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On the ionospheric effects of 26 June, 1999 solar flare

A. Abseim [a], M. Youssef [b,*], S.M. Youssef [c], Magdy Y. Amin [c], M.G. Rashed [b], M.A. Semeida [b]

[a] The Libyan Center of Remote Sensing and Space Science, Tripoli, Libya
[b] National Research Institutes of Astronomy and Geophysics (NRIAG), Egypt
[c] Astronomy Department, Faculty of Science, Cairo University, Egypt

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KEYWORD

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Abstract In this paper we traced the possible influence of the solar flare of June 26, 1999 on the ionosphere throughout the F2-layer parameters. This study concentrated on two parameters, f_oF_2, the critical frequency of the ordinary component of the F2-layer; and *hc*, the height of the maximum obtained by fitting a theoretical h′F curve for the parabola of best fit to the observed ordinary mode trace near f_oF_2 and correcting for under-lying ionization. The results showed that the relation between the amplitude of averaged sudden enhancements of the perturbations for the critical frequency of the ionospheric F2 region, Δf_oF_2 (for data obtained from 8 ionosonde stations), and the duration of the flare is more applicable to the empirical formula given by Youssef (2008). Since we found this relation is linear and has a very strong correlation. In addition, we found that the relation between the average amplitude, of Δf_oF_2, for the 8 selected ionosonde stations, and the flare flux is not a linear. For the second parameter, *hc*, it was found that, the *hc* amplitude depends on the location of the station on the Earth, and it reaches its maximum value during the decay phase of the studied flare.

Introduction

Since 1960s, the responses of the ionosphere to solar flares have been studied continuously with various methods, such as the Faraday rotation measurement, incoherent scatter radar (ISR), and global positioning system (GPS). For example, Donnelly (1967, 1969) reported the sudden frequency deviation (SFD) during flare events. Thome and Wagner (1971) analyzed the height distribution of increases in electron density Ne during the May 1967 flares on the basis of ISR observations. Mendillo et al. (1974) analyzed the global solar flare observations by using 17 stations in North America, Europe, and Africa for the first time and proposed that the enhancement of TEC at low latitude was higher than that at high latitude. Wan et al. (2005) analyzed the sudden increase of total electron content (SITEC) during July 14, 2000 flare by the GPS data and they found that both the flare-induced TEC variation rate and the TEC enhancement are proportional to the flare radiation and inversely proportional to the Chapman function ch(w). Global views of solar flare effects of the ionosphere by using the GPS network observations have been

* Corresponding author. Tel.: +20 02 25560046.
E-mail address: ghareebmoh94@yahoo.com (M. Youssef).
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achieved (e.g. Afraimovich, 2000; Leonovich et al., 2002; Liu et al., 2004; Tsurutani et al., 2005; Zhang and Holt, 2002; Zhang and Xiao, 2005). Afraimovich (2000) developed a novel technique to detect global ionospheric effects of solar flares, and effects of two powerful flares of the ionosphere were studied as examples. Leonovich et al. (2002) proposed a new method to estimate the contribution to the enhancements of TEC at different altitudes for the July 14, 2000 flare, and found that 25% of the TEC increments come from altitudes above 300 km. Zhang et al. (2002) reported that the TEC enhancement becomes smaller when the solar zenith angle (SZA) is larger. Liu et al. (2004) suggested that TEC is a suitable tool to monitor the overall variations of flare radiations, while the rate of change of TEC (rTEC) is capable of detecting sudden changes in the flare radiations. Tsurutani et al. (2005) reported persistence in TEC for several hours on the October 28, 2003 flare and found strong center-to-limb effects in the solar flare EUV spectra by comparing the October 28, 2003 flare event with the November 4, 2003 event. By using the GPS data from 114 GPS stations of the International GPS Service for Geodynamics (IGS), Zhang and Xiao (2005) analyzed the morphological features of the TEC variations in the sunlit hemisphere during the solar flare on October 28, 2003. Furthermore, it is found that, there is a negative relationship between the TEC enhancements and the distance between the Earth and Sun (seasonal effect), and also a negative relationship between the amplitude of SITEC and the duration of the flares. In space physics researches it is important to use the data from mission and satellites. So we have used two types of data, one for the X-ray flux measured by GOES and the other for the f_oF_2 obtained from ionosonde stations. The dependence of ionospheric characteristics on solar activity, such as solar flares was ascertained in the early regular ionospheric observations. The vertical-incidence ionosonde network with its long series of measurements over the world provides the basis for F-region predictions.

