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# Latitudinal variation of *fo*F2 hysteresis of solar cycles 20, 21 and 22 and its application to the analysis of long-term trends

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**Abstract.** Noon *fo*F2 monthly median values for equinoctial months of solar cycles 20, 21 and 22, were analyzed for 37 worldwide stations. For each solar cycle and for a given $R_z$, the difference between *fo*F2 in the falling branch of the cycle and the corresponding value of the rising branch is evaluated. The maximum difference, considered as the hysteresis magnitude, varies systematically with geomagnetic latitude. The pattern is similar for every cycle, with greater hysteresis magnitudes for stronger solar cycles. It is positive between 45° S and 45° N, with minimum values at equatorial latitudes and maximum at around 25°–30° on either side of the equator. For latitudes greater than 50° negative values are observed. At around 25°–30° and at high latitudes the hysteresis magnitude reaches 2 MHz for solar cycle with high activity levels, which represents around 20% of *fo*F2. The effects of *fo*F2 hysteresis on the analysis of long-term data sequences is analyzed. In the case of long-term trend analysis, the hysteresis behavior may induce spurious trends as a consequence of the filtering processes applied to *fo*F2 time series previous to trend values estimation. This problem may be solved by considering time series covering several solar cycles.

**Keywords.** Ionosphere (Ionospheric disturbances; General or miscellaneous)

## 1 Introduction

The F2 critical frequency *fo*F2, for a given station and a constant value of the solar activity level, such as the sunspot number $R_z$, can differ for the rising and falling parts of the 11-year solar cycle. The variation of *fo*F2 over a complete solar cycle displays a curve similar to the hysteresis variation of a magnetization cycle. The enhanced geomagnetic activity during the falling phase of the solar cycle would produce stronger F2 layer storm effects.

The phenomenon of ionospheric hysteresis has been known for a long time (Naismith and Smith, 1961; Naismith et al., 1961; Huang, 1963; Rao and Rao, 1969; Muggleton, 1969; Smith and King, 1981). Rao and Rao (1969), considering noon *fo*F2 values, evaluated the magnitude of the hysteresis of solar cycle 19 (1954–1964) by the area between rising and falling parts of the solar cycle, and reported its dependence on geomagnetic latitude with maximum magnitude values at mid-latitudes (around 25°) and minimum values at equatorial and high latitudes. The observed latitudinal variation indicate a geomagnetic control of the hysteresis phenomenon.

Apostolov and Alberca (1995) analyzed the seasonal variation of the *fo*F2 hysteresis area for Slough (51.5° N, 0.6° W) of solar cycles 17 (1933–1944) to 21 (1976–1986). The annual variation, with maxima near the equinoxes, supports the idea of the geomagnetic control of this phenomenon. This idea is also suggested by Mikhailov and Mikhailov (1995) who attribute the hysteresis to the behavior of geomagnetic activity throughout the solar cycle.

Buresova and Lastovicka (2000) analyzed the *fo*F2 hysteresis for solar cycles 20 (1964–1976) and 21 (1976–1986) estimating its magnitude as the difference between *fo*F2 values of years just before and just after the solar cycle minimum since they expect the most pronounced hysteresis near the minimum solar activity epoch.

In the present work, the variation of *fo*F2 hysteresis magnitude with geomagnetic latitude is analyzed using data of 37 worldwide ionospheric stations of solar cycles 20 (1964–1976), 21 (1976–1986) and 22 (1986–1996). The hysteresis magnitude in our case is the maximum difference between *fo*F2 in the falling branch of the cycle and the corresponding value at the same activity level of the rising branch. The possibility that a *fo*F2 hysteresis behavior may affect long-term trend estimation is discussed.

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**Table 1.** Ionospheric stations analyzed in the present work (World Data Center for Solar Terrestrial Physics, WDC1 in England, Data Archives).

