**Response to reviewer 1.:**

**Comments on manuscript** "Investigation of the ionospheric absorption response to flare events during the solar cycle 23 as seen by European and South African ionosondes"

The analysis of the absorption induced by the solar flares was performed in this paper. The ionosonde data located at different latitudes were considered. The methods of the fmin and dfmin were applied.

I think this is interesting paper. The problem of the absorption due to solar events is one of the topical problem in the wave propagation investigation. In the paper a lot of data were analysed.

We thank the Reviewer #1 for expressing their appreciation on our work. We addressed all their points by providing changes/additions in the revised manuscript, and responses here to their comments. We believe our paper is now improved by making changes and short additions throughout the text, mostly in the introduction and discussion. A few more references have also been added.

We hope that the revised paper will now meet with the referee's approval. The changes in the manuscript which have been performed based on the first referee's questions/comments are indicated by pink.

**Main concern:** In section Results: "These measurements may inform models in the future in describing the changes in ionospheric absorption during solar flares with different intensities." What models do you mean? How results of this paper could be used in them? For example, the main outcome of the D-RAP models [https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap/] is a global map of the absorption, corresponding to a number of operating frequencies.

Thank you for the referee to call our attention to the D-RAP model. We have already known this model and we agree that it is important to mention it in our manuscript. We completed the introduction part of the manuscript with a paragraph about this model:

"… describing, modelling and monitoring of the ionospheric absorption is an important issue from a practical point of view as well. The process of the ionospheric absorption has been described more extensively by Davies (1990) and Sauer and Wilkinson (2008). Based on these studies the Space Weather Prediction Center (SWPC) has developed a model (D-Region Absorption Prediction, D-RAP2, https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap ) to predict the ionospheric absorption in the D-region. The product provides graphical information about High Frequency (HF) radio propagation conditions around the globe. According to the model the Highest Affected Frequency (HAF) is largest at the sub-solar point and it decreases with increasing solar zenith angle, $\chi$ (the frequencies taper off from the maximum as $(\cos\chi)^{0.75}$)."

What models do you mean? How results of this paper could be used in them?

Unfortunately, we can not compare the D-RAP model with our results quantitatively because the absorption can not directly be calculated from the fmin parameter. Furthermore, the D-RAP data is available since 2012 (https://www.ngdc.noaa.gov/stp/drap/data/) and we analyzed flare events which occurred between 2001 and 2006 during the solar cycle 23. However our systematic analysis of ionograms can give information on the frequencies below them the sounding electromagnetic waves suffer complete attenuation up to the height of the first reflection (fmin) in the ionosphere depending on the flare intensity (X-ray) and solar zenith angle.

Moreover, these results can contribute to refine the existing (D-RAP model) and future models to describe the changes in ionospheric absorption during solar flares with different intensities. The performance of the D-RAP model has been evaluated with respect to observations at several riometer stations during a representative set of historic events (https://www.ngdc.noaa.gov/stp/drap/DRAP-V-

Report1.pdf). However, riometers operate only at high latitudes and at high frequencies. The data investigated in the report have been measured at station with higher latitude than 50° and at f >= 30 MHz. Further studies based on our results using the systematic analysis of fmin can help to refine the model describe the attenuation in response to solar flares (described by D-RAP as well) at lower operating frequencies (2-10 MHz) at mid-, and low-latitudes.

Nevertheless, we deleted this general sentence from the discussion part:
"These measurements may inform models in the future in describing the changes in ionospheric absorption during solar flares with different intensities."
Instead we added the following to the text:
"Therefore, our observations confirm the results of Zhang and Xiao (2005), Spirathi et al. (2013) and the D-RAP model that the solar zenith angle plays an important role in the ionospheric response to solar flares."

I suggest the following minor revision before it is published:

1. I suppose that the structure of the paper is being difficult to understand.

    1) The section Introduction is very long. I suggest reducing the part regarding proton precipitation in polar cap (really it is not the main topic of the paper).

    Thank you for the suggestion. The paragraph related to the Polar Cap Absorption, and another paragraph about the VLF and ELF records have been deleted from the Introduction. Furthermore, we deleted all the sentences, tables etc. in connection with the Solar Proton Event and PCA. We agree that it is not the main topic of the paper.

    2) I suggest to split "Introduction" into a few of paragraphs, otherwise the perception of the text is obstructed.

    The introduction has been splited into a few paragraphs.

    3) Please, in section "Data and Methods" separate one item from another.

    We separated the Method and the Data parts into different paragraphs. Moreover, we completed the data part with the source of the used data.

    4) The understanding of section "Results" seems to be difficult. I thing that the structure of this section should be change. This section would be better for understanding corresponding to following scheme: particular issue of research, the figures description, provisional conclusion.

    Thank you for your suggestions, we changed the structure of the results part based on them. In the first paragraph we determined the particular issue of research:
    "In the present study we investigated the response of ionospheric absorption to solar flares with particular interest of the solar zenith angle dependence variation of it. We used ionograms measured at ionosonde stations under different solar zenith angle for the analysis. We calculated the solar zenith angles of the stations at the time of the peak of the 8 flares for the analysis. We examined three parameters that can be determined from ionograms: duration of the total radio fade-out, the value of the fmin parameter and the value of the dfmin parameter. In the first step we analyzed how the duration of the fade-out during the flare event depended on the solar zenith angle (Sec. 3.1). Secondly the solar zenith angle dependence of the fmin and dfmin parameters measured just after the fade-out were investigated (Sec 3.2). Then we repeated the analysis for the fmin and dfmin parameters measured at a certain time after the fade-out when we again recorded them at all the stations (3.3). In the last step the impact of the intensity variation on the absorption has been considered (3.4)."
    Then we wrote the figures descriptions with some provisional conclusions.

2. The sense of the paragraphs (Page 2-3 (30)) in "Introduction" is not clear to me. "The electron density (Ne) of the D region is enhanced by up to one order of magnitude down to about 55 km prior to, during and after the solar proton event (SPE) on January 17, 2005. The largest Ne are found during the maximum of the X-ray flare on January 17. The electron density is still enhanced on January 18 when the X-ray flare decayed but the solar proton fluxes are still enhanced (Singer et al., 2011)." Is it continuation of the paragraph about Patterson et al. (2001) or not?

Not, this sentence is related to the study of Singer et al., 2011. However, this part of the introduction has been deleted from the manuscript based on you previous suggestion.

3. Page .2 (10) I suggest to replace citing Sauer and Wilkinson (2008) text (in italics) by your expression.

The part indicated by italics has been replaced by the following text:
"The physical background of the ionospheric radio wave absorption mechanism is that the electrons accelerated by the electric field of the propagating radio waves collide with the atmospheric constituents. The absorbed energy of the electrons would reradiate without the presence of the neutral atmosphere. However, the electrons lose their energy due to the collisions with neutral particles which cause reduction of their reemitted signal."

4. Please clarify the reason of the analysis of the critical frequencies foE and foF2 (Fig. 1,2) while the absorption is the main subject of the paper.

Thank you for the question. Although the main subject of our manuscript is the absorption we wanted to show the behaviour of the ionospheric layers during the selected periods, too.
However, based on your question and the comment of the other reviewer the Fig. 1., 2., 3. and their description can confuse the reader. Therefore, we deleted the first three Figures and their descriptions and we added a figure what shows a sequence of ionograms measured at two stations during the most intense flare events of our study (Fig. 1. in the revised manuscript). We hope that it helps to follow the behaviour of the ionosphere during this intense solar event. Furthermore, it makes clear the observation of total and partial radio fade-out and of fmin parameter at stations under different solar zenith angle what is the crucial part of our study.

We added the description of the Fig. 1. (in the revised manuscript) to the text as follows:
"Here we demonstrate in detail the ionospheric response to an intense X17-class eruption that occurred on 28 October 2003. The European and South African ionosonde stations were located in the sunlit hemisphere during this flare event. Fig.1 shows a sequence of ionograms recorded close to the equator (Ascension Island) and at mid-latitude (San Vito) from 09:00 UTC to 14:30 UTC on 28 October 2003. Ionograms measured every 15 min were available for the analysis, however we show the records with 30 minute time resolution to cover the whole time interval of the flare from the start until the end of decay. The upper panel of Fig. 2 shows the X-ray variation between 06 (UTC) and 18 (UTC) recorded by GOES12 satellite. In the X-ray flux we can clearly observe the flare event that started at 09:51, reached its peak at 11:10 and ended at 11:24. The most directly observed ionospheric effect due to the X-class solar flare is the total and partial fade-out of the sounding HF waves on the ionograms (Fig. 1.). The disappearance of the traces caused by the enhanced ionospheric absorption was recorded at both stations. However, the duration of the total fade-out measured at the two observation sites was different. We may notice that an increase in the fmin parameter was first detected in the ionogram at 10:00 (UTC) over Ascension Island, close to the dip equator (fmin increased to 5.4 MHz). At San Vito, located in southern Italy at mid-latitude, the effect was weaker at this time (fmin ~ 2.9 MHz). The total attenuation of the radio waves was first recorded at Ascension Island at 11:00 (UTC). In the subsequent ionograms at 11:15 UTC (not shown here) and at 11:30 the total blackout was observed at both stations which coincided with the peak in the X-ray flux as it is shown at the upper panel in Fig. 2. The trace of the F region appears on the ionogram at San Vito at 12:00 (UTC), while the total radio fade-out remains at Ascension Island until 12:30 (UTC). With the decay in the X-ray flux the blackout became partial at both stations. The fmin parameter returns to its regular daily value (~ 2.3 MHz) at San Vito at 14:00. The recovery over Ascension occurs later, partial radio fade-out was still detected at 14:30. We believe

that the different duration of the total radio fade-out recorded in the ionograms at the two stations can be explained by the different solar zenith angle at the two sites. Since the degree of the radio wave absorption in the ionosphere varies with the solar zenith angle, we compared ionograms measured at stations under different solar zenith angles to research into the solar zenith angle dependence of the ionospheric response."

