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# The Impacts of CMEs on the Ionospheric Critical Frequency foF2

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## Introduction

Tele:

Different scientists discussed the solar activity impact on the ionosphere, especially CMEs and flares among the solar activity phenomena (see Liu Libo et al, 2006; Iyer K. N. et al., 2006 and Ivan Kutiev et al., 2013).

CME events are usually the origin of intense geomagnetic storm and they occur predominantly during solar maximum phase. Coronal holes emit high-speed solar wind (HSS), capable of producing a series of moderate and weaker geomagnetic storms that continuously (recurrently) appear during periods longer than one solar rotation. The latter storms more frequently appear during declining and solar minimum phases (Borovsky et al., 2006).

The widely used critical frequency of the F-layer (foF2) is well-defined parameter extracted from ionograms of groundbased ionosondes (Piggot and Rawer, 1972). The ionospheric electron density is highest around the F2 peak, and thus, the F2 peak has been the subject of many investigations. The widely used critical frequency of the F-layer (foF2) is a well-defined parameter extracted from ionograms of ground-based ionosondes. The critical frequency of the F2 layer (foF2) or peak density (NmF2), peak height (hmF2), total electron content (TEC), plasma temperature, scale height, thermosphere winds, temperature and neutral compositions have been recently investigated (Liu Libo, 2006).

The F layer critical frequency foF2 is used because of its direct relationship with the F layer peak electron density NmF2 (which is a measure of positive or negative storm effects through its significant increases or decreases about the mean position respectively) i.e. foF2 (Hz) = 9.0 x  $\sqrt{[NmF2]}$  (m<sup>-3</sup>) (Adebesin B. O. et al., 2012).

Fujiwara H. et al. (2014) successfully observed variations of the polar ionosphere due to shock downstream structure of the solar wind, which was caused by the arrival of a CME associated with the M8.4 solar flare event on March 10 2012. Before the arrival of the interplanetary shock, the ion temperature at the higher latitude in the polar cap region is much

# ABSTRACT

We have studied the impact of CMEs on the ionospheric critical frequency foF2 during the period 1996-2013. We have correlated the monthly maximum values of foF2 with monthly averages of CME's energy, mass and speed; we found that the correlation coefficient R is 74%, 52% and 65% respectively. This indicates that the energetic, massive and fast CMEs can affect the ionospheric critical frequency foF2 more efficiently. In addition, the monthly average CME's width correlates with the monthly maximum foF2 with R~57%. This implies that as the width of the CME increases, the possibility of this event to hit the Earth increases and the ionospheric-targeted area increases, thus the foF2 values; as an implication of increasing the ionization of the ionosphere; subsequently increases.

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larger (by more than 1000 K) than that at the lower latitude. The impacts of a CME arrived at the Earth's ionosphere occurs through the two-step process: In the first stage, there was strong heating in the higher latitude region of the polar ionosphere, which was in association with passage of the shock structures of the solar wind. At that time, the polar cap size seemed to be small although the polar cap potential seemed to be large. In the second stage, there was strong heating in the lower latitude region of the polar ionosphere, which was in association with the southward interplanetary magnetic field (IMF)-Bz component lasting more than 1.5 h after the passage of the shock structures. The polar cap size seemed to be large.

Iyer K. N. et al. (2006) discussed the CME event on November 4, 2001; the speed of this halo CME (~1868 km s<sup>-1</sup>) with some acceleration is considered high, however the resulting geomagnetic storm on November 6, 2001 with Dst~ -300 nT may seem relatively weak. They mentioned that during the midday sector (1000–1500 local time, LT) high values of vertical TEC are observed around the magnetic equator while low values are seen around 1900 LT. This is the typical quiet time situation. The effect of the ionospheric storm appeared on November 6, 2001 around the same UT period, but about 2 hours after the arrival of the IP shock at 1 AU. The daytime region of high TEC has expanded to higher latitudes of ~30° N&S. In general, when the TEC increases, this indicates a positive ionospheric storm.

Ivan Kutiev et al. (2013) concluded that there are several physical processes that can affect the ionospheric F-region electron density profile. The lower thermospheric temperatures, because of an unusually long minimum in solar extremeultraviolet flux, not only decreased density, but the contraction of the upper atmosphere also lowered the height of the peak of the ionospheric F-layer. In general, the differences between monthly medians of foF2 obtained for solar minimum years 1996 and 2006-2009 and for selected middle latitude stations fit to the range of (-0.7 to 1.5) MHz.