Results and discussion

The critical frequency of F2 region f_oF_2

We have studied the effect of the selected solar flare of June 26, 1999 on the ionosphere. The spectral characteristics of this event are shown in Table 1, where its x-ray flux equal o 3×10^{-3} erg cm^{-2} s^{-1}. Since the ionospheric electron density is produced mainly by solar radiations (EUV, X-rays, etc.), which are generated mostly by solar flare events, these radiations are known to show very definitive solar cycle variations, therefore, electron concentration and critical frequency of F2 region (f_oF_2 in MHz) are also expected to reflect these variations. So we try to examine the response of the critical frequency of F2 region (f_oF_2 in MHz), by measuring the amplitude of the short period enhancement disturbances of f_oF_2 caused by the selected solar flare. The station codes, names and their geographical longitudes and latitudes used to measure f_oF_2 are listed in Table 2.Now there are many data available such as Spider Data for ionosphere to show the connection between the F-layer parameters variations with solar activity. The physical nature and dependence of the ionospheric characteristics remains the important subject of investigation up till now. In this section, the f_oF_2 of F_2 region, which is an important parameter namely, the critical frequency of F_2-layer, a measure of maximum electron density of the peak of F_2-layer is studied. The response of the critical frequency of F_2 region (f_oF_2) can be estimated by measuring the amplitude of the short period enhancement disturbances of (f_oF_2) caused by the studied solar flare that occurred on June 26, 1999. The characteristics of spectra of this solar event are shown in Table 1, with its X-ray flux equal to 1.1×10^{-2} erg cm^{-2} s^{-1}. The critical frequency of F2 region (f_oF_2) has been measured by different ionosonde stations on the earth. Among more than 100 stations included in this study, eight stations recorded a noticeable variation in (f_oF_2) value during the duration of the Table flare. Table 2 gives the station names, station codes, the geographical longitudes and latitudes of these eight ionosonde stations and the measured amplitude in MHz as well.

Table 2 A list of ionosond stations from which data were selected with their geographical longitude and latitude.

Station name	Code	Lat. (0.0)°	Long. (0.0)°	Amplitude (A) (f_oF_2) (MHz)
Magadan	MG560	60.0	151.0	1.04
Townsville	TV51R	−19.7	149.9	1.15
Salekhrad	SD266	66.5	66.50	0.22
Rostov	RV149	47.2	39.70	0.31
Grahmstown	GR13L	60.0	26.50	1.50
Kiruna	KI167	67.8	20.40	0.44
Lycksele	SD266	64.7	18.80	0.91
Boulder	BC840	40.0	−105.3	0.33

It is found that the considerable changes of critical frequency of F_2 region (f_oF_2) were mostly recorded through most stations that are located in the northern hemisphere of the Earth. Many stations did not record any data, while few of them had a little response to this solar event. Their responses depend on their location relative to the solar disk at the observation time. The amplitude (A) of the enhancement disturbances of (Δf_oF_2) is then measured in MHz during the period of the solar flare, with respect to a quite ionospheric day as base line. Then the value of (Δf_oF_2) can be calculated as following:

$$\Delta_oF_2 = (f_oF_2)_a - (f_oF_2)_q \tag{1}$$

Table 1 The list of selected flare spectra characteristics.

