on July 11, 1991 over Mexico showing the magnetic observing points.

Table 4

F routine observation at Teoloyucan, Tehuacan, and Actopan

Local time (Hours)	Time between measures
10:00 - 11:00	15 minutes
11:00 - 11:50	10 minutes
11:50 - 13:00	5 minutes
13:00 - 13:20	1 minute
13:20 - 13:50	0.5 minute
13:50 - 14:10	1 minute
14:10 - 15:20	5 minutes
15:20 - 16:10	10 minutes
16:10 - 17:10	15 minutes

where H_{obs} and F_{obs}, and H_o and F_o are the one minute samples of the observed horizontal component and total intensity values, and the 'undisturbed' H and F variations, respectively.

In Figures 4a, b, c the eclipse effects on the total intensity at the three stations are shown. From these figures it is possible to estimate a value of -12 to -14 nt for the maximum effect of the eclipse on this element. According to Nagata *et al.* (1955) and Matsushita (1966) the similitude of these values could be expected as the area affected by the eclipse is very large. The effect on the horizontal component at Teoloyucan is about 27 to 30 nt. This difference indicates that the changes in the S_q currents are mainly overhead.

The maximum effect on the horizontal component of the geomagnetic field at Teoloyucan show a clear lag of around 10 minutes respect to the middle of the optical eclipse (see Figure 2). Such lag is not evident in the total magnetic intensity in any of the three stations. The ionospheric soundings reported by Pérez de Tejada (1992) also shows a clear asymetry between the initial and recovery phase of the event at the F-region. From the few values for Z, D and I that were obtained before, during and after the eclipse at Teoloyucan, a possible maximum effect of about