| Station | Geographic latitude (° N) | Geographic longitude (° W) | Geomagnetic latitude (° N) | Geomagnetic longitude (° W) |
|---|---|---|---|---|
| Ahmedabad | 23.0 | 72.6 | 13.8 | 214.8 |
| Akita | 39.7 | 140.1 | 29.8 | 206.8 |
| Alma Ata | 43.3 | 76.9 | 33.5 | 151.9 |
| Argentine Islands | −65.2 | 295.7 | −54.0 | 4.4 |
| Argentia | 47.3 | 306.0 | 58.9 | 21.6 |
| Arkhangelesk | 64.6 | 40.5 | 58.7 | 129.1 |
| Ashkabad | 37.9 | 58.3 | 30.4 | 134.5 |
| Athens | 38.0 | 23.6 | 36.4 | 102.5 |
| Boulder | 40.0 | 254.7 | 48.9 | 318.7 |
| Brisbane | −27.5 | 152.9 | −35.4 | 228.3 |
| Budapest | 47.4 | 19.2 | 45.9 | 101.3 |
| Camden | −34.0 | 150.7 | −42.0 | 227.6 |
| Campbell | −52.5 | 169.2 | −57.1 | 254.4 |
| Canberra | −35.3 | 149.0 | −43.7 | 225.7 |
| Casey | −66.3 | 110.5 | −77.6 | 178.2 |
| Christchurch | −43.6 | 172.8 | −47.7 | 253.5 |
| Concepcion | −36.6 | 287.0 | −25.5 | 357.6 |
| Dakar | 14.8 | 341.6 | 21.4 | 56.0 |
| Darwin | −12.5 | 131.0 | 22.9 | 202.7 |
| Dourbes | 50.1 | 4.6 | 51.7 | 88.9 |
| Grahamstown | −33.3 | 26.5 | −33.9 | 89.4 |
| Huancayo | −12.0 | 284.7 | 0.7 | 355.2 |
| Johannesburg | −26.1 | 28.1 | −27.2 | 92.8 |
| Kodaikanal | 10.2 | 77.5 | 0.6 | 148.5 |
| Mundaring | −32.0 | 116.3 | −43.2 | 187.7 |
| Okinawa | 26.3 | 127.8 | 15.5 | 196.9 |
| Poitiers | 46.6 | 0.4 | 49.2 | 83.0 |
| Port Stanley | −51.7 | 302.2 | −40.6 | 10.3 |
| Rome | 41.8 | 12.5 | 42.3 | 93.2 |
| Slough | 51.5 | 359.4 | 54.0 | 84.4 |
| Sodankyla | 67.4 | 26.6 | 63.6 | 120.8 |
| Tahiti | −17.7 | 210.7 | −15.2 | 284.4 |
| Taipei | 25.0 | 121.5 | 13.8 | 190.9 |
| Tomsk | 56.5 | 84.9 | 46.0 | 160.6 |
| Uppsala | 59.8 | 17.6 | 58.3 | 106.9 |
| Vanimo | −2.7 | 141.3 | 12.3 | 212.5 |
| Yamagawa | 31.2 | 130.6 | 20.6 | 199.1 |

## 2 Data analysis

Noon *fo*F2 monthly median data from 37 ionosonde worldwide stations, available at the World Data Center for Solar Terrestrial Physics, WDC1 in England, were analyzed. The stations, listed in Table 1, were selected according to the completeness of its *fo*F2 records. The equinoctial months (April, March, September and October), when the hysteresis is expected to be best developed, were analyzed.

In the present work, the hysteresis magnitude was estimated as the maximum difference during a given solar cycle, between *fo*F2 value in the falling phase and the corresponding value in the rising phase for a constant $R_z$. Figure 1 shows, as an example, the *fo*F2 hysteresis (points in the scatterplot of *fo*F2 vs. $R_z$ joined chronologically) for three ionospheric stations. The hysteresis magnitude is shown as a vertical dashed line. Its value, in MHz, corresponds to the maximum *fo*F2 difference between the rising and the falling branch of the hysteresis for a given $R_z$ value. Within a solar cycle, we considered every *fo*F2 point (in the rising and falling phases of the solar cycle) and calculated the difference between it and the corresponding value in the falling phase