Date	Time of our observed spectra		Solar geographic data			Geographic		NOAA/USAF region	Dur. (Min)	IMP	
	Start h: m: s	End h: m: s	Start h: m	Max. h: m	End h: m	Lat.	Long.			Opt.	X-ray
26 June, 1999	07:23:33	08:05:51	07:18	07:20	08:09	20N	09E	8598	51	sF	C7.0

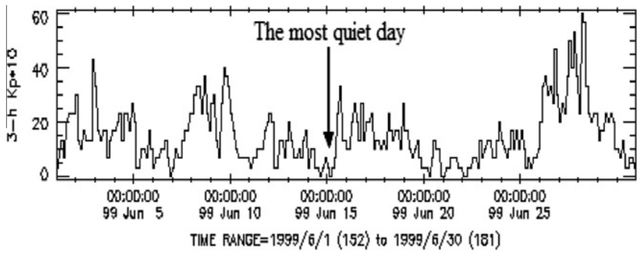

Fig. 1 The most quite day during June 1999.

where (f_oF_2) is the value of empirical frequency of the F2 region (f_oF_2) recorded when the flare event occurred, $(f_oF_2)_q$ is the value of f_oF_2 during the most quiet ionospheric day of the same month of the flare event as a base line or reference value. Fig. 1 shows the most quiet ionospheric day which is chosen according to the time series of the K_p index (the index measures the magnetic disturbances of the ionosphere region at middle latitudes) during the month of the flare event. This most quiet ionospheric day was found on June 15, 1999.

The sudden enhancement of (Δf_oF_2) during the studied flare of June 26, 1999 observed from eight ionosond stations is presented in Figs. 2–5. These figures illustrate noticeable positive enhancement of (Δf_oF_2). It is natural to expect an increase in the electron density in response to the solar flare. It is seen from these figures that the (f_oF_2) during the duration of studied flare was gradually increasing. The maximum in (f_oF_2) is observed about 07:56:57 UT, i.e. nearly at the end of the decay phase of the flare. It is found that the value of measured amplitude (A) clearly depends on the location of the station on the Earth and the universal time. Its maximum value is obtained from Garhamstown station. In 2008, Youssef studied the effect of the most powerful solar flares recorded during the 23rd solar cycle. These flare events have been selected from IPS Radio and Space Services as shown in Table 3.

Youssef (2008) found that the dependence of the amplitude (A) of sudden enhancement of (Δf_oF_2) on the duration of the most eight powerful flare events during 23nd solar cycle had nearly linear relation with correlation coefficient (R = 0.89) as seen in the Fig. 6 and was given by:

$$\Delta f_oF_2 = -1.6434 + 0.13475(f_D) \qquad (2)$$

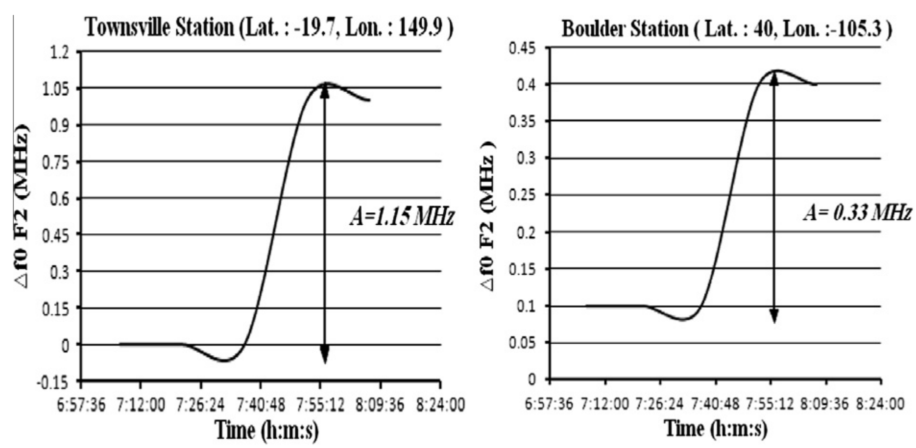

Fig. 2 The value of the amplitude (A) of the sudden enhancement of (A/5}(Δf_oF_2) during the period of the studied flare on June 26, 1999 observed from Townsville and Boulder ionosonde stations respectively.