5. As I understand "The aim of the present study is the investigation of the solar flare effects on ionospheric absorption at mid- and low-latitudes taking into account the solar zenith angle: : :.". I would like once again to draw you attention to the D-RAP model (which is definitely based on the solar zenith angle dependence). I think that this model should be mention in your paper. The correlation between your results and D-RAP model results should be discussed.

Based on our results the solar zenith angle has to be take into account in the models describing the absorption of the ionosphere, like in the D-RAP model. We wrote few sentences about the importance of the solar zenith angle and the D-RAP model in the discussion part as well:

"Our results are in agreement with D-RAP model (https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap/) on the dependence of solar zenith angle. This model was developed based on the theoretical descriptions of the ionospheric absorption by Davies (1990) and Sauer and Wilkinson (2008). According to the model the Highest Affected Frequency (HAF) is largest at the sub-solar point and it decreases with increasing solar zenith angle."
…
"Therefore, our observations confirm the results of Zhang and Xiao (2005), Spirathi et al. (2013) and the D-RAP model that the solar zenith angle plays an important role in the ionospheric response to solar flares."

6. I suppose that the number of references to other authors in section "Results" could be diminished.

Thank you. We deleted them from there and discuss their results in comparison with our findings in the discussion part.

7. Table 2. Please, mention in the caption the unit ("UT", probably).

Thank you, we added UTC to the header of the table.

8. Table 3 and 4. Please, add the units in the titles "Solar zenith angle", "Duration of fade-out", "fmin" and "dfmin".

Thank you, we added the units to the header of the table.

9. I suppose that the values of the fmin have to be presented with equal (and reasonable) precision (perhaps one decimal point) in the Tables 3 and 4. The similar issue with dfmin.

We agree with your suggestion and changed the values in Table 3 and 4.

10. Figure 1. I thing it is better to write "first panel", "second panel" etc., instead of "upper plot" and "second upper plot"

We changed the word "plot" to "panel" in the figures's captions.

11. It seems to me that axes labels size and titles font size in the Figures 2-5 looks like very small.

Thank you. The labels and titles of the figures (Fig. 1-3 in the revised manuscript) have been increased in order to be more readable.

**Response to reviewer 2**.:

**Comments on the manuscript Angeo-2019-14**

'Investigation of the ionospheric absorption response to flare events during the solar cycle 23 as seen by European and South African ionosondes'
Submitted to Annales Geophysicae By Veronika Bartaet al.

**General Comments:**
This work shows an analysis of ionospheric parameters in midand low-latitudes in relation to solar flares occurred in solar cycle 23. The authors investigated the radio wave absorption in D layer, in which they defined a dfmin parameter as a good qualitative measurement to analyze this absorption.
They show an interest analysis with interesting results. However, the authors needs to organize the results and deepen in the physical discussions. Therefore, the authors need to improve significant modifications. This paper needs a major revision. Furhermore, the authors need to improve English significantly.

We would like to thank the work of Reviewer #2 and their advices. We took into account them and we refined the text of the manuscript based on their comments (as it will be listed below). We made changes and additions throughout the text, mostly in the introduction, results and discussion. A few more references have also been added based on the Reviewer's suggestion. We tried to correct the typos and mistakes and improve the English of the whole manuscript.

We hope that the revised paper will now meet with the referee's approval. The changes in the manuscript which have been performed based on the second referee's questions/comments are indicated by red.

**Major Comments:**
1. **Abstract**: The abstract is not well written. I do not understand the main objective of this study. There are some typo English mistakes as "mimimum", "ionosopheric". The authors need to clarify better the purpose of this work.

Thank you for the comment. The first part of the abstract has been rewritten taking into account your suggestions. In the first sentence we tried to clarify better the purpose of our study. Furthermore, the typos have been corrected. The revised abstract is the following:

"We have investigated the solar flare effects on ionospheric absorption with the systematic analysis of ionograms measured at mid- and low-latitude ionosonde stations under different solar zenith angles. The lowest recorded ionosonde echo, the minimum frequency (fmin, a qualitative proxy for the ''nondeviative'' radio wave absorption occurring in the D-layer), furthermore and the dfmin parameter (difference between the value of the fmin and the mean fmin for reference days) have been considered. Data was provided by at meridionally distributed ionosonde stations in Europe and South Africa during eight X and M class solar flares in solar cycle 23. Total and partial radio fade-out was experienced at every ionospheric stations during intense solar flares (> M6). The duration of the total radio fade-out varied between 15 and 150 min and it was highly dependent on the solar zenith angle of the ionospheric stations. Furthermore, a solar zenith angle-dependent enhancement of the fmin (2-9 MHz) and dfmin (1-8 MHz) parameters was observed at almost every stations. The fmin and dfmin parameters show an increasing trend with the enhancement of the X-ray flux. Based on the our results, the dfmin parameter is a good qualitative measure for the relative variation of the "nondeviative" absorption especially in the case of the less intense solar flares which do not cause total radio fade-out in the ionosphere (class < M6)."

**2 Introduction (pag. 2, line 25):** The solar flares cause an extra ionization in the D region, which causes an absorption of the HF waves, impairing the visualization of the E region in the data (ionograms, for example), and partially

or totally in the F region. The authors affirm that there is an absorption in the E region, also. Please, clarify this part.

During a solar flare event, a great enhancement in extreme ultraviolet (EUV) and X-ray radiation causes increases in the ionospheric electron density not only in the D but also in the E and F regions (Tsurutani et al., 2005; Nogueira et al., 2015;). The electron collision frequency is highest in the D region ($2 \times 10^6$ s$^{-1}$) and the HF radio waves below 10 MHz can be attenuated principally there (Zolesi and Cander, 2014). However, further studies have shown that solar flares can also cause enhancement of the neutral density and temperature of the thermosphere (Pawlowski and Ridley, 2008, 2011; Le et al., 2015). E. g. the model study by Pawlowski and Ridely (2008) has shown flare-induced density and temperature enhancements, with the effect decreasing from the 400 km (CHAMP satellite height) down to 110 km. According to the physical background of the ionospheric absorption the electrons accelerated by the electric field of the transiting radio wave suffer collisions with the atmospheric constituents because of the presence of the neutral atmosphere and induce an energy loss which results in a reduction of their reemitted signal (Sauer and Wilkinson, 2008). Consequently, the enhanced neutral density and the temperature in response to solar flare increasing also the number of collisions thus the ionospheric absorption.

In the above mentioned part of the manuscript (Introduction (pag. 2, line 25):) we wrote the following: "The loss of HF communication as a consequence of the enhanced absorption affects navigation systems, especially commercial aircraft operations. Thus the monitoring of the absorption and D-, E-region electron density variation is an important issue from a practical point of view as well."
Therefore, we didn't write about the absorption occurring in the E region explicitly. We only stated that "...E-region electron density variation is an important issue..."

Nevertheless, in our study we focus on the ionospheric absorption variation in response to solar flares and not on the E region electron density variation. Thus, we changed the text of the manuscript (page 2, lines 23-25) as follows:
"The loss of HF communication as a result of the enhanced absorption affects navigation systems, especially in commercial aircraft operations. Therefore, describing, modelling and monitoring of the ionospheric absorption is an important issue from a practical point of view as well."

References:
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- Sauer, H. H., and Wilkinson, D. C.: Global mapping of ionospheric HF/VHF radio wave absorption due to solar energetic protons. Space Weather, 6(12)., 2008
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- Zolesi, B. and Cander, L.: Ionospheric Prediction and Forecasting, Springer Geophysics, Springer Heidelberg New York Dordrecht London, DOI 10.1007/978-3-642-38430-1., 2014

**3 Introduction (pag. 3, line 32)**: It is necessary to define the fmim parameter; fmim of the F region, E region or both regions? The definition in the section "Method and data" is not enough to understand this part. The authors mention only the discussions about the fmim to be the minimum frequency of ionosphere, but in results (form of the data), I believe that fim refers to the F region. Please, clarify this part

Thank you for the question. In our study we analyzed the "general" fmin parameter, the minimum frequency of the echo trace observed in the ionograms. During our analysis we examined day-time ionograms, so generally the fmin should be the fmin of the E region. However, an enhancement in the fmin parameter can be occurred as a consequence of the increased D region radio wave absorption (see e.g. in study of Nogueira et al., 2015). In this case the first echo can be from the F region, consequently the fmin is fmin of the F region. To clarify it, we completed this part with the following sentence:
 "The fmin represents the minimum frequency of the echo trace observed in the ionogram and it is a rough measure of the nondeviative absorption (e.g. Davies, 1990)."
Furthermore, we present a sequence of ionograms in Fig. 1. in the revised manuscript (as it was seen in previous papers e.g. Sahai et al. 2008, Nogueira et al., 2015, Denardini et al. 2016.) providing the possibility to follow the variation of the fmin before and after the total radio fadeout.