Adebesin B. O. et al. (2012) aimed at exploring the geomagnetic storm of April 14, 2006, they concluded that (The ionospheric stations under analysis include high and mid-latitude stations), the variation of the peak electron density of the F2 layer appears to acquire the signature of the impact of the solar wind. F2 layer is often profoundly affected during the magnetic storms, with severe effects on radio propagation. At midlatitudes the F2 layer electron density initially increases then often decrease during the storms main phase, and recovers in 2-3 days. The observed decrease in foF2 during the storm is related to the neutral composition disturbances. Heating at auroral and high latitudes causes expansion of the neutral atmosphere, and enhanced neutral winds carry disturbed composition. However, enhancement in the mean molecular mass in the neutral composition disturbance zone leads to an increase in the loss rate of ions, resulting in a decrease of the ionospheric plasma density and thus a negative storm.

Haider S. A. et al. (2009) compared the ionospheres of Mars and Earth in response to solar flare and CME occurred on May 13 2005. They searched measurements made by three ionosonde stations in the E region ionosphere. They concluded that the ionosonde at Sondrestrom station measured an increase by a factor of ~3.5 in foEs (The normalized sporadic E layer plasma frequency, foEs) at 17:30 UT just after the solar flare (the cause of this is still unknown). The major signature of the 13 May flare on Earth was a large enhancement in the E layer peak density, and results suggest that foEs and TEC can increase by factors of 3 to 6 during the arrival of a CME.

Frédéric Ouattara and Jean Louis Zerbo (2011) analyzed the effects of these solar disturbance events on Ouagadougou ionosphere F2 parameters (foF2 and hmF2) variations during the three solar cycles (cycles 20, 21 and 22). They concluded that: (1) Severe storms are responsible for equinoctial anomaly in foF2; (2) shock activity causes vernal equinoctial asymmetry in foF2 and autumnal equinoctial asymmetry in hmF2; (3) fluctuating wind streams produce autumnal equinoctial asymmetry in foF2 and vernal equinoctial asymmetry in hmF2.

Olawepo A. O. and AdeniyiJ. O. (2012) mentioned that intense storms are capable of producing all time depletion in the electron density of the F2-layer within the equatorial ionosphere of the African sector in addition to the previous results of daytime enhancement and nighttime depletion.

Some of the previous authors worked upon a long period and others concentrated on certain events in order to investigate to what extent the ionospheric parameters can respond to different solar activity levels.

Most of past studies investigated the effect of solar activity on the ionosphere in terms of some parameters such as F10.7, R, foF2 and TEC, but there a little was interested in dealing with CMEs features such as energy, mass, width and initial speed, and show their impact on the ionospheric parameters especially foF2.

In this paper, we introduce a new trend in which we discuss the critical frequency foF2 dependency on energy, mass and speed of CMEs. However, the interaction between the CME/solar wind and magnetosphere is very complex and varies from event to event. Hence, in order to make space weather prediction one has to study a large number of such events (Iyer K. N. et al., 2006), so we have decided to work upon a long period (1996-2013) including solar minimum and maximum to show different solar activity levels affecting the ionosphere.

## **Data Sources**

The Ionospheric data used in this study consists of values of foF2 obtained from some of the National Geophysical Data Centers SPIDR (Space Physics Integrative Data Research Source) global network of ionosonde stations. The data span between 1996 and 2013 consists of minutely values of foF2 with 5 minutes resolution. Table (1) gives the details of the used ionosonde stations with their locations.

CME data was taken from SOHO LASCO CME Catalog obtained from URL http://cdaw.gsfc.nasa.gov/CME list/, we obtained 20635 CME events during the period 1996 to 2013. Approach

The coronal mass ejection can reach the earth in the range from one to seven days (Owens M. and Cargill P., 2004). The problem that faces our work is how we can predict the impact time of CME on the ionosphere. The previous authors overcame this problem by studying individual cases by specifying some events manually (see, Iyer K. N. et al., 2006, Haider S. A. et al., 2009 and Adebesin B. O. et al., 2012). Rather than this, we worked upon a long period to differ from previous studies.

We decided to use the monthly average values of the CMEs parameters and foF2 to overcome the problem of travel time of the CMEs.