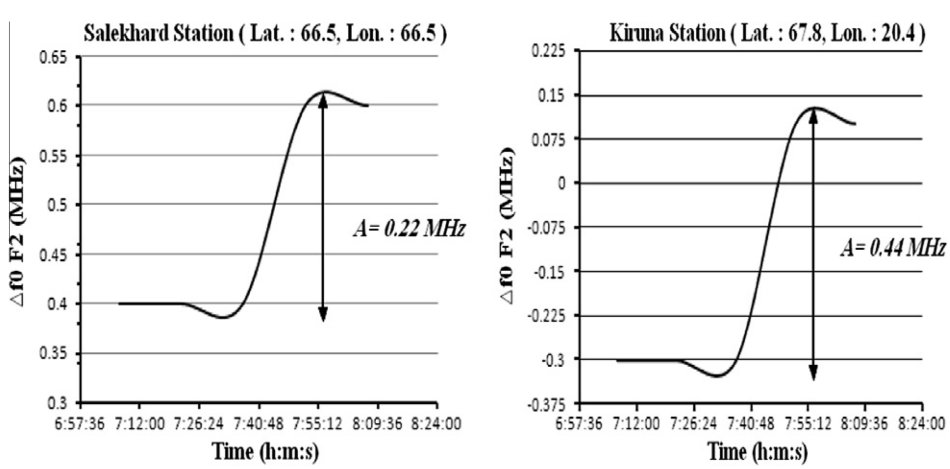

Fig. 3 The value of the amplitude (A) of the sudden enhancement of (Δf_oF_2) during the period of the studied flare on June 26, 1999 observed from Salekhrad and Kiruna ionosonde stations respectively.

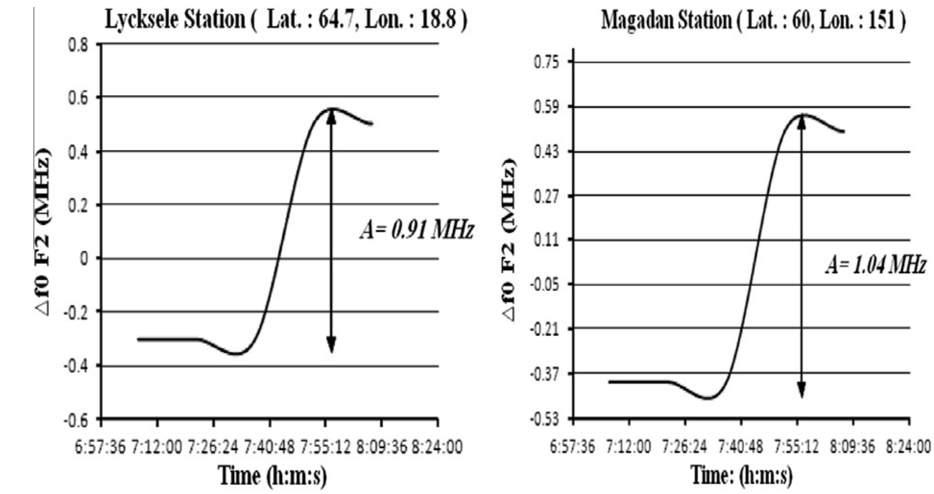

Fig. 4 The value of the amplitude (A) of the sudden enhancement of ($\Delta f_o F_2$) during the period of the studied flare on June 26, 1999 observed from Lycksele and Magadan ionosonde stations respectively.

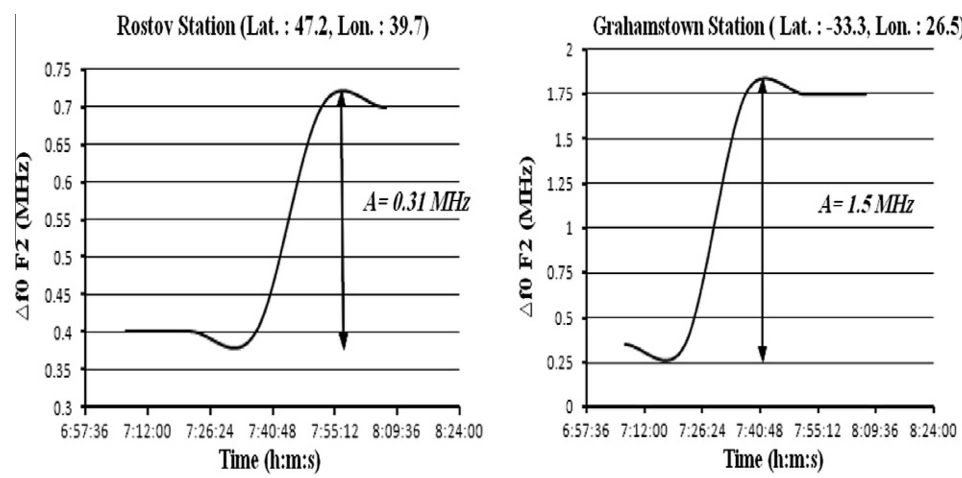

Fig. 5 The value of the amplitude (A) of the sudden enhancement of ($\Delta f_o F_2$) during the period of the studied flare on June 26, 1999 observed from Rostov and Grahamstown ionosonde stations respectively.