**4. Results**: The results are interesting. Although this absorption is well known in the ionospheric data (Denardini et al, 2017, doi: 10,116/s40623-016-0456-7, Sahai et al., cited by authors, and other authors), the relation with the solar zenith angle is present in different form.

Thank you for the suggested papers. We read them carefully and wrote the most important findings into the introduction part. The text that has been added to the manuscript is the following:

"Solar flare effects on the equatorial and low- latitude ionosphere have been described by Sripathi et al 2013. They observed the lack of ionospheric traces in the ionograms during an X class solar flare and a strong blanketing type Es layer before and after the flare event. The total radio fade-out in the ionograms was observed simultaneously with an amplified signal amplitude in ground based VLF records. They suggested that the reason of the amplified VLF signals could be enhanced D region ionization due to solar flare which could also cause the increased absorption of HF radio waves observed in the ionograms. Partial radio fade-out and a blanketing type sporadic E layer were also detected in ionograms measured close to the equator in the Brazilian sector (Denardini et al. 2016). They determined a 42-146 % enhancement in the electron density of the E-layer after X-class solar flares with the observation of peaks in the fbEs parameter. The attenuation of radio waves (below 5–8 MHz) caused by ionospheric absorption occurred some minutes before the abnormal changes in the E region electron density and can be attributed to the additional X-ray ionization due to solar flares. Total radio blackout for about 70 min and increased values of the fmin parameter inferred from ionograms registered at two ionosonde stations in the equatorial region have been reported by Nogueira et al. (2015). The onset and recovery of the flare effect were observed with a consistent time difference at the two stations. Nogueira et al. (2015) stated that the reason for this time delay is the east-west separation of the observing sites."
… "Nogueira et al. (2015) observed an abrupt increase of the TEC in the sunlit hemisphere due to a flare event. The plasma density perturbation seems larger and remains for longer time in the crest region of the equatorial ionization anomaly (EIA) than at the subsolar point. However, Spirathi et al (2013) demonstrated a good correlation between the TEC enhancement caused by a solar flare and solar zenith angle. This result verifies the study of Zhang and Xiao (2005) who have shown that the ΔTEC varies with solar zenith angle."

 However, the results are arranged in numerous figures and presented with a confusing text. It would be better to present the figures together (for example Figures 1 and 2 are a single figure)

Thank you for the suggestion. We changed the structure of the results part to make it clear and more readable. In the first paragraph we determined the particular issue of research:

"In the present study we investigated the response of ionospheric absorption to solar flares with particular interest of the solar zenith angle dependence variation of it. We used ionograms measured at ionosonde stations under different solar zenith angle for the analysis. We calculated the solar zenith angles of the stations at the time of the peak of the 8 flares for the analysis. We examined three parameters that can be determined from ionograms: duration of the total radio fade-out, the value of the fmin parameter and the value of the dfmin parameter. In the first step we analyzed how the duration of the fade-out during the flare event depended on the solar zenith angle (Sec. 3.1). Secondly the solar zenith angle dependence of the fmin and dfmin parameters measured just after the fade-out were investigated (Sec 3.2). Then we repeated the analysis for the fmin and dfmin parameters measured at a certain time after the fade-out when we again recorded them at all the stations (3.3). In the last step the impact of the intensity variation on the absorption has been considered (3.4)."

Based on your comment and question/comments of the other reviewer the Fig. 1., 2., 3. and their description can confuse the reader. Therefore, we deleted the first three Figures and their descriptions and we added a figure what shows a sequence of ionograms measured at two stations during the most intense flare events of our study (Fig. 1. in the revised manuscript). We hope that it helps to follow the behaviour of the ionosphere during this intense solar event. Furthermore, it makes clear the observation of total and partial radio fade-out and of fmin parameter at stations under different solar zenith angle what is the crucial part of our study.

We added the description of the Fig. 1. (in the revised manuscript) to the text as follows:
"Here we demonstrate in detail the ionospheric response to an intense X17-class eruption that occurred on 28 October 2003. The European and South African ionosonde stations were located in the sunlit hemisphere during this flare event. Fig.1 shows a sequence of ionograms recorded close to the equator (Ascension Island) and at mid-latitude (San Vito) from 09:00 UTC to 14:30 UTC on 28 October 2003. Ionograms measured every 15 min were available for the analysis, however we show the records with 30 minute time resolution to cover the whole time interval of the flare from the start until the end of decay. The upper panel of Fig. 2 shows the X-ray variation between 06 (UTC) and 18 (UTC) recorded by GOES12 satellite. In the X-ray flux we can clearly observe the flare event that started at 09:51, reached its peak at 11:10 and ended at 11:24. The most directly observed ionospheric effect due to the X-class solar flare is the total and partial fade-out of the sounding HF waves on the ionograms (Fig. 1.). The disappearance of the traces caused by the enhanced ionospheric absorption was recorded at both stations. However, the duration of the total fade-out measured at the two observation sites was different. We may notice that an increase in the fmin parameter was first detected in the ionogram at 10:00 (UTC) over Ascension Island, close to the dip equator (fmin increased to 5.4 MHz). At San Vito, located in southern Italy at mid-latitude, the effect was weaker at this time (fmin ~ 2.9 MHz). The total attenuation of the radio waves was first recorded at Ascension Island at 11:00 (UTC). In the subsequent ionograms at 11:15 UTC (not shown here) and at 11:30 the total blackout was observed at both stations which coincided with the peak in the X-ray flux as it is shown at the upper panel in Fig. 2. The trace of the F region appears on the ionogram at San Vito at 12:00 (UTC), while the total radio fade-out remains at Ascension Island until 12:30 (UTC). With the decay in the X-ray flux the blackout became partial at both stations. The fmin parameter returns to its regular daily value (~ 2.3 MHz) at San Vito at 14:00. The recovery over Ascension occurs later, partial radio fade-out was still detected at 14:30. We believe that the different duration of the total radio fade-out recorded in the ionograms at the two stations can be explained by the different solar zenith angle at the two sites. Since the degree of the radio wave absorption in the ionosphere varies with the solar zenith angle, we compared ionograms measured at stations under different solar zenith angles to research into the solar zenith angle dependence of the ionospheric response."

**5. Discussions and conclusions**: The part of the discussion is actually a conclusion. The authors did not elaborate on the physical discussions. There are numerous studies about the subject of relation between flare solar and ionospheric parameters. I suggest that the authors to discuss further the results, that are very interesting, before being published in this journal.

Thank you for your suggestion. We read the papers carefully what you previously proposed in the review and compared our results with the most important findings of them. We believe that the more detailed discussion improved the quality of the manuscript.

We must mention here that the coupled mechanisms in the magnetosphere-ionosphere-atmosphere system in response to solar flares are very complex but we focus on the changes of the ionospheric absorption and its solar zenith angle dependence in our study. Therefore, we discussed the results of previous papers only in connection with this topic.

We added the following parts to the discussion:

"Total and partial radio fade-out were experienced at every ionospheric station during and after the X class solar flares (on 2001-09-24, 2003-10-28, and on 2005-12-05) and also in the case of some M class flares (e. g. on 2006-12-06). The observed time of the absence of the echoes was between 15 min and 150 min, similar to the findings of Sahai et al. (2006) with ionosondes over the Brazilian sector on 28 October 2003. Similarly, Nogueira et al. (2015) found from a total to partial HF blackout for about 70 min in ionograms measured at the São Luís and Fortaleza equatorial stations as a result of an X2.8 solar flare. They observed a consistent time difference in the beginning and the end of the flare effect in the sequences of ionograms and they explained this phenomenon by the east-west separation of the observing sites. We investigated the beginning and the end of the total radio fade-out measured at the eastern locations as compared to the western locations. E.g. comparing the beginning and the end of the blackout at Chilton (west) with Juliusruh (east) or at Ascension Island (west) with Grahamstown (east) during the X17 flare occurring on 28 October 2003 (Fig. 2.) we cannot detect a systematic delay. Based on our results there is no detected east-west separated consistent time difference of the flare effect. Whereas, examining the duration of the total radio fade-out at the time of the same flare (28 October 2003, Fig. 2.) it seems to depend on the solar zenith angle. The smaller the zenith angle of the observation site (Grahamstown, Ascension Island) the longer the detected blackout of the HF waves. We observed a similar trend for the flares occurring on 05 December, 2006 and on 06 December, 2006 (Fig. 4.). The total radio fade-out during the time of intense solar flares (M > 5) could be understood due to absorption of radio signals by enhanced D region ionization. Previous studies reported that enhanced ionization of the D region can lower the reflection height of the VLF radio waveguide and amplify the amplitude of the propagating signals (Thomson and Clilverd, 2001; Thomson et al., 2004; Kolarski and Grubor, 2014). Sripathi et al 2013 observed lack of ionospheric traces in the ionograms simultaneously with an amplified amplitude signal of ground based VLF records during an X class solar flare. Their results suggest there could be enhanced D region ionization due to solar flare which also caused absorption of HF radio waves in the ionograms."