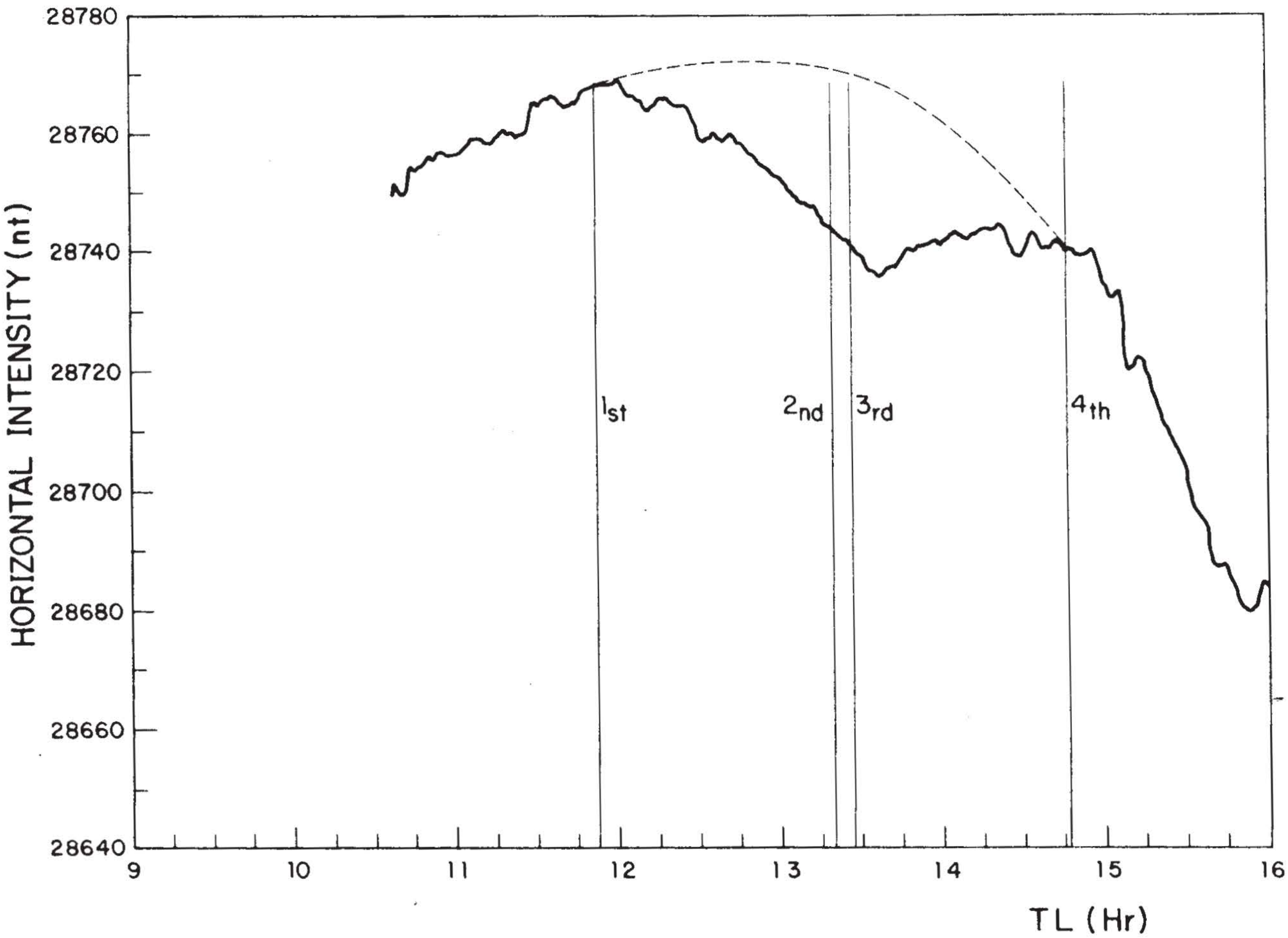


Fig. 2. The July 11, 1991 digitized Teoloyucan horizontal component magnetogram indicating the eclipse contact times. The dashed line represents the expected Solar quiet variation for the day.

-6 to -8 nt on Z (calculated) and +10' in D was noticed. Inclination values did not show any conclusive effects.

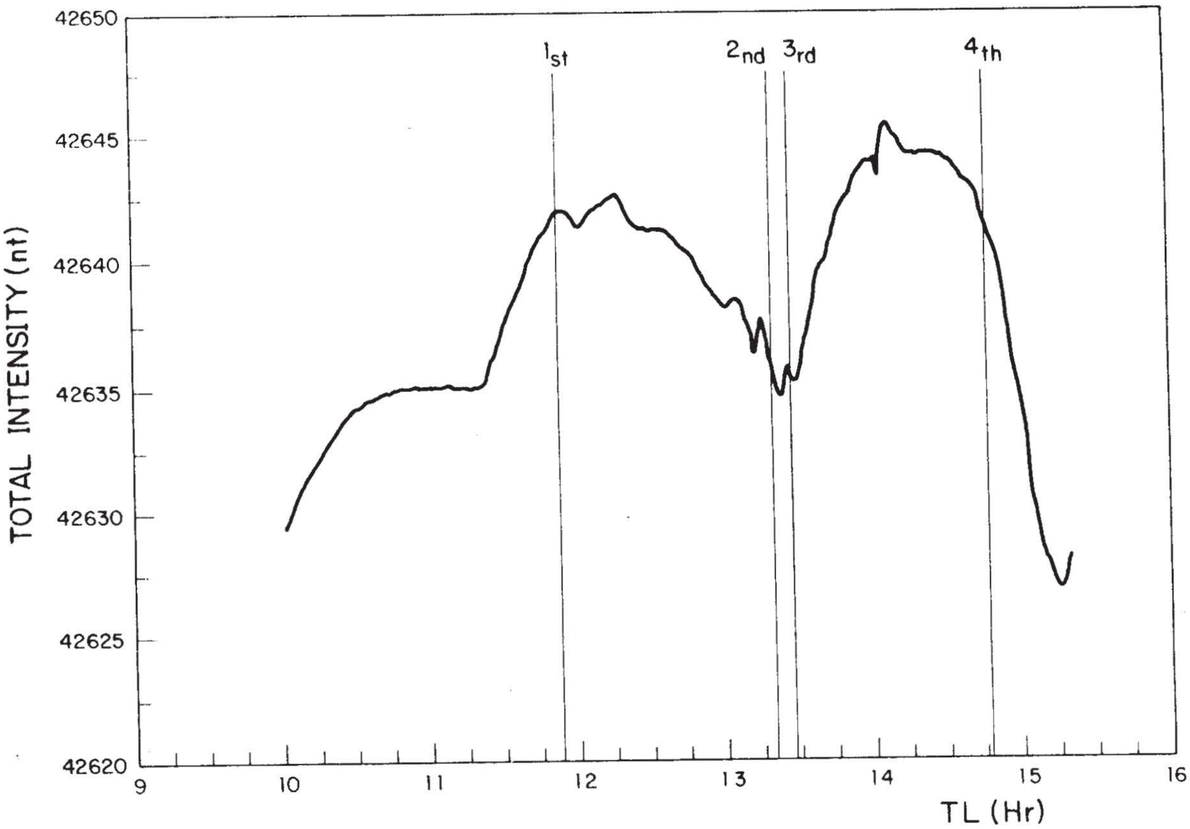
The total intensity changes observed at the three stations clearly resemble those reported previously in the literature. Kato (1960), and Bomke *et al.* (1967) reports changes in H of the same shape and magnitude as that observed in our experiment. Also, the changes in the ion-pair production rate reported by Bomke *et al.* (1970) and the effective electron content changes reported by Bienstock *et al.* (1970) show a very similar pattern.