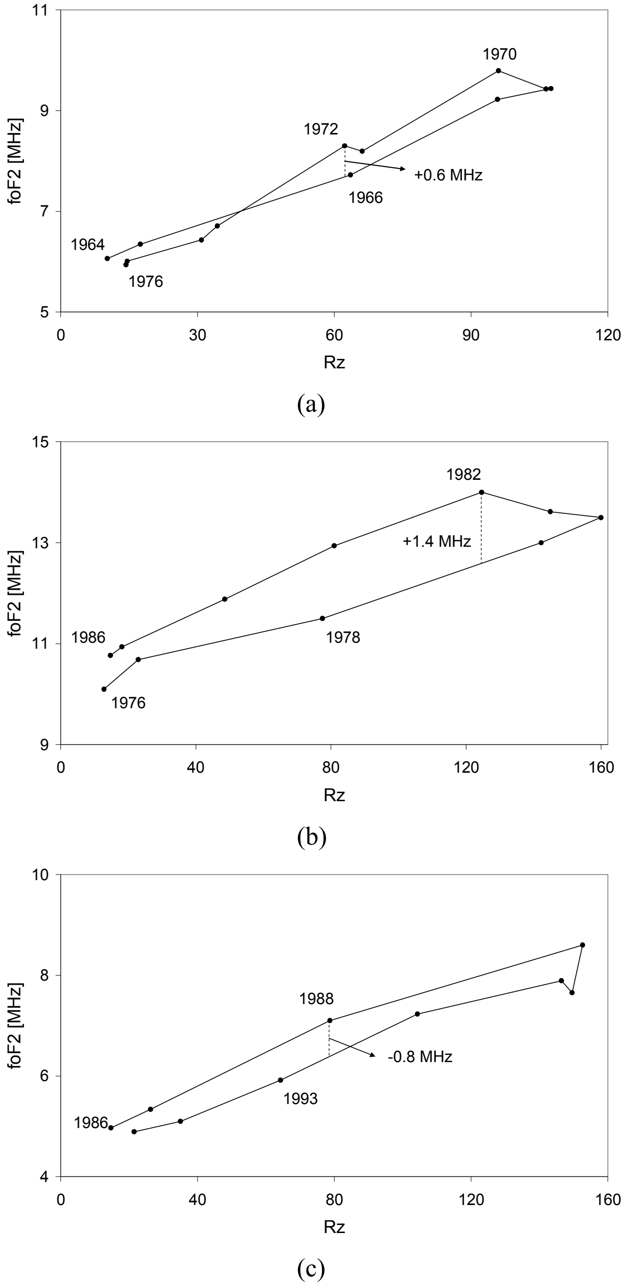


**Fig. 1.** Monthly median *fo*F2 at noon in terms of $R_z$ for **(a)** Mundaring in September during solar cycle 20 **(b)** Ahmadabad in April during solar cycle 21 and **(c)** Argentine Islands in April during solar cycle 22. The vertical dashed line indicate the maximum amplitude of the hysteresis which is given in MHz.

(if the considered *fo*F2 point is in the rising phase) or in the rising phase (if the *fo*F2 point is in the falling phase). The positive sign corresponds to a higher *fo*F2 value at the falling than at the rising phase of the cycle, and the negative sign, to a higher *fo*F2 value at the rising phase. Usually, the values of the monthly $R_z$ time series during a solar cycle phase do not

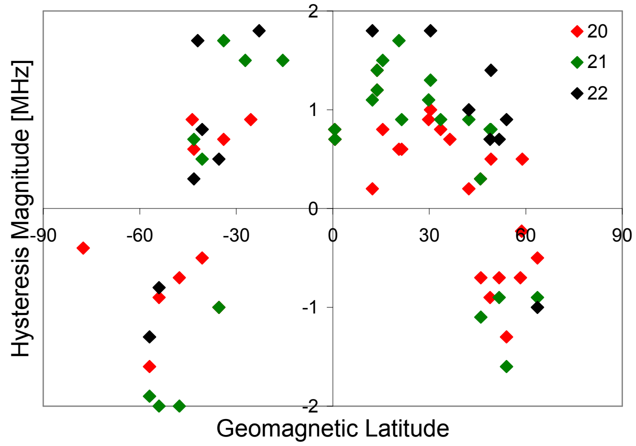


**Fig. 2.** *fo*F2 hysteresis magnitude (maximum difference during a given solar cycle between *fo*F2 value in the falling phase and the corresponding value in the rising phase for a constant $R_z$) for solar cycles 20 (red diamonds), 21 (green diamonds) and 22 (black diamonds).

coincide with the values during the other phase of the same cycle, so that the required *fo*F2 value was assessed from a linear interpolation between the pair of (*fo*F2, $R_z$) points whose interval contains the $R_z$ value needed. The hysteresis magnitude corresponds, within a solar cycle, to the maximum *fo*F2 difference thus estimated.

The hysteresis magnitude for solar cycles 20 (1964–1976), 21 (1976–1986) and 22 (1986–1996) (maximum $R_z$: 136, 188 and 200, respectively) are shown in Fig. 2. The latitudinal pattern for cycles 20 and 21 presents maximum magnitude values at latitudes around 25°–30° and at high latitudes, and minimum values around the equator and at latitudes around 45°–50°. The latitudinal pattern of solar cycle 22 is similar except for the lack of data at the equator.