…

"Contradictory results have been reported in the literature about the solar zenith angle dependence of the ionospheric response to solar flares. Our results are in agreement with D-RAP model (https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap/) on the dependence of solar zenith angle. This model was developed based on the theoretical descriptions of the ionospheric absorption by Davies (1990) and Sauer and Wilkinson (2008). According to the model the Highest Affected Frequency (HAF) is largest at the sub-solar point and it decreases with increasing solar zenith angle. Moreover, Zhang and Xiao (2005) and Spirathi et al. (2013) have demonstrated a good correlation between the TEC enhancement caused by solar flares and the solar zenith angle, too. However, Li et al. (2018) concluded that there is no strong relationship between the Ne variation of the D region and the solar zenith angle. Furthermore, Nogueira et al. (2015) demonstrated an abrupt increase of the TEC. The observed anomaly seemed larger and remained for a longer time in the crest region of the equatorial ionization anomaly (EIA) than at the subsolar point. We also observed the largest and the longest-lasting perturbation of the ionospheric absorption in the equatorial region (at Ascension Island) in most of the cases. However, our results suggest that the solar zenith angle of the observation site plays an important role. For instance, at the peak time of the X9 flare (05 December 2006) the zenith angle of the ionosonde station at Ascension Island (geomagnetic latitude: -2.31°) was 36.14° and the duration of the fade-out was 60 min, smaller than measured at Grahamstown (geomagnetic latitude: -34.01°, see Table 3.). Even a larger difference was observed at the two stations during the M5-class flare at 09:27 on 27 October 2003. The solar zenith angle of Ascension Island was 47.96° at the peak time and there was no detected total radio fade-out. While at Grahamstown with a smaller solar zenith angle (21.77°) the duration of

the total attenuation of HF waves was 150 min (Table 3.). Therefore, our observations confirm the results of Zhang and Xiao (2005), Spirathi et al. (2013) and the D-RAP model that the solar zenith angle plays an important role in the ionospheric response to solar flares."

**Minor Comments:**
• English needs to improve in all manuscript: grammar, typo mistakes, absence of commas, and verbal agreement.

We tried to correct the typos and mistakes and improve the English of the whole manuscript.

• Legend of the figures (1 up to 5) are very difficult to see.
Thank you. The labels and titles of the figures (Fig. 1-3 in the revised manuscript) have been increased in order to be more readable.

# Investigation of the ionospheric absorption response to flare events during the solar cycle 23 as seen by European and South African ionosondes

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**Abstract.** We have investigated the solar flare effects on ionospheric absorption with the systematic analysis of ionograms measured at mid- and low-latitude ionosonde stations under different solar zenith angles. The lowest recorded ionosonde echo, the minimum frequency (fmin, a qualitative proxy for the ''nondeviative'' radio wave absorption occurring in the D-layer), ~~furthermore~~ and the dfmin parameter (difference between the value of the fmin and the mean fmin for reference days) have been considered. Data was provided by ~~at~~ meridionally distributed ionosonde stations in Europe and South Africa during eight X and M class solar flares in solar cycle 23. Total and partial radio fade-out was experienced at every ionospheric stations during intense solar flares (> M6). The duration of the total radio fade-out varied between 15 and 150 min and it was highly dependent on the solar zenith angle of the ionospheric stations. Furthermore, a solar zenith angle-dependent enhancement of the fmin (2-9 MHz) and dfmin (1-8 MHz) parameters was observed at almost every stations. The fmin and dfmin parameters show an increasing trend with the enhancement of the X-ray flux. Based on ~~the~~ our results, the dfmin parameter is a good qualitative measure for the relative variation of the "nondeviative" absorption especially in the case of the less intense solar flares which do not cause total radio fade-out in the ionosphere (class < M6).

## 1. Introduction

The most intense external ~~forcing of~~ impact on the ionosphere from above is related to solar flares. These events are giant explosions on the surface of the Sun that suddenly release large amounts of electromagnetic energy at a broad range of wavelengths, particularly in the bands of X-radiation and extreme ultraviolet (EUV), for a very short duration (~30 minute to ~1 hour, Tsurutani et al., 2009). Solar flares are classified as large (X), medium-size (M) and small (C) according to their peak flux (in watts per square meter, $Wm^{-2}$, $M \sim 10^{-5} – 10^{-4}\ Wm^{-2}$, $X > 10^{-4}\ Wm^{-2}$) of 0.1 to 0.8 nm X-rays near Earth, as measured on the GOES spacecraft. During solar flares, the suddenly increased radiation causes extra ionization of the neutral components in the sunlit hemisphere of the Earth's atmosphere over short time intervals (few minutes to 1 hour (Rishbeth and Garriot, 1969; Tsurutani et al., 2009; Zolesi and Cander, 2014)). While hard X-rays (< 1 nm) penetrate deeply into the ionosphere and

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could cause enhanced ionization in the D region during solar flares (Brasseur and Solomon, 1986; Rees, 1989; Hargreaves, 1992), the less energetic soft X-ray (1-10 nm) and far UV flux (80-102.6 nm) rather enhances the ionization in the E region (Rishbeth and Garriot, 1969). In addition to electromagnetic radiation, solar flares are also accompanied by energetic particles (protons and electrons) with energies from some tens of keV to some hundreds of MeV. They reach the Earth's atmosphere

5    between a half hour and a few hours later, and cause impact ionization (Rishbeth and Garriot, 1969; Bothmer and Daglis, 2007; Tsurutani et al., 2009). The approximate peak electron energy of a few keV causes the largest ionization in the lower E region while during the so-called solar proton events (SPE) high energy protons (up to more than 100 MeV) cause ionization much deeper, namely in the D region (Reid, 1986; Rees, 1989; Bothmer and Daglis, 2007).

10    The significant enhancement of the electron density as a result of solar flares can create increased attenuation of electromagnetic waves propagating through the ionosphere. The physical background of the ionospheric radio wave absorption mechanism is that the electrons accelerated by the electric field of the propagating radio waves collide with the atmospheric constituents. The absorbed energy of the electrons would reradiate without the presence of the neutral atmosphere. However, the electrons lose their energy due to the collisions with neutral particles which cause reduction of their reemitted signal. Since

15    the atmospheric density, the collision frequency and also the recombination rate also changes with altitude, the efficiency of the radio wave absorption in the ionosphere strongly varies with altitude. The electron collision frequency is high in the D region ($2\times10^6$ s$^{-1}$) and the HF radio waves below 10 MHz can be strongly attenuated there (Zolesi and Cander, 2014). Therefore, total radio fade-out lasting for tens of minutes or hours can be caused by the enhancement of electron density induced by increased electromagnetic radiation or energetic particles. Protons with energy less than 100 MeV will penetrate

20    the Earth's atmosphere only at high latitudes (> 60°), causing radio wave fade out, so called Polar Cap Absorption (PCA) events there (Bailey, 1964; Sauer and Wilkinson, 2008; Tsurutani et al., 2009). Generally, a PCA event begins a few hours after solar flares and lasts for some days (Rishbeth and Garriot, 1969; Zolesi and Cander, 2014).

    The loss of HF communication as a result of the enhanced absorption affects navigation systems, especially in

25    commercial aircraft operations. Therefore, describing, modelling and monitoring of the ionospheric absorption and D , E region electron density variation is an important issue from a practical point of view as well. The process of the ionospheric absorption has been described more extensively by Davies (1990) and Sauer and Wilkinson (2008). Based on these studies the Space Weather Prediction Center (SWPC) has developed a model (D-Region Absorption Prediction, D-RAP2, https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap ) to predict the ionospheric absorption in the D-

30    region. The product provides graphical information about High Frequency (HF) radio propagation conditions around the globe. According to the model the Highest Affected Frequency (HAF) is largest at the sub-solar point and it decreases with increasing solar zenith angle, $\chi$ (the frequencies taper off from the maximum as $(\cos\chi)^{0.75}$).

Enhanced X-ray fluxes during solar flares are known to cause increased ionization in the Earth's lower ionosphere (mainly in the D region). Sahai et al. (2006) have studied the 28 October 2003 solar flare event over the Brazilian sector using ionosonde data and detected a lack of echoes in the ionograms for a 1 h period during the flare onset. They suggested that the reason for complete or partial radio signal fade-out could be intense absorption. The minimum frequency of reflection in radio soundings by ionosondes (fmin) depends on the absorption within the D region. Sharma et al. (2010) reported on a connection between the solar flares and enhancement of fmin (> 100 %) in the ionosphere. Solar flare effects on the equatorial and low-latitude ionosphere have been described by Sripathi et al 2013. They observed the lack of ionospheric traces in the ionograms during an X class solar flare and a strong blanketing type Es layer before and after the flare event. The total radio fade-out in the ionograms was observed simultaneously with an amplified signal amplitude in ground based VLF records. They suggested that the reason of the amplified VLF signals could be enhanced D region ionization due to solar flare which could also cause the increased absorption of HF radio waves observed in the ionograms. Partial radio fade-out and a blanketing type sporadic E layer were also detected in ionograms measured close to the equator in the Brazilian sector (Denardini et al. 2016). They determined a 42-146 % enhancement in the electron density of the E-layer after X-class solar flares with the observation of peaks in the fbEs parameter. The attenuation of radio waves (below 5–8 MHz) caused by ionospheric absorption occurred some minutes before the abnormal changes in the E region electron density and can be attributed to the additional X-ray ionization due to solar flares. Total radio blackout for about 70 min and increased values of the fmin parameter inferred from ionograms registered at two ionosonde stations in the equatorial region have been reported by Nogueira et al. (2015). The onset and recovery of the flare effect were observed with a consistent time difference at the two stations. Nogueira et al. (2015) stated that the reason for this time delay is the east-west separation of the observing sites. Zaalov et al. (2018) developed an empirical absorption model combining the Global Ionospheric Radio Observatory (GIRO, http://giro.uml.edu) data and ionogram modelling. More reliable and accurate evaluation of minimum frequency is possible thanks to their proposed method.