Table 3 The physical parameters of the flare events studied by Youssef et al. (2008).

Date (Y/M/D)	Location (Deg.)	Duration (min)	X-type	Flux (erg cm^{-2} s^{-1})	Amplitude (A) $\Delta f_o F_2$ (MHZ)
03/11/04	S19 W 83	21	X28	2.3E+00	1.1
01/04/02	–	19	X20	1.5E+00	2.4
03/10/28	S16 E 08	79	X17	1.8E−00	9.9
03/10/29	S15 W 02	12	X10	8.7E−01	0.6
050907	S11 E 77	23	X17	2.6E−00	0.2
010415	S20 W 85	31	X14	6.1E−01	0.1
971106	S18 W 63	06	9.4	3.6E−01	0.4
061205	S07 E 68	17	X9.0	7.1E−01	0.18

In the present study, when the studied solar flare of June 26, 1999 has been added to these most eight powerful flares, it is also found that the dependence of the average amplitude (A) of sudden enhancement of ($\Delta f_o F_2$) on the duration of solar flare of June 26, 1999 obtained from eight ionosonde stations is still a linear relation with correlation coefficient ($R = 0.88$) as seen in the Fig. 7 and is given by:

$$\Delta f_o F_2 = -1.7683 + 0.12953(f_D) \qquad (3)$$

where f_D is the X-ray duration of the flare, in general agreement with the empirical formula Eq. (2) obtained by Youssef (2008).

This shows that the flare duration is an important physical parameter that the sudden ionospheric disturbance induced

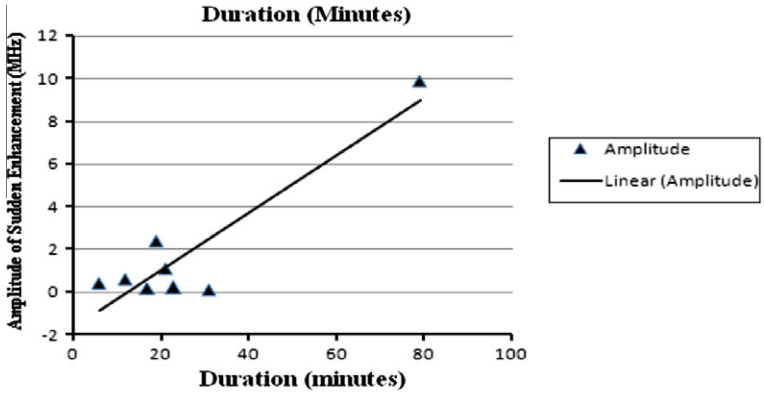

Fig. 6 The dependence of the amplitude (A) of sudden enhancement of (Δf_oF_2) on the X-ray duration of the most eight powerful flare events during 23 nd solar cycle without the studied flare event of June 26, 1999.

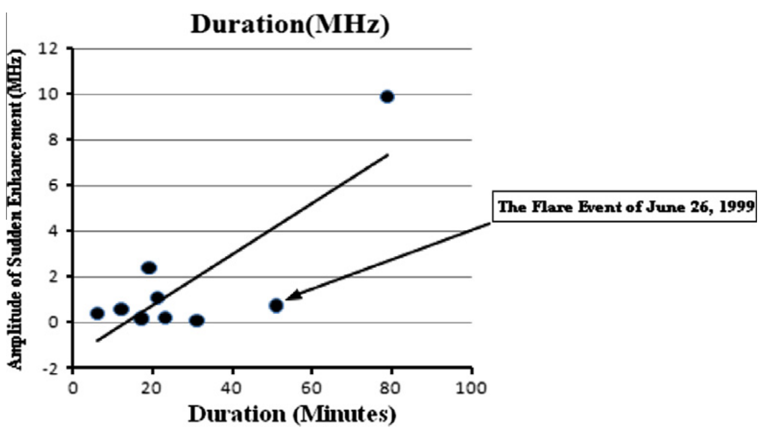

Fig. 7 The dependence of the amplitude (A) of sudden enhancement of (Δf_oF_2) on the duration of the most eight powerful flare events during 23 nd solar cycle with the addition of the studied flare event of June 26, 1999. The arrow shows the average value of amplitude (Δf_oF_2) throughout the X-ray duration of the studied flare.