## 3 Analysis of long-term *fo*F2 data sequences presenting hysteresis

In long-term trend assessments the hysteresis may induce spurious trends in filtering processes. As the ionosphere seems to be sensitive to climate variations (Rishbeth, 1990; Rishbeth and Roble, 1992), trend assessments in ionospheric parameters have gained importance in studies related to climate change, which try to elucidate the origin (natural or anthropogenic) of global warming. *fo*F2 long-term trend estimations, are based on a previous filtering of the *fo*F2 data series which relies on a linear relationship with solar activity. An hysteresis behavior may induce in this case a spurious trend. As an example, Fig. 3 shows an artificial hysteresis of $y$ in terms of $x$ during a single cycle. If $x$ is linearly filtered from $y$, a trend is detected in $y$ only as a result of the filter used. This spurious trend can be offset as one considers more

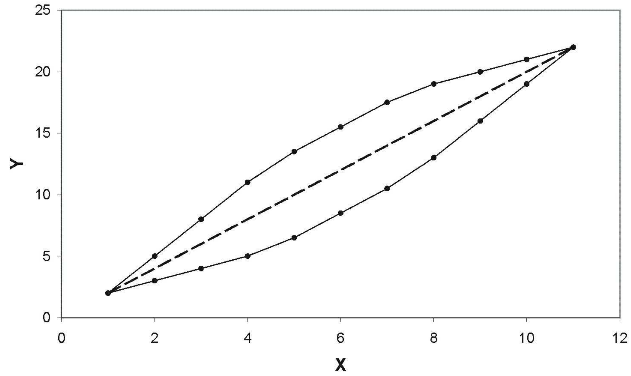


**Fig. 3.** Artificial hysteresis of $y$ in terms of $x$ during a single cycle (solid line) and the "ideal" linear function of $y$ in terms of $x$ during the same cycle (dashed line).

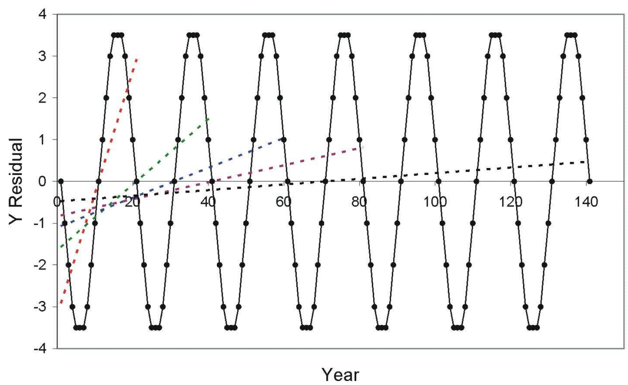


**Fig. 4.** $y$ (during several cycles) after filtering $x$ using a linear filter (solid black line), and the linear trends obtained if only one cycle is used (red dashed line), two (green dashed line), three (blue dashed line), and following on.

cycles in the trend estimation (as can be seen in Fig. 4) or, as suggested by Danilov and Mikhailov (1999), using only the points around the maximum and minimum of a cycle.

Figure 5 shows two real cases where the linear trend of *fo*F2 for two stations here analyzed (Slough and Argentine Islands) was estimated considering just one solar cycle, then two, and finally three.

As a first step in assessing trends, the solar activity variation has to be filtered out from *fo*F2 data series. This was done estimating the residuals of a linear fit between *fo*F2 and a solar activity proxy ($R_z$ in our case), that is

$$foF2\ \text{residual} = foF2_{\text{exp}} - foF2_{\text{mod}}$$

where $foF2_{\text{exp}}$ is the experimental data and $foF2_{\text{mod}}$ is *fo*F2 modeled through a linear regression with $R_z$. Then, the linear trend ($\alpha$) was estimated through least squares from

$$foF2\ \text{residual} = \alpha\ \text{year}\ + \beta$$

As in the ideal case shown in Fig. 3, in Fig. 5 it can be noticed how the slope of the trend, that is $\alpha$, decreases as more cycles