The D region electron density ($N_e$) response to solar flares was studied with a medium frequency (MF) radar at Kunming (25.6°N, 103.8°E) (Li et al., 2018). They found a strong and positive correlation between $N_e$ and X-ray changes during thirteen M class flares. Based on the results the $N_e$ changes also depended on the onset time and the duration of the flare. Moreover, the GNSS ground and satellite receivers offered further possibilities to study the solar flare effects on total electron content (TEC) in high time (~ 30 s) and spatial resolution (Afraimovich, 2000; Zhang et al., 2002; Tsurutani et al., 2005 and 2006). Nogueira et al. (2015) observed an abrupt increase of the TEC in the sunlit hemisphere due to a flare event. The plasma density perturbation seems larger and remains for longer time in the crest region of the equatorial ionization anomaly (EIA) than at the subsolar point. However, Sripathi et al (2013) demonstrated a good correlation between the TEC enhancement caused by a solar flare and solar zenith angle. This result verifies the study of Zhang and Xiao (2005) who have shown that the ΔTEC varies with solar zenith angle. Tsurutani et al. (2009) summarized the "solar flare effects" on the ionosphere, and especially on TEC in a comprehensive review paper.

In addition, during solar flares and high energy particle precipitation events, enhanced ionization of the D region can lower the reflection height of the VLF, ELF radio waveguide and perturb the amplitude of the propagating signals (Thomson and Clilverd, 2001; Thomson et al., 2004; Kolarski and Grubor, 2014). Guha et al. (2017) investigated solar flare effects on the D region during 12 solar flares using a portable VLF station installed at Antarctica during summertime. They applied a Long Wave Propagation Capability (LWPC) model to study the daytime electron density changes during the flares and found an excellent correlation between the exponential fit of the modeled electron density change and the average X-ray flux change. Based on VLF measurements and TEC calculations Drakul et al. (2011) showed that the D region's electron content (TECD) contribution in TEC can reach several percent during solar flares. The effects of two extraordinary solar events, the Bastille Day event and the Halloween event, have been studied by the characteristic height of the ELF waveguide through measurement of Schumann resonance (SR) parameters (Sátori et al., 2016). The observational results verify the conclusion by Sátori et al. (2005) that the hard solar X-ray has an important role in modifying the Earth ionosphere cavity, with changes in the electron density in the height range from ~ 90km -100 km.

The aim of the present study is to investigate the solar flare effects on ionospheric absorption at mid- and low-latitudes, taking into account the solar zenith angle with the systematic analysis of the ionospheric fmin parameter measured at different ionosonde stations. The fmin parameter represents the minimum frequency of the echo trace observed in the ionogram and it is a rough measure of the "nondeviative" absorption (e.g. Davies, 1990). Following this introduction, the exact method and the data examined are described in section 2. We will detail the results in section 3. Finally, the results are discussed and the concluding remarks are written in section 4.

## 2. Method and data

We analyzed the time series of the fmin parameter inferred from ionograms during solar flares and solar proton events (SPE) of with different intensities occurring in solar cycle 23. The ionospheric parameters ionograms have been manually verified and evaluated before the analysis. The fmin parameter, representing the lowest recorded ionosonde echo, is usually considered as a qualitative measure of the so-called ''nondeviative'' radio wave absorption in the ionosphere (Risbeth and Gariott, 1969, Davies, 1990). It has been used It is regularly used to investigate the absorption of the D region in the last decades (Lusignan, 1960; Oksman et al., 1981; Kokourov, 2006; Sharma et al, 2010; Schmitter et al, 2011, Sripathi et al, 2013; Nogueira et al., 2015). However, the fmin parameter also depends on the radar instrumental characteristics and the radio-noise level. In order to minimize and compensate for the instrumental errors, only data measured by Lowell type digisondes (Global Ionospheric Radio Observatory (GIRO, http://giro.uml.edu) data) were used for the investigation. Furthermore, a dfmin parameter (difference between the value of the fmin and the mean fmin for reference days) have also been determined for the analysis. We chose at least 10 reference days have been selected before and after the selected flares based on the X-ray radiation ($< 0.5*10^{-4}$) and proton flux [0.8-4 MeV] ($< 3*10^3$) measured by GOES satellites. The analysis has been repeated for ionospheric data recorded at meridionally distributed ionosonde stations (the selected stations with their geographical coordinates are found in Table 1.).

The solar zenith angle of the observation sites has been also taken into account in the case of the selected flare events. The solar zenith angle dependence of the ionospheric response has also been investigated. We determined the solar zenith angle of the ionospheric stations at the peak time of the selected flare events. Generally, the zenith angles of the observation sites were large in Europe and small in South Africa in the case of the same flare because there are no GIRO stations between these two regions. Firstly, we investigated how the duration of the total radio fade-out depended on solar zenith angle. Then the solar zenith angle dependence of the first measured value of the fmin and dfmin parameters after the fade-out was considered. In the case of the X-class solar flares the radio fade-out took 1-2 hours especially at-stations with low solar zenith angle. Consequently, in the next step we compared the solar zenith angle dependence of the fmin and dfmin parameters detected at the different stations at a certain time after the fade-out when there were measured data at most of the stations.

Three solar events from solar cycle 23. have been selected for analysis when a strong X-class flare has been accompanied by a strong solar proton event. We chose three X-class and further five M-class flares from three active periods for the investigation. Further conditions that We also had to considered in the selection that the European and South African ionosonde stations had to be in the sunlit hemisphere during the flares. Therefore, the variation of absorption variation caused by the radiation could be determined using the fmin parameter measured at these stations. Some less intense (M-class) flares which have occurred during the days before and after the X-class flares have also been analyzed. The selected solar flares and

are listed in Table 2 The ionograms used for the analysis were derived from the Global Ionospheric Radio Observatory network (GIRO, http://giro.uml.edu) and were processed by the SAO-X program. The data from the GOES 11 and 12 satellite used to investigate the X-ray and solar proton flux were available at the omniweb data base (https://omniweb.gsfc.nasa.gov/).

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## 3. Results

In the present study we investigated the response of ionospheric absorption to solar flares with particular interest of the solar zenith angle dependence variation of it. We used ionograms measured at ionosonde stations under different solar

10  zenith angle for the analysis. We calculated the solar zenith angles of the stations at the time of the peak of the 8 flares for the analysis. We examined three parameters that can be determined from ionograms: duration of the total radio fade-out, the value of the fmin parameter and the value of the dfmin parameter. In the first step we analyzed how the duration of the fade-out during the flare event depended on the solar zenith angle (Sec. 3.1). Secondly the solar zenith angle dependence of the fmin and dfmin parameters measured just after the fade-out were investigated (Sec 3.2). Then we repeated the analysis for the fmin

15  and dfmin parameters measured at a certain time after the fade-out when we again recorded them at all the stations (3.3). In the last step the impact of the intensity variation on the absorption has been considered (3.4).

Here we demonstrate in detail the ionospheric response to an intense X17-class eruption that occurred on 28 October 2003. The European and South African ionosonde stations were located in the sunlit hemisphere during this flare event. Fig.1

20  shows a sequence of ionograms recorded close to the equator (Ascension Island) and at mid-latitude (San Vito) from 09:00 UTC to 14:30 UTC on 28 October 2003. Ionograms measured every 15 min were available for the analysis, however we show the records with 30 minute time resolution to cover the whole time interval of the flare from the start until the end of decay. The upper panel of Fig. 2 shows the X-ray variation between 06 (UTC) and 18 (UTC) recorded by GOES12 satellite. In the X-ray flux we can clearly observe the flare event that started at 09:51, reached its peak at 11:10 and ended at 11:24. The most

25  directly observed ionospheric effect due to the X-class solar flare is the total and partial fade-out of the sounding HF waves on the ionograms (Fig. 1.). The disappearance of the traces caused by the enhanced ionospheric absorption was recorded at both stations. However, the duration of the total fade-out measured at the two observation sites was different. We may notice that an increase in the fmin parameter was first detected in the ionogram at 10:00 (UTC) over Ascension Island, close to the dip equator (fmin increased to 5.4 MHz). At San Vito, located in southern Italy at mid-latitude, the effect was weaker at this time

30  (fmin ~ 2.9 MHz). The total attenuation of the radio waves was first recorded at Ascension Island at 11:00 (UTC). In the subsequent ionograms at 11:15 UTC (not shown here) and at 11:30 the total blackout was observed at both stations which coincided with the peak in the X-ray flux as it is shown at the upper panel in Fig. 2. The trace of the F region appears on the ionogram at San Vito at 12:00 (UTC), while the total radio fade-out remains at Ascension Island until 12:30 (UTC). With the decay in the X-ray flux the blackout became partial at both stations. The fmin parameter returns to its regular daily value (~

2.3 MHz) at San Vito at 14:00. The recovery over Ascension occurs later, partial radio fade-out was still detected at 14:30. We believe that the different duration of the total radio fade-out recorded in the ionograms at the two stations can be explained by the different solar zenith angle at the two sites. Since the degree of the radio wave absorption in the ionosphere varies with the solar zenith angle, we compared ionograms measured at stations under different solar zenith angles to research into the solar zenith angle dependence of the ionospheric response.