In the other Latin-American observatories the magnetic records don't show any conclusive eclipse effect. This could be explained by the fact that the Moon's shadow at this later stage of the phenomena is much more grazing and the shadow's velocity increases steeply at the end causing the duration of the eclipse to become shorter and the ion production capacity of the Sun's radiation to be greatly reduced.

CONCLUSIONS

A clear solar eclipse effect on the geomagnetic field at three Mexican stations was recorded. The strong similitude of the effect on points separated by more than 150 km indicates that the effect is not local in accordance with the works by Nagata *et al.* (1955) and Matsushita (1966). The maximum effect of the eclipse on the total intensity F, of about -12 to -14 nt, is practically of the same magnitude at the three stations. At Teoloyucan the horizontal component shows a relatively large lag between the maximum of the optical eclipse and the maximum effect on the geomagnetic field; this lag is not apparent in the total intensity. A lag of this kind in H has been reported several times (Bomke *et al.* 1970, Flaherty *et al.* 1970, Bomke *et al.* 1967, Pérez de Tejada, 1992) and it could be related to photochemical inertia in the ionospheric layers or the influence of X-ray sources outside of the Sun's disk. The asymmetry in the behaviour of the F_oF2 between the initial and final phases of the eclipse at "El Cerrillo" also supports this conclusion. The lack of effects at the other Latin-American observatories supports the interpretation that the ionospheric E-layer is the place where the magnetic changes are generated.

The lack of a clear lag in the total intensity in any of the stations points to the fact that this is a geometric characteristic of the eclipse effect. In fact the long duration of