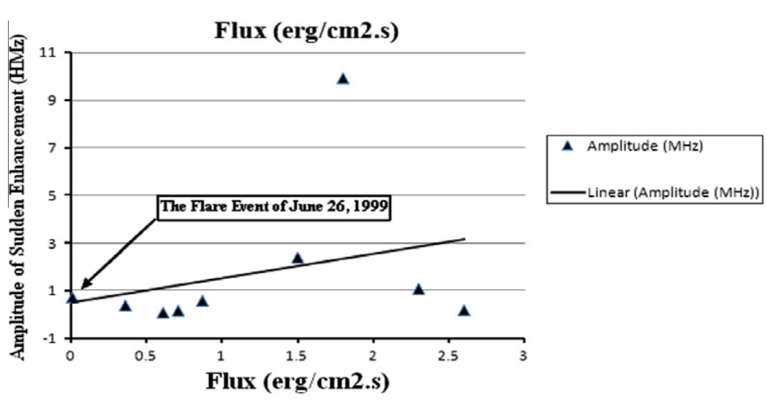

Fig. 8 The dependence of the amplitude (A) of sudden enhancement of (Δf_oF_2) on the X-ray flux of the most eight powerful flare events during 23nd solar cycle with the addition of the flare event of June 26, 1999. The raw shows the average value of amplitude (Δf_oF_2) against the flux value of the studied flare.

by a solar flare depends on. This result is in general agreement and more applicable to the empirical formula (1) obtained by Youssef (2008).

On other hand, when the flare event of June 26, 1999 is added to the most eight powerful flare events during 23nd solar cycle, the average amplitude (A) of the sudden enhancement of (Δf_oF_2) on the flux of the studied solar flare of June 26, 1999 obtained from the same eight ionosonde stations shows a weak dependence as shown in Fig. 8.

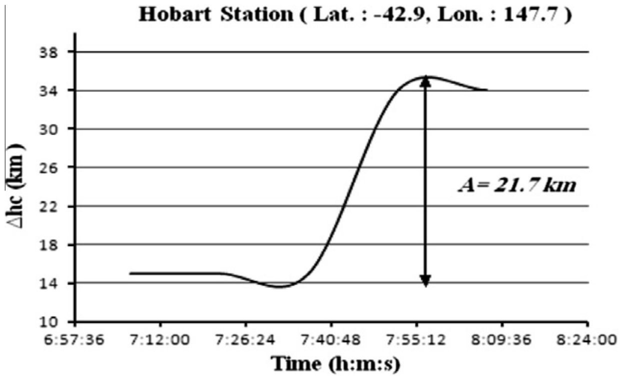

Fig. 9 The value of the amplitude (A) of the sudden enhancement of (Δch) during the period of the studied flare on June 26, 1999 observed from Hobart ionosonde station.

Fig. 8 illustrates this weak correlation coefficient (R = 0.29802) with empirical formula of this relation is given by:

$$\Delta f_o F_2 = -0.48213 + 1.0435(f_{flux}) \quad (4)$$

where f_{flux} is the X-ray flux of the selected flare.

hc parameter, the height of the maximum

The *hc,* is an important parameter of the *F*2-layer. It represents the height of the maximum that has been obtained by fitting a theoretical *h'F* curve for the parabola of best fit to the observed ordinary mode trace near f_oF_2 and correcting for the underlying ionization. This parameter is also examined using Spider data. Table 3 gives the code, latitude and longitude in degrees, and the values of amplitude in km that is obtained by subtracting the values of *hc* parameter of the quiet day and the flare event day during the X-ray duration of the studied flare of June 26, 1999 of every ionosonde station. The variations of *hc* parameter as a function of the X-ray observation time are presented in Figs. 9–12.