Three time periods (2001-09-23 – 2001-09-28; 2003-10-27 – 2003-11-02; 2006-12-04 – 2006-12-08), when the eight X and M class flares and three SPEs occurred, have been selected for this study. First the fmin, foE, foF2 parameters have been investigated during these special periods (Fig. 1. and Fig. 2.). On the upper plots the variation of the X-rays are shown, while on the second upper plot the changes of the proton flux are shown during the three mentioned special periods. The changes of the fmin, foE and foF2 parameters detected at meridionally distributed stations are seen on the lower panels of the plots from higher to lower latitudes consecutively. The times of the X and M class flares which have been selected for further analysis are indicated by green dashed lines. Total and partial radio fade-out was experienced at every ionospheric station during and after the X class solar flares (on 2001-09-24, 2005-12-05 and on 2003-10-28 (shown later)) and also in the case of some M class flares (e. g. on 2006-12-06). The detected time periods of the total radio fade-out were between 15 min and ~150 min. The observed time of the lack of the reflected echoes is similar to the results of Sahai et al. (2006) detected by ionosondes over the Brazilian sector on 28 October 2003. Extreme increases of the fmin values (4-9 MHz) were observed at almost every stations at the time of the X class solar flares (on 2001-09-24, 2005-12-05 (Fig. 1. and 2.) and on 2003-10-28 (not shown here). Furthermore, the variation of the fmin parameter was well pronounced (2-7 MHz) during the M class solar flares as well (e. g. on 28 September 2001 and on 06 December 2006, Fig. 1. and 2.). During the time of the increased values of the fmin parameters the co-occurring absence of the foE parameter was detected (Fig. 1. and 2.). There were no detected changes of the fmin parameter at high latitude (Tromso) during the X9.0 (on 5 December, 2006) and M6.0 (on 6. December, 2006) class solar flares. However, total radio fade-out was observed for almost two days at Tromso on 07 and 08 December, 2006 due to the polar cap absorption (PCA) (Fig. 2.) caused by the precipitation of energetic charged particles (Rose and Ziauddin, 1962; Bothmer and Daglis, 2007). Data was not available from high latitude for the periods 2001-09-23 – 2001-09-28 and 2003-10-27 – 2003-11-02. The changes of the dfmin parameter during the selected time periods (2001-09-23 – 2001-09-28; 2003-10-27 – 2003-11-02; 2006-12-04 – 2006-12-08) have been analyzed as well. The variation of the dfmin parameter between 2003-10-27 and 2003-11-02 can be seen on Fig. 3. Huge variations also occurred in the value of the dfmin at the time of the X and M class flares on 27 and 28 October, 2003. The detected total radio fade-out, observed at every ionosonde stations at the time of the X17 flare on 28 October 2003, can be seen in Fig. 3. as well. In addition, the observed changes of the dfmin parameter was 4-8 MHz at the time of the X class flares (e.g. on 28 October, 2003, Fig. 3.) and 1-4 MHz at the time of the M class flares (e. g. 2 flares on 27 October 2003, Fig. 3.).

~~In the next step of the analysis the solar zenith angle dependence of the duration of the fade-out, the fmin and dfmin parameters have been investigated during and after the time of the selected solar flares. The solar zenith angles of the stations at the time of the peak of the 8 flares have been determined for the analysis.~~

5        The X-ray flux changes and dfmin parameter measured at stations with different solar angles on 27 and 28 October, 2003 are shown here (Fig. 2. and 3.). We may notice in Fig. 2 that the duration of the total radio fade-out tends to show a solar zenith angle dependence. ~~The duration of the fade-out and also the dfmin~~ It goes from smaller to larger values at stations with larger to smaller zenith angle. Looking at the values of the dfmin parameter detected just after the fade-out at the stations on 28 October it seems that they also follow this trend. However, this relation is not as unambiguous as in the previous case. ~~at~~

10 ~~the time of the X17 solar flare on 28 October (Fig. 4.) it seems that the total radio fadeout and also the measured peak value of dfmin show a solar zenith angle dependence.~~ We also compared the dfmin values recorded at a certain time after the total fade-out when was observed data at all of the stations. We chose 13:00 UTC on 28 October 2003 for this comparison. As seen in the upper plot the X-ray flux at 13:00 UTC was still enhanced in contrast with its values before the flare. The values of the dfmin parameter were ~ 2-3 MHz at the mid-latitude stations at 13:00 UTC while the detected record is ~ 4 MHz at

15 Grahamstown (low-latitude) and 6 MHz at Ascension Island (close to the equator). We can conclude in this case as well that the smaller the solar zenith angle the larger the detected value of the dfmin. A similar tendency of the dfmin parameter can be seen during the two M class solar flares on 27 October 2003 (Fig. 3.). We must note that these two M class solar flares did not cause total radio fade-out in the ionosphere except at Grahamstown. The echoes were not detected there between 08:00 and 10:00 UTC. However, the solar zenith angle of the station was low (21.77°) at the peak time (at 09:30) of the M5-class flare.

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        We investigated the solar zenith angle dependence of these parameters (total fade-out, fmin, dfmin) during the other five flares. The X-ray flux and dfmin changes are not detailed here in the other cases. Nevertheless, in the next sections we will show summary plots about the solar zenith angle dependence of the values. We must note here that generally the number of observations (N) is limited to say anything about statistical significance but the plots are illustrative.

25

### 3.1 Duration of the fade-out

        Total and partial radio fade-out was experienced at every ionospheric station during and after the X class solar flares (on 2001-09-24, 2005-12-05 and on 2003-10-28) and also in the case of some M class flares (e. g. on 2006-12-06). The detected time periods of the total radio fade-out were between 15 min and ~150 min. ~~There were four flares during the selected time~~

30 ~~periods when total radio fade-out was detected at least at four stations.~~ The solar zenith angle dependence of the duration of the total fade-out has been investigated during these four events. The results ~~can be seen~~ are shown in the Table 3. and in Fig. 4. The solar zenith angle dependence of the duration of the total radio fade-out can be clearly seen on Fig. 4. especially during the X17 flare on 28 October 2003 (Fig. 4a.) and the X9 flare on 5 December, 2006 (Fig. 4b.). The duration of the fade-out tends to increase with decreasing solar zenith angle. The tendency is similar in the other two cases but is not that pronounced.

8

~~It has to be mentioned We must note here that generally the number of observations (N) is limited to say anything about statistical significance but the plots are illustrative.~~

**3.2 Variation of the fmin and dfmin values just after the fade-out**

5        The solar zenith angle dependence of the fmin and dfmin values measured at the peak time of the flares or immediately after the fade-out has been analyzed in the next step. The results are shown in Table 3 and Fig's 5. and 6. Extreme increases of the fmin values (4-9 MHz) were observed at almost every stations at the time of the X-class solar flares (on 2001-09-24, 2005-12-05 and on 2003-10-28 (Fig. 5a, 5b and 5c). Furthermore, the variation of the fmin parameter was well pronounced (2-7 MHz) during the M class solar flares as well (e. g. on 28 September 2001 (Fig. 5d.) and on 06 December 2006 (Fig. 5e.)).

10   The solar zenith angle dependence of the fmin and dfmin values can be seen in most cases. The fmin values are increasing with decreasing solar zenith angle. This increasing trend of the fmin parameter is especially pronounced on the panels Fig. 5b., Fig. 5c. and Fig. 5e in the case of the flares 2006-12-05, 2001-09-24 and 2006-12-06 respectively. The trend can be recognized in the panels 5d., 5e, 5g and 5h, although points are more scattered. However, there is no observable trend in Fig. 5a. in the case of the most intense flare of the Halloween event on 28 October, 2003. Looking at the fmin values during the flares the

15   effect of the different flare intensities on the ionosphere can be detectable as well. The fmin values in the case of the X-class flares in Fig. 5a. (2003-10-28) and in Fig. 5c. (2001-09-24) are larger (fmin > 5 MHz) than in the case of the M class flares from the same periods (3 < fmin < 8 MHz on Fig. 5d., 5f., 5g. and 5h.). A seasonal dependence of the fmin parameter is also evident. The values are larger in September and October (3 < fmin < 11 MHz) than in December (2< fmin < 7 MHz).

The increasing trend with decreasing solar zenith angle is also detectable in the dfmin values. Moreover, the points are not that

20   scattered in the Fig. 6e, 6f, 6g and 6h, in the case of the M class flares. Nevertheless, the increasing trend cannot be seen in Fig. 6a and 6d. during the flares that occurred at 12:43 on 27 and at 11:24 on 28 October, 2003. The lack of an increasing trend in these cases can be explained that the times of the fade-out are very different at the different ionospheric stations (see Fig. 4.). Therefore, the first fmin and dfmin values just after the fade-out were measured at different times when also the X-ray radiation of the flare was different. In order to eliminate this possible cause for variability, we analyzed the fmin and dfmin

25   parameters at a certain time after the peak of the flares when there were detectable values at the most stations.