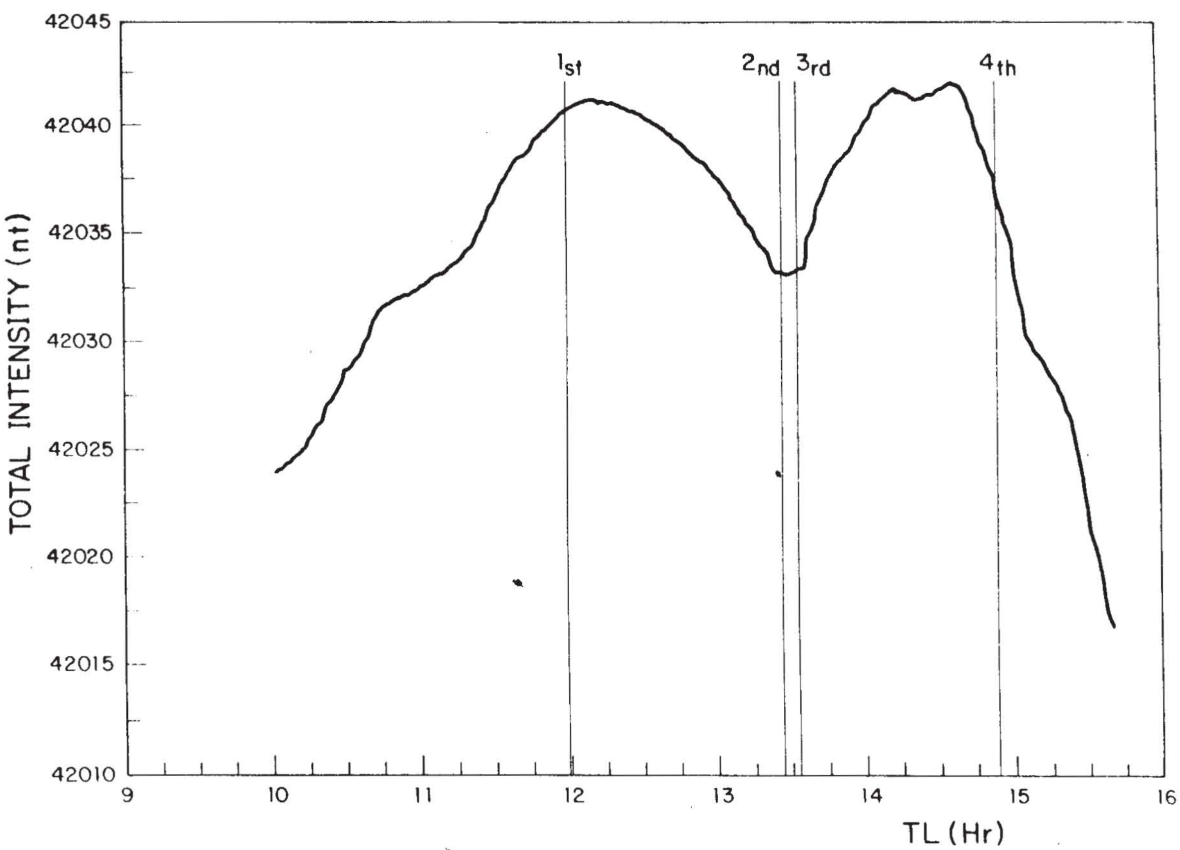
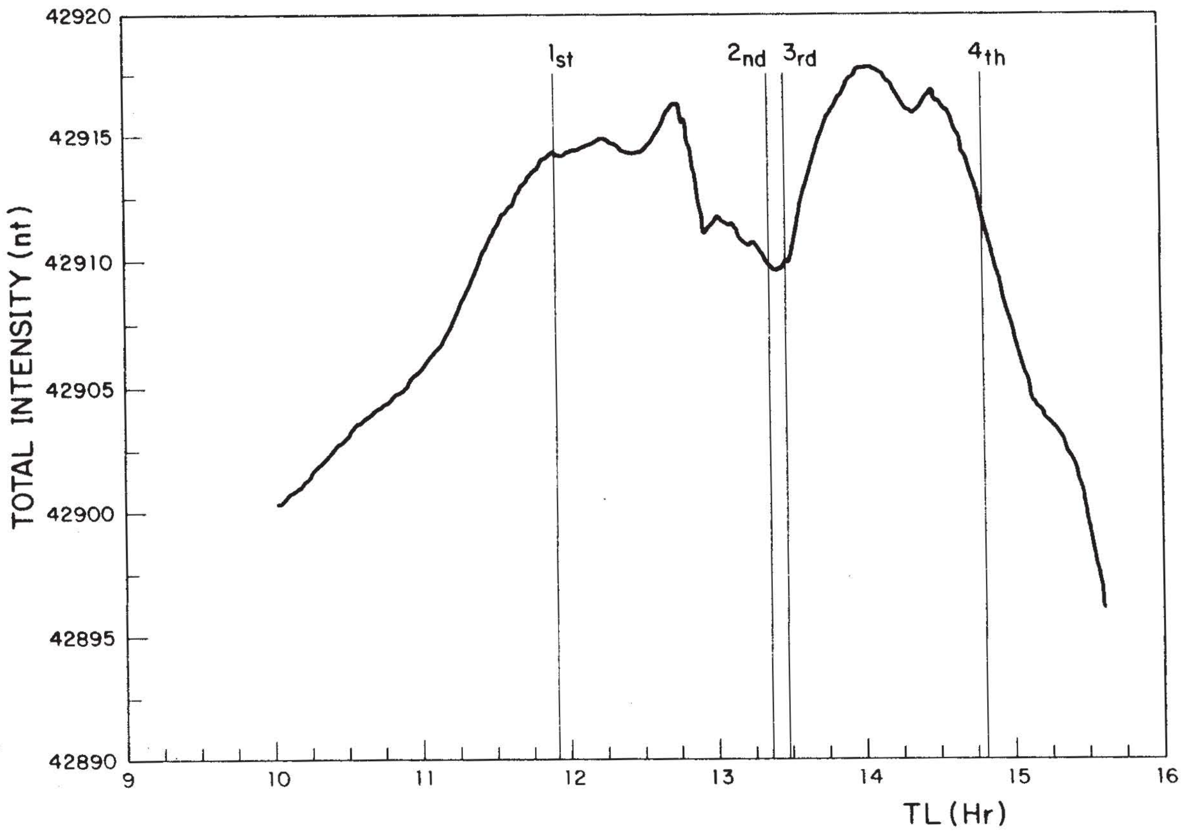