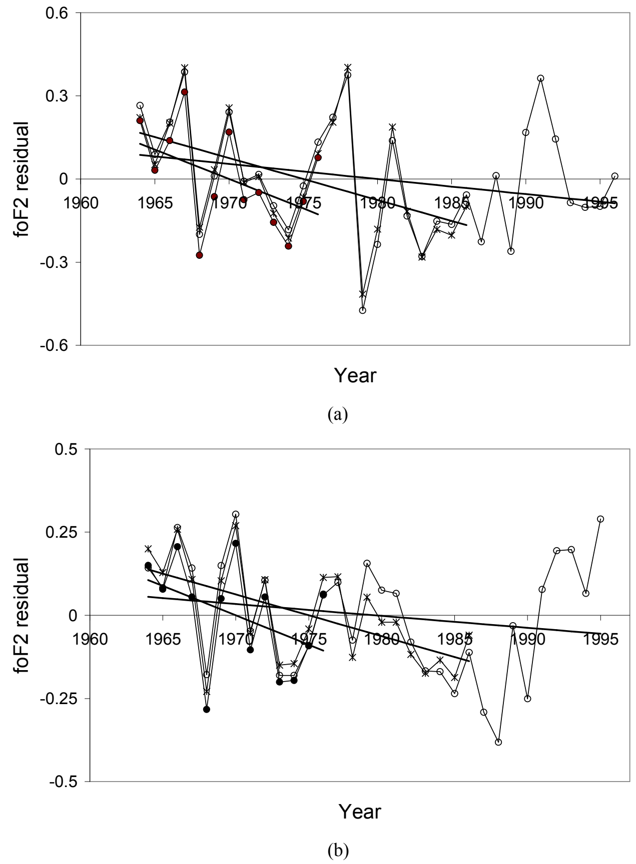


**Fig. 5.** Time series of *fo*F2 residuals and long term trend (enhanced line) considering solar cycle 20 (solid circle), solar cycles 20+21 (asterisk) and solar cycles 20+21+22 (empty cicrcle) for noon values **(a)** in September at Slough and **(b)** in April at Argentine Islands.

are considered for trend estimation. In the case of Slough, $\alpha$ is $-0.02$ MHz/year when only solar cycle 20 is considered, $-0.015$ MHz/year when solar cycles 20 and 21 are considered, and $-0.005$ MHz/year when solar cycles 20, 21 and 22 are considered. In the case of Argentine Islands these values are $-0.02$, $-0.012$ and $-0.004$ MHz/year, respectively.

## 4 Discussion

The hysteresis magnitude for solar cycles 20 (1964–1976), 21 (1976–1986) and 22 (1986–1996) estimated in this work as a difference, and that obtained by Rao and Rao (1969) for solar cycle 19 (1954–1964) but assessed as the area, present similar latitudinal patterns. Except that, in our case, negative values at high latitudes are as important as the positive values around mid-latitudes.

The latitudinal pattern of the hysteresis magnitude is similar in shape to that of *fo*F2 diurnal mean values, which shows a pronounced trough at the magnetic equator and crests at about 30° N and 30° S magnetic dip (equatorial anomaly).

The hysteresis magnitude increases with solar activity. As an example, for Ashkabad (30.4° N) the hysteresis magnitude for cycles 20, 21 and 22 are 1, 1.3 and 1.8 MHz, respectively. At 25°–30° and at high latitudes it can reach 2 MHz for the solar cycle with high activity level, which represents around 20% of *fo*F2.

The latitudinal pattern of the hysteresis magnitude may be compatible with the idea of a geomagnetic control for each of the solar cycles here analyzed (20 to 22), and also during cycle 19 (shown by Rao and Rao, 1969). Geomagnetic disturbances are accompanied by large changes in the ionospheric F2 layer, but neither the morphology nor the physics is fully known. The ionospheric response to geomagnetic activity is highly complex due to the many physical processes involved. However there are underlying trends that are useful in characterizing the ionosphere response to storms in a relatively simple way (Fuller-Rowell et al., 2000; Araujo-Pradere et al., 2002). The picture widely used regarding the latitudinal pattern of ionospheric storms is the following: mainly negative storms at high latitudes and more prevalent positive storms at mid and low latitudes (Rishbeth and Field, 1997; Field and Rishbeth, 1997). Taking into account that geomagnetic activity is higher on average during the descending phase of the solar cycle than during the ascending phase, a clockwise or counter-clockwise hysteresis should be expected at a location depending on its prevalent negative or positive ionospheric storms. By clockwise or counter-clockwise we mean the path followed by joining the points in an *fo*F2 vs. $R_z$ plot, begining at the year of the first minimum of the cycle and ending at the year of the following minimum. In terms of the hysteresis magnitude here estimated, this implies negative or positive hysteresis magnitude, respectively. This consideration leads to a latitudinal pattern of hysteresis magnitude highly consistent with the pattern we observe.

Although the phenomenon of ionospheric hysteresis has been known for a long time, a linear relationship between *fo*F2 and $R_z$ is used in forecasting and long-term trend estimations.

Models used in ionospheric condition predictions for radiowave propagation do not consider the *fo*F2 hysteresis effect. However, according to our results, hysteresis magnitudes as high as 2 MHz (20% of *fo*F2 mean values for certain ionospheric stations) can occur for strong solar cycles and at mid-latitudes.

In long-term trends analysis the hysteresis may induce spurious trends due to the filtering processes applied to *fo*F2 time series previous to trend values estimation. As shown here, this problem can be partially solved by considering long time series covering several solar cycles; at least more than one.

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