**3.3 Variation of the fmin and dfmin parameters at a certain time after the fade-out**

       Table 4, Fig. 7 and 8 show the results ~~of the comprehensive investigation of~~ in connection with the solar zenith angle dependence of the fmin and dfmin values measured at a certain time after the fade-out (We demonstrated on a sample

30   previously on Fig.2 in the case of the X17 flare occurred on 28 October 2003) ~~peak of the flares are shown in Table 5 and in Fig. 9 and 10. The exact time when the measurement occurred are shown in the header of different cases in Table 5. and inFig.9 and 10.~~ The exact time of the fmin and dfmin parameter's observation, considered in this analysis, are shown in the header of different cases in Table 4. and in Fig.7 and 8. The solar zenith angle dependence of the fmin and dfmin values are more conspicuous than in the previous case. The fmin values are increasing with decreasing solar zenith angle in every case, also

after the most intense flare of the Halloween event on 28 October, 2003 (see Fig. 7a.). The solar zenith angle dependence seems well defined in the dfmin values. The increasing trend appears in every case, and also after the flares that occurred at 12:43 on 27 and at 11:24 on 28 October, 2003 (Fig. 8a. and 8d.). Moreover, the points in Fig. 8. are less scattered than in the case of fmin, in Fig. 7.

5

### 3.4 Comprehensive investigation of the intensity of flares and the solar zenith angle dependence

The results showed that the ionospheric response depended also on the intensity of flare (changes in the X-ray flux). The value of the dfmin variation reached 6-9 MHz during and after the X17 (2003-10-28, Fig. 6a.) and X2 (2001-09-24, Fig.
10  6c.) flares. Whereas the dfmin values varied between 1 and 3 MHz in the cases of the M3.3 and M 2.4 flares on 28 September, 2001 (Fig. 6g. and 6h.). Therefore, a comprehensive analysis, taking into account the solar zenith angle and the intensity together, has also been performed. The solar zenith angle and the X-ray radiation dependence of the fmin and dfmin parameters measured at the peak of the flare events or just after the fade-out are shown in Fig. 9a. and 9b. respectively. The results show that the value of the fmin and dfmin parameters depend on the intensity of the X-ray radiation, but they also depend on the
15  solar zenith angle of the stations where they have been measured. The largest fmin (> 7 MHz) and dfmin (> 5MHz) values have been detected during the X-class solar flares (X-ray radiation > 2.61E-04 Wm-2) and at the stations with low (< 40 °) solar zenith angle. Since, the exact time of the measurements were different (because of the different duration of the total radio fade-out), this analysis has been repeated for fmin and dfmin values measured at a certain time after the peak of the flares fade-out when the parameters were detectable at most of the stations. (The exact observation time and the detected X-ray intensity
20  by GOES satellites at that time are shown in the header of different cases in Table 4.) The results of the analysis are shown in Fig. 10. The X-ray radiation dependence can be seen in the value of the fmin parameter in this case as well. However, it is much better defined in the case of the dfmin parameter. Larger dfmin values (> 4.5 MHz) are related to the measurements when the X-ray radiation exceeded 3.4E-05 Wm$^{-2}$. Moreover, the lowest fmin and dfmin values were measured when the X-ray radiation was weaker (< 1.33E-05 Wm$^{-2}$) and the solar zenith angle of the stations was above 35 °.

25

### 4. Discussion and conclusion

The solar flare effects on ionospheric absorption at mid- and low-latitude have been investigated with the systematic analysis of ionograms in this study. Three solar events periods from solar cycle 23. have been were selected for analysis when
30  eight X and M class flares occurred and have been accompanied by three strong solar proton events. The solar zenith angle of the observation sites at the time of the selected flares has also been considered in the analysis.

The lowest recorded ionosonde echo, characterized by the minimum frequency (fmin), has been used as a qualitative measure of the so-called ''nondeviative'' radio wave absorption in recent decades (Lusignan, 1960; Oksman et al., 1981;

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Kokourov, 2006; Sharma et al, 2010; Schmitter et al, 2011). However, a systematic analysis of this parameter measured at different ionospheric stations during solar flares has not been previously investigated. To reduce ~~minimize~~ the instrumental errors a dfmin parameter (the difference between the value of the fmin and the mean fmin for reference days) has also been determined for the analysis.

5

Total and partial radio fade-out were experienced at every ionospheric station during and after the X class solar flares (on 2001-09-24, 2003-10-28, ~~2005-12-05~~ and on 2005-12-05) and also in the case of some M class flares (e. g. on 2006-12-06). The observed time of the absence of the echoes was between 15 min and 150 min, similar to the findings of Sahai et al. (2006) with ionosondes over the Brazilian sector on 28 October 2003. Similarly, Nogueira et al. (2015) found from a total to
10 partial HF blackout for about 70 min in ionograms measured at the São Luís and Fortaleza equatorial stations as a result of an X2.8 solar flare. They observed a consistent time difference in the beginning and the end of the flare effect in the sequences of ionograms and they explained this phenomenon by the east-west separation of the observing sites. We investigated the beginning and the end of the total radio fade-out measured at the eastern locations as compared to the western locations. E.g. comparing the beginning and the end of the blackout at Chilton (west) with Juliusruh (east) or at Ascension Island (west) with
15 Grahamstown (east) during the X17 flare occurring on 28 October 2003 (Fig. 2.) we cannot detect a systematic delay. Based on our results there is no detected east-west separated consistent time difference of the flare effect. ~~Based on the present results, the duration of the total radio fade-out during intense solar flares (> M6) is highly dependent on the solar zenith angle of the observation sites.~~ Whereas, examining the duration of the total radio fade-out at the time of the same flare (28 October 2003, Fig. 2.) it seems to depend on the solar zenith angle. The smaller the zenith angle of the observation site (Grahamstown,
20 Ascension Island) the longer the detected blackout of the HF waves. We observed a similar trend for the flares occurring on 05 December, 2006 and on 06 December, 2006 (Fig. 4.). The total radio fade-out during the time of intense solar flares (M > 5) could be understood due to absorption of radio signals by enhanced D region ionization. Previous studies reported that enhanced ionization of the D region can lower the reflection height of the VLF radio waveguide and amplify the amplitude of the propagating signals (Thomson and Clilverd, 2001; Thomson et al., 2004; Kolarski and Grubor, 2014). Sripathi et al 2013
25 observed lack of ionospheric traces in the ionograms simultaneously with an amplified amplitude signal of ground based VLF records during an X class solar flare. Their results suggest there could be enhanced D region ionization due to solar flare which also caused absorption of HF radio waves in the ionograms.

~~No detected changes were noted in the fmin parameter at high latitude (Tromso) during the X9.0 (on 5 December, 2006) and~~
30 ~~the M6.0 (on 6 December, 2006) class solar flares. However, total radio fade-out was observed for almost two days at Tromso on 07 and 08 December, 2006 due to the polar cap absorption (PCA) caused by the precipitation of energetic charged particles (Rose and Ziauddin, 1962; Bothmer and Daglis, 2007).~~

Extreme increases of the fmin ~~values~~ (4-9 MHz during X class and 2-7 MHz during M class flares) and of the dfmin (4-8 MHz at the time of the X-class flares and 1-4 MHz at the time of the M class flares) values were observed at almost every stations at the time of the flare events. These enhancements of fmin during solar flares are in good agreement with the results reported by Sharma et al. (2010) and with the values measured in South America during X-class flares (Nogueira et al. 2015,

5  Denardini et al. 2016). ~~During the time of the increased values of the fmin parameters the co-occurring absence of the foE parameter was detected. Huge variations (4-8 MHz at the time of the X-class flares and 1-4 MHz at the time of the M class flares) were found in the dfmin parameter as well.~~ The analysis of the fmin and dfmin values measured at the peak time of the flares or just after the fade-out shows a solar zenith angle dependence as well. The fmin and dfmin values are increasing with decreasing solar zenith angle. However, this increasing trend is not clear in the case of the most intense (X2 and X17) solar

10  flares when the detected durations of fade-out are very different at the various ionospheric stations. The explanation for that can be that the first fmin and dfmin values just after the fade-out were measured at different time points when also the X-ray radiation of the flare was different. Therefore, in the next step we analyzed the solar zenith angle dependence of the fmin and dfmin parameters at a certain time after the peak of the flares when there were detectable values at most stations. The solar zenith angle dependence of the fmin and dfmin parameters is more conspicuous than in the previous case. The fmin and dfmin

15  values are increasing with decreasing solar zenith angle in every case. ~~Moreover, they are less scattered.~~

Contradictory results have been reported in the literature about the solar zenith angle dependence of the ionospheric response to solar flares. Our results are in agreement with D-RAP model (https://www.swpc.noaa.gov/products/d-region-absorption-predictions-d-rap/) on the dependence of solar zenith angle. This model was developed based on the theoretical

20  descriptions of the ionospheric absorption by Davies (1990) and Sauer and Wilkinson (2008). According to the model the Highest Affected Frequency (HAF) is largest at the sub-solar point and it decreases with increasing solar zenith angle. Moreover, Zhang and Xiao (2005) and Sripathi et al. (2013) have demonstrated a good correlation between the TEC enhancement caused by solar flares and the solar zenith angle, too. However, Li et al. (2018) concluded that there is no strong relationship between the $N_e$ variation of the D region and the solar zenith angle. Furthermore, Nogueira et al. (2015)

25  demonstrated an abrupt increase of the TEC. The observed anomaly seemed larger and remained for a longer time in the crest region of the equatorial ionization anomaly (EIA) than at the subsolar point. We also observed the largest and the longest-lasting perturbation of the ionospheric absorption in the equatorial region (at Ascension Island) in most of the cases. However, our results suggest that the solar zenith angle of the observation site plays an important role. For instance, at the peak time of the X9 flare (05 December 2006) the zenith angle of the ionosonde station at Ascension Island (geomagnetic latitude: -2.31°)

30  was 36.14° and the duration of the fade-out was 60 min, smaller than measured at Grahamstown (geomagnetic latitude: -34.01°, see Table 3.). Even a larger difference was observed at the two stations during the M5-class flare at 09:27 on 27 October 2003. The solar zenith angle of Ascension Island was 47.96° at the peak time and there was no detected total radio fade-out. While at Grahamstown with a smaller solar zenith angle (21.77°) the duration of the total attenuation of HF waves

was 150 min (Table 3.). Therefore, our observations confirm the results of Zhang and Xiao (2005), Sripathi et al. (2013) and the D-RAP model that the solar zenith angle plays an important role in the ionospheric response to solar flares.