Fig. 3. Total magnetic intensity (F) observations at: a) Teoloyucan, b) Tehuacán, c) Actopan.



Cont. Fig. 3.

the totality could also possibly explain the large lag as the ionization reduction is larger than in short phenomena. This difference in the effects on H and F has not been reported previously in the literature and we think that this indicates that the magnetic vector experiences a rotation during the eclipse. However, it is necessary to have continuous three-component magnetic observations in order to reach more secure conclusions.

The behaviour of the magnetic field during the eclipse does not resembles that predicted by Matsushita (1966). According to the time of the day, the geomagnetic latitude at Teoloyucan and the expected S_q current sistems, no effect should have been present in D and Z. As this is not the case, we consider that it may be convenient to revise the theoretical aspects of the Solar daily variation and its relation to the ionospheric current systems. It is interesting to note that the duration of the total eclipse does not appear to affect the magnitude of the decrease in the H or F magnetic elements. Also, the reported lag in H between the maxima of surface optical totality and the maximum ionospheric and magnetic effects is possibly due to the geometric characteristics of the event.

Comparing the behaviour of the horizontal component changes and of the electron concentration and F_oF2 frequency during the eclipse it is apparent that the relation between them is quasi-linear. The growth, maximum and decrease of these parameters are quite similar in shape and time, indicating that second-order effects are relatively small and that the magnetic effect is almost simultaneous with the ionospheric one. From this we conclude that the changes in H at the Earth's surface and the changes of the free electron concentration, ionospheric conductivity, and E-region parameters at the ionosphere are mainly linearly related.

For this reason and in order to establish a more detailed relation for the different physical processes involved it is suggested that in future total solar eclipses, coordinated observations of the Sun's X-ray and EUV emissions, electron concentration, electric fields and vertical motions at the lower ionosphere and vectorial surface geomagnetic changes must be conducted. From these simultaneous observations, a more clear cause-effect relation could be obtained.