Table 4 These figures exhibit a gradual increase of the F-layer during the X-ray duration of the flare. Its value ranging from 1.15 to 33.27 km depends on the degree that the location

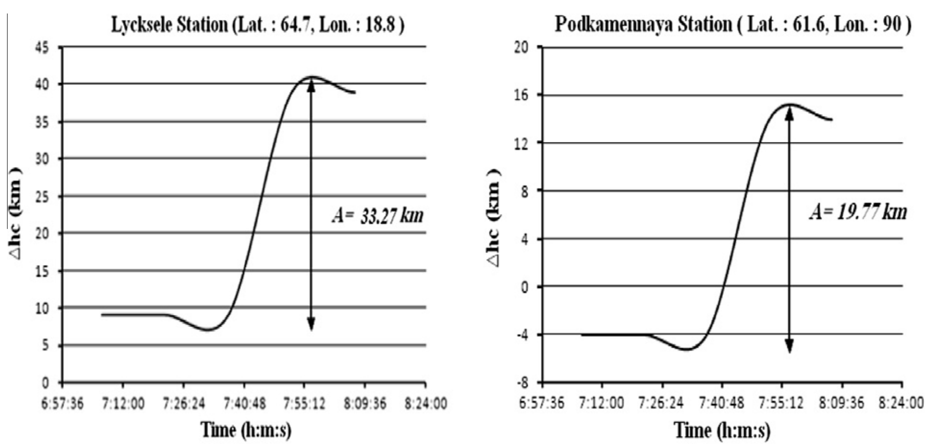

Fig. 10 The value of the amplitude (A) of the sudden enhancement of (Δch) during the period of the studied flare on June 26, 1999 observed from Lycksele and Podkamennaya ionosonde stations respectively.

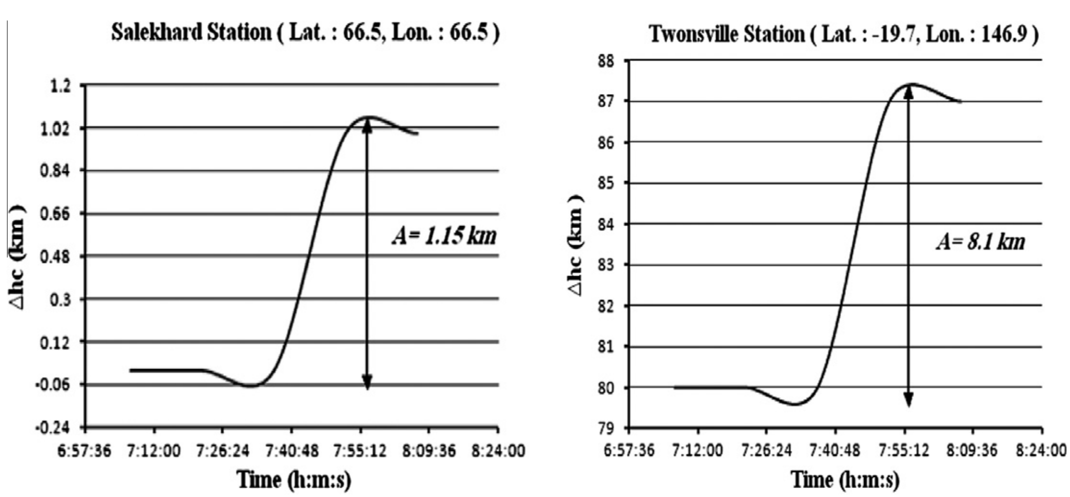

Fig. 11 The value of the amplitude (A) of the sudden enhancement of (Δch) during the period of the studied flare on June 26, 1999 observed from Salekhard and Twonsville ionosonde stations respectively.