The impact of CMEs on the ionospheric critical frequency foF2 can be certain by applying the following steps:

1. Calculate the daily maximum value of foF2.

2. Estimate the monthly maximum value of foF2.

3. Calculate the monthly average values of energy, mass, initial speed, and angular width of CMEs, considering the Halo CMEs. 4. Plot the relation between energy, mass, initial speed and width of CME with foF2.

5. Plot the time series of monthly average of CMEs and monthly maximum foF2.

#### **Results and discussion**

A strong relationship between Monthly averages of CME's energies with Monthly maximum values of foF2 is shown in figure 1. We found that the correlation coefficient R~ 74% as given from equation 1. This is due to the impact ionization of the CMEs on the ionosphere that leads to an enhancement in the electrons density thus increment in the critical frequencies of F2 layer. We expect that the correlation may increase if we consider the travel time of CMEs in our calculation since so far there is no accurate prediction model of CME travel time (Gopalswamy, N.et al., 2001; Owens, M. and Cargill, P., 2004).

The fitting equation between CME's energy and critical frequency foF2 is given by:



Fig. 1. The relationship between the Monthly average of CME's energy and monthly maximum of foF2 for the period 1996-2013

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Table 1. The Ionosonde Stations					
Code	Name	Latitude	Longitude	Data interval	
PRJ18	Puerto Rico	18.5°	-67.2°	1957-01-01 - 2014-10-31	
EG931	Eglin AFB	30.4°	-86.7°	1991-01-01 - 2014-10-31	

Figure 2 shows the monthly time series of average of CME's energy and maximum of foF2 during the period 1996-2013; we found a semi-coincidence between the two time series. In addition, this semi-coincidence is sometimes not valid due to not all CMEs are directed toward Earth.

Time series of Monthly Maximum foF2 and monthly average of CME Energy



Fig. 2. Time series of Monthly maximum foF2 and Monthly average of CME energy



Fig. 3. Correlation between the Monthly average mass of CMEs and monthly maximum foF2 values through the period 1996-2013

Figure 3 displays the monthly average CME's masses and monthly maximum foF2 values in the period range 1996-2013. There is a fair relationship between the CME's mass and foF2 with  $R\sim52\%$ . This can be attributed to as the CME's mass increases, the solar particles density increases within the CME and that in turn raises the possibility of ionizing solar energetic particles pouring down to the ionosphere.

Figure 4 shows a linear relation between the monthly average angular width of the CME and the monthly maximum foF2 with R~57. This may be due to that as the width of the CME increases, including Halo CMEs, the possibility of this event to reach the Earth increases (XuePe Zhao, 2004), and then foF2 values; as an implication of increasing the ionization of the ionosphere; subsequently increases.

The Monthly average of the CMEs initial speeds in relation with the monthly maximum foF2 values is plotted in figure 5.



Fig. 4. The relation between the Monthly average CMEs angular widths with the monthly maximum foF2 values



Fig. 5. The relationship between the monthly average CME's initial speed and the monthly maximum foF2 values

The correlation coefficient R is ~ 66%. This high correlation implies that as CME's initial speed increases, the probability of foF2 response increases. The figure shows that the monthly average speeds of CMEs, have a mean value of 362 km/s, slower than solar wind average speeds, in agreement with Biktash, L.Z., (2014) who concluded that the interplanetary solar wind velocity that affect foF2 studied in the solar minima (1996-1997 and 2008-2009) is 320 km/s.

### Conclusion

We have studied the impact of CMEs on the ionospheric critical frequency foF2 during the period 1996-2013. The monthly averages of CME's energies is correlated with foF2 with correlation coefficient  $R \sim 74\%$  as given from the fitting equation 1. Monthly time series of average CME's energy and maximum of foF2 during the period 1996-2013 shows a semicoincidence between the two time series, in addition, this semicoincidence is sometimes not valid due to not all CMEs are directed toward Earth. We correlated the monthly maximum value of foF2 with monthly average CME's energy, mass and speed, the correlation coefficient R is 74%, 52% and 65% respectively. This indicates that the energetic, massive and fast CMEs can affect the ionospheric critical frequency foF2 more efficiently. Heavier CMEs, i.e. higher density CME particles increase the CME ionizing capacity of the ionosphere.

In addition, the monthly average CME's width correlates with the monthly maximum foF2 with  $R\sim57\%$ , larger CME's width increases the CME probability to target the earth and increase the volume targeted in the ionosphere thus increase ionization.

# Erratum

In the originally published version of this article, the equation 1 and its mention in figure 1 were incorrect. The equation have since been updated, and this version may be considered the authoritative version of record.

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