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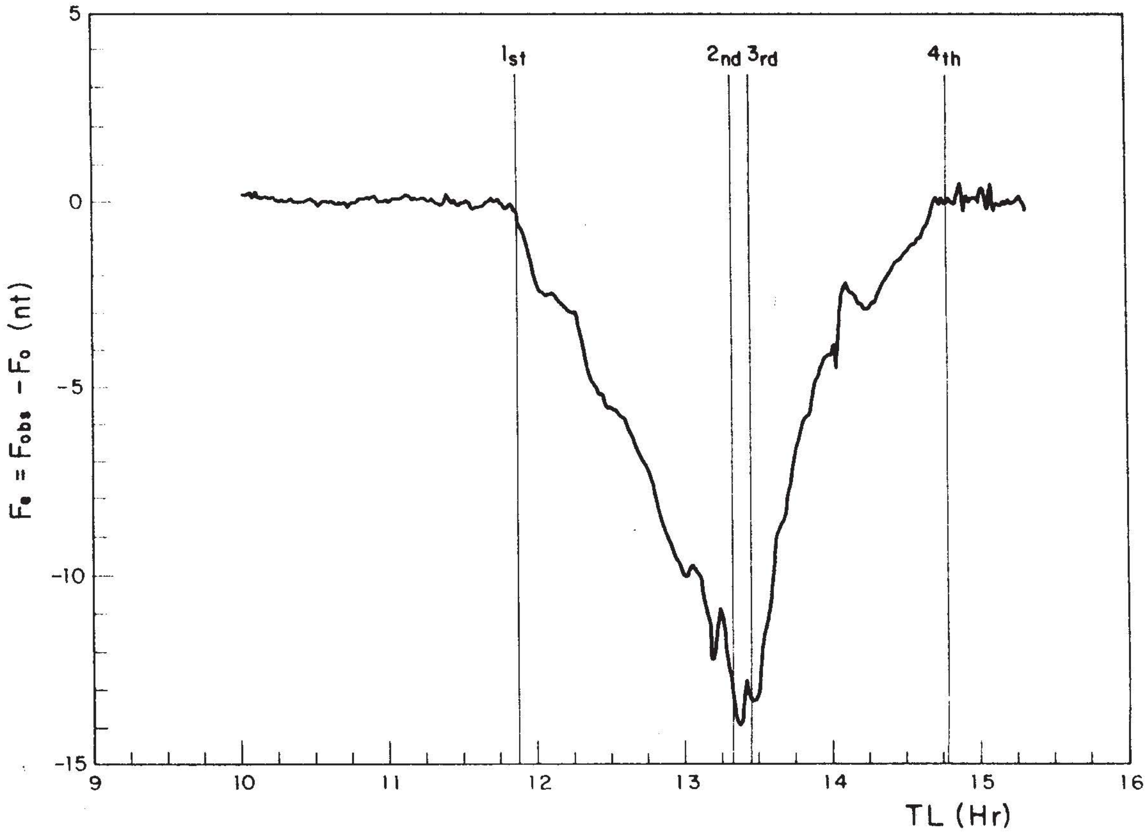