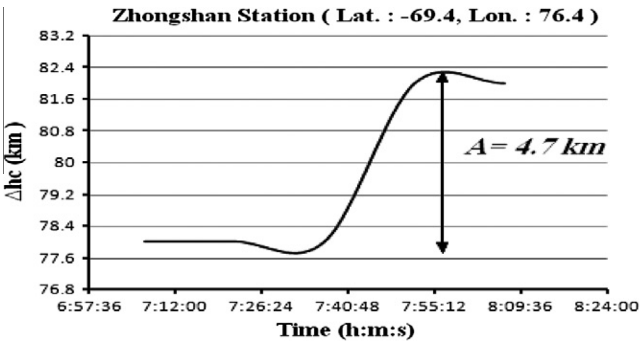

Fig. 12 The value of the amplitude (A) of the sudden enhancement of (Δch) during the period of the studied flare on June 26, 1999 observed from Zhongshan ionosonde station.

Table 4 A List of ionospheric stations from which data were used to study the variation of *hc* parameter with the measured amplitude in km unit.

Station name	Code	Lat. (0.0)°	Long. (0.0)°	(*hc*)Amplitude (A) (km)
Townsville	TV51R	−19.7	149.9	8.10
Hobart	HO54K	−42.9	147.3	21.70
Podkamennaya	TZ362	61.6	90.00	19.77
Zhongshan	ZS36R	−69.4	76.40	4.70
Salekhrad	SD266	66.5	66.50	1.15
Lycksele	LY164	64.7	18.80	33.27
Juliusruh/Rugen	JR055	54.6	13.40	10.79

of ionosonde station facing the solar disk at that time. The maximum of the amplitude is observed also at about 07:56:57 UT.

Conclusions

Results derived from analyzing the ionosphere response to the faint solar flare of June 26, 1999 are presented. The study aims to trace the possible influence of the selected flare on the ionosphere throughout the *F2*-layer parameters. This study concentrates on two parameters, f_oF_2, the critical frequency of the ordinary component of the *F2*-layer; i.e., that frequency at which the signal from the ionosonde just penetrates the *F2*-layer, and *hc*, the height of the maximum obtained by fitting a theoretical *h'F* curve for the parabola of best fit to the observed ordinary mode trace near f_oF_2 and correcting for under-lying ionization. Spider data collected from more than 100 ionosonde stations spread around the Earth have been used in this study. The method that has been used to examine the effect of the studied flare is very simple. The amplitude of the sudden enhancement of both parameters is found. This can be done by subtracting the values of these two parameters that are recorded at ionosonde stations of the most quiet date of the month when the studied flare was observed which was June 15, 1999, from the same values recorded on June 26, 1999 during the X-ray duration of the flare. In the case of the first parameter, f_oF_2, it is found that, the amplitude of the sudden enhancement ranges from 0.22 to 1.50 MHz with an average of about 0.73 MHz. The value of f_oF_2 parameter exhibits a gradual increase with the increase of the duration of the studied flare and reaching its maximum about 07:56:57 UT, i.e. almost at the end of the decay phase of the flare. To examine the correlation degree of the average amplitude (A) of sudden enhancement of (Δf_oF_2) on the X-ray duration and flux of solar flare of June 26, 1999, this average f_oF_2 amplitude (A) has been used together with the average f_oF_2 amplitude (A) of the most powerful solar flares recorded during the 23rd solar cycle. Youssef (2008) found that, the average f_oF_2 amplitude (A) of these powerful flares exhibits linear relationship with their X-ray duration (correlation coefficient = 0.89). On the contrary a very weak correlation is found with their flux (correlation coefficient = 0.29802). When the average amplitude (A) of the selected flare of June 26, 1999 is used together with the average f_oF_2 amplitude (A) of these most powerful solar flares, the results is quite consistent with those of Youssef (2008). Now, in the case of the second parameter, *hc*, it is found that, the *hc* amplitude of the sudden enhancement ranges from 1.15 to 33.27 km with an average of about 14.21 km. Although, the value of the *h* amplitude is varying from station to another, i.e. it depends on the location of the station on the Earth, but it reaches its maximum value at about the same time, i.e. about the decay phase of the studied flare. The studied flare on June 26, 1999 was a faint flare and had an X-ray flux of only 1.1×10^{-2} erg cm^{-2} s^{-1}, and caused some enhancement in the ionosphere that lasted 51 min. It seems that the X-ray flare duration of flares is an important parameter that should be taken into account on studying the influence of solar flares on the Earth's ionosphere.

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