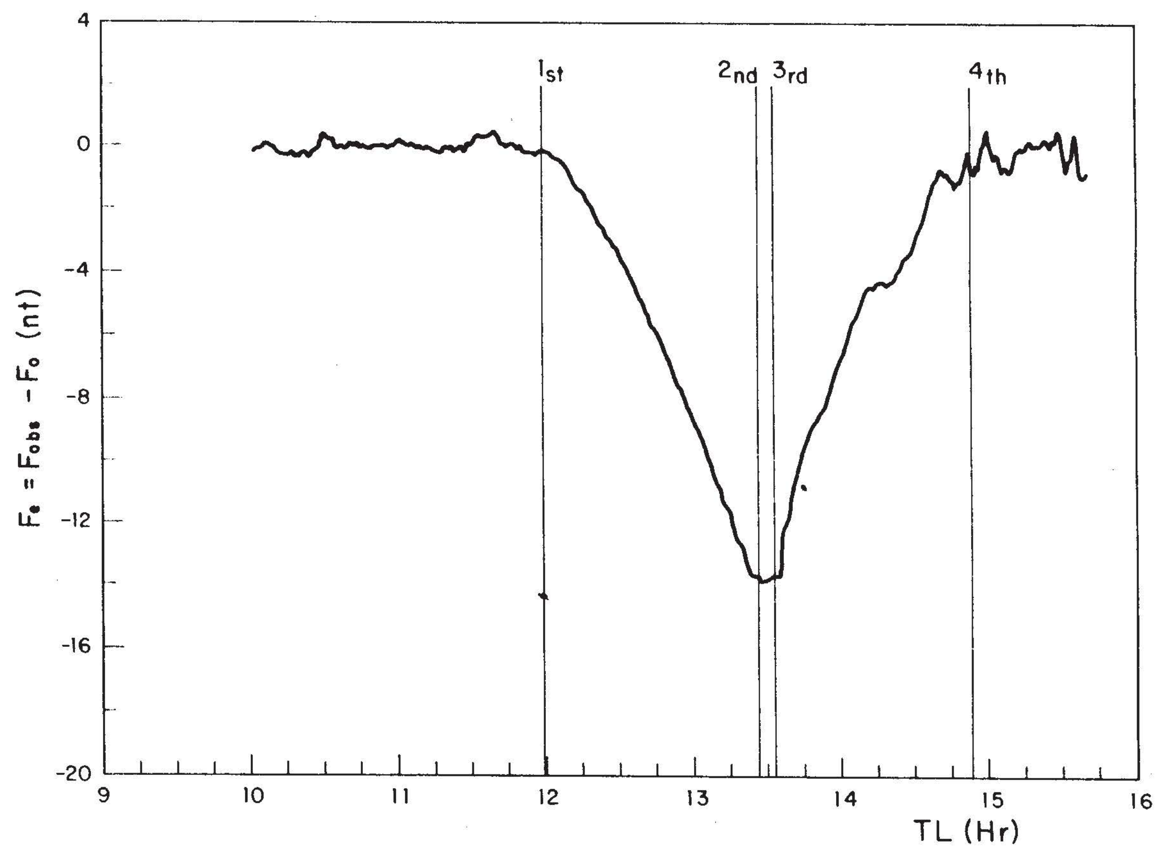
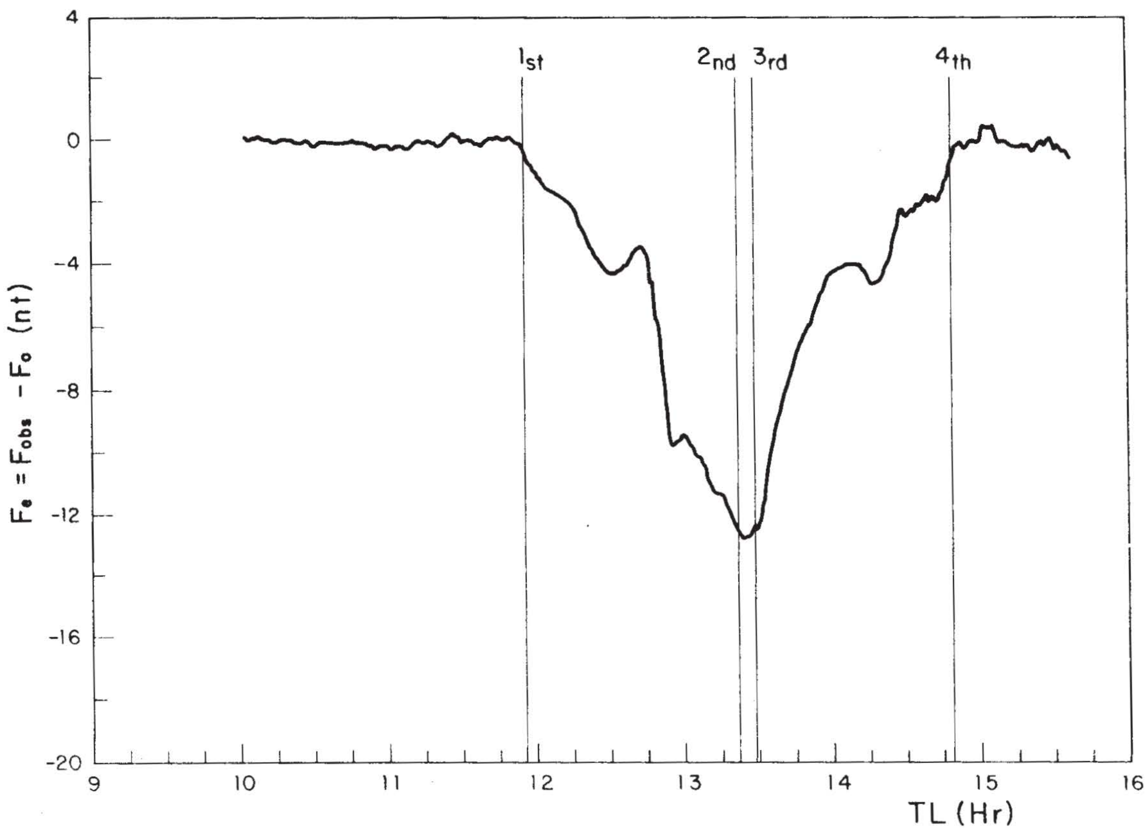


Fig. 4. Solar Eclipse effect on the total magnetic intensity (F) at: a) Teoloyucan, b) Tehuacán, c) Actopan.



Cont. Fig. 4.

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