According to the results of Li et al (2018) there is a ~~large~~ strong correlation between the flare-induced $N_e$ enhancement in the D-layer and the X-ray flux intensity of the flare. In order to study the impact of the X-ray flux on the fmin and dfmin parameters a comprehensive analysis, taking into account the solar zenith angle and the intensity of the flare together, has also been performed. The results show that the value~~s~~ of the fmin and dfmin parameters ~~are~~ is highly dependent on the X-ray radiation intensity, but ~~they~~ it also depends on the solar zenith angle of the station~~s~~ where ~~they have~~ it has been measured.

Based on the results, the dfmin parameter is a good qualitative measure for the relative variation of the "nondeviative" absorption especially in the case of ~~the~~ less intense solar flares which do not cause total radio fade-out in the ionosphere (class < M6). ~~These measurements may inform models in the future in describing the changes in ionospheric absorption during solar flares with different intensities.~~ However, further analysis of this ionosonde parameter and its comparison with other techniques to measure the ionospheric absorption are necessary to confirm its use as a reliable index.

*Competing interests*. The authors declare that they have no conflict of interest.

13

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| Ionospheric Station | Latitude (°) | Longitude (°) |
|---|---|---|
| Tromso | 69.6 | 19.2 |
| Juliusruh | 54.6 | 13.4 |
| Chilton | 51.5 | 359.4 |
| Pruhonice | 50 | 14.6 |
| Rome | 41.9 | 12.5 |
| San Vito | 40.6 | 17.8 |
| Ascension Isl. | -7.95 | 345.6 |
| Madimbo | -22.39 | 30.88 |
| Grahamstown | -33.3 | 26.5 |

**Table 1.** The selected ionosonde stations and their geographical coordinates.

| | Selected time period | | | |
|---|---|---|---|---|
| Date | X-ray class | Start [UTC] | Peak [UTC] | End [UTC] |
| 2001-09-23 - 2001-09-28 | | | | |
| 2001-09-24 | X2.6 | 9:32 | 10:38 | 11:09 |
| 2001-09-28 | M3.3 | 8:10 | 8:30 | 9:10 |
| 2001-09-28 | M2.4 | 9:34 | 10:14 | 10:50 |
| 2003-10-27 - 2003-11-02 | | | | |
| 2003-10-27 | M5 | 9:21 | 9:27 | 9:32 |
| 2003-10-27 | M6.7 | 12:27 | 12:43 | 12:52 |
| 2003-10-28 | X17 | 09:51 | 11:10 | 11:24 |
| 2006-12-04 - 2006-12-08 | | | | |
| 2006-12-05 | X9.0 | 10:18 | 10:35 | 10:45 |
| 2006-12-06 | M6.0 | 8:02 | 8:23 | 9:03 |

**Table 2**. List of selected flare events for this study.

| Start Date | Maximum | Proton Flux (pfu @ >10 MeV) | Associated flare |
|---|---|---|---|
| 2001-09-24 12:15 [UTC] | 2001-09-25 22:35 [UTC] | 12900 | 2001-09-24 10:38 [UTC] |
| 2003-10-28 12:15 [UTC] | 2003-10-29 06:25 [UTC] | 29500 | 2003-10-18 11:10 [UTC] |
| 2006-12-06 15:55 [UTC] | 2006-12-07 19:30 [UTC] | 1980 | 2006-12-05 10:35 [UTC] |

5    **Table 3.** List of the SPEs (and their proton fluxes) which followed the X-class solar flares.

| X-ray class and time of the solar flare [UTC] | | | | |
|---|---|---|---|---|
| Station name | Solar zenith angle [°] | Duration of fade-out [min] | fmin [MHz] | dfmin [MHz] |
| X17, 2003-10-28, 11:24 | | | | |
| Juliusruh | 67.77 | 15 | 8.5 | 6.7 |
| Chilton | 65.15 | 50 | 10.4 | 7.8 |
| Rome | 55.07 | 75 | 8.5 | 5.8 |
| San Vito | 54.06 | 30 | 7.4 | 4.8 |
| Grahamstown | 26.09 | 150 | 6.7 | 4.2 |
| Ascension Isl. | 22.9 | 135 | 10.1 | 7 |
| X9, 2006-12-05, 10:35:00 | | | | |
| Pruhonice | 72.5 | 30 | 4.2 | 2.1 |
| Rome | 64.64 | 60 | 4.6 | 2.0 |
| San Vito | 63.05 | 30 | 4.2 | 2.4 |
| Ascension Isl. | 36.14 | 60 | 6.6 | 4.1 |
| Grahamstown | 12.29 | 75 | 6.7 | 3.6 |
| Madimbo | 9.63 | 90 | 6.1 | 3.5 |
| X2, 2001-09-24, 10:38 | | | | |
| Juliusruh | 55.31 | 45 | 5.3 | 3.8 |
| Chilton | 54.62 | 30 | 6.2 | 3.9 |
| Rome | 42.76 | 180 | 7.0 | 2.9 |
| Grahamstown | 33.69 | 0 | 10.6 | 8.1 |
| Madimbo | 25.05 | 90 | 8.0 | 5.6 |
| M6.7, 2003-10-27, 12:43 | | | | |
| Juliusruh | 71.41 | 0 | 4.3 | 3.2 |
| Chilton | 65.34 | 0 | 4.9 | 2.8 |
| Rome | 60.11 | 0 | 7.6 | 4 |
| San Vito | 61.34 | 0 | 5.1 | 3.4 |
| Grahamstown | 42.8 | 0 | 4.9 | 1.9 |
| Ascension Isl. | 4.82 | 15 | 6.7 | 3.1 |

| X-ray class and time of the solar flare [UTC] | | | | |
|---|---|---|---|---|
| Station name | Solar zenith angle [°] | Duration of fade-out [min] | fmin [MHz] | dfmin [MHz] |
| M6.0, 2006-12-06, 08:23 | | | | |
| Pruhonice | 79 | 0 | 2.5 | 0.5 |
| Rome | 73.19 | 15 | 4.6 | 3.1 |
| San Vito | 69.98 | 0 | 3.6 | 1.9 |
| Ascension Isl. | 63.51 | 75 | 5.6 | 3.2 |
| Grahamstown | 23.49 | 75 | 6.4 | 3.6 |
| Madimbo | 18.16 | 90 | 6.9 | 4.1 |
| M5.0, 2003-10-27, 09:27 | | | | |
| Juliusruh | 69.56 | 0 | 4.3 | 3.1 |
| Chilton | 71.22 | 0 | 3.9 | 2.3 |
| Rome | 58.13 | 0 | 6.6 | 3.2 |
| San Vito | 55.41 | 0 | 5.1 | 3.3 |
| Grahamstown | 21.77 | 150 | 6.2 | 2.4 |
| Ascension Isl. | 47.96 | 0 | 7.5 | 4.8 |
| M3.3, 2001-09-28, 08:30 | | | | |
| Chilton | 68.97 | | 3.7 | 1.7 |
| Juliusruh | 64.28 | | 3.7 | 1.8 |
| Rome | 55.63 | | 7.5 | 2.7 |
| Grahamstown | 38.25 | | 5.4 | 3.0 |
| Madimbo | 27.86 | | 6.6 | 3.1 |
| M2.4, 2001-09-28, 10:14 | | | | |
| Chilton | 57.85 | | 3.2 | 0.9 |
| Juliusruh | 57.42 | | 3.9 | 2.1 |
| Rome | 45.27 | | 8.9 | 2.6 |
| Grahamstown | 31.25 | | 4.8 | 2.4 |
| Madimbo | 21.25 | | 6.5 | 2.9 |

**Table 3.** The ionosonde stations (first column) with their solar zenith angle (second column) at the time of the peak of the selected solar flares. The duration of the total radio fade-out at the station appear in the third column. The tabulated fmin (4th column) and dfmin (5th column) values were measured at the peak time of the flares or directly after the fade-out.

5

Intensity of X-ray rad. [Wm$^{-2}$], time of the measurement [UTC]

| Station name | Solar zenith angle [°] | Duration of fade-out [min] | fmin [MHz] | dfmin [MHz] |
|---|---|---|---|---|
| 7.89E-05, 2003-10-28, 13:30 | | | | |
| Juliusruh | 74.68 | 15 | 2.9 | 1.9 |
| Chilton | 67.64 | 50 | 5.5 | 3.7 |
| Rome | 64.41 | 75 | 6.3 | 1.9 |
| San Vito | 66.26 | 45 | 3.8 | 2.6 |
| Grahamstown | 50.09 | 150 | 6.7 | 3.6 |
| Ascension Isl. | 10.81 | 135 | 8.1 | 6.6 |
| 1.33E-05, 2006-12-05, 12:00 | | | | |
| Pruhonice | 73.87 | 30 | 2 | 0.1 |
| Rome | 65.7 | 60 | 4.4 | 1.7 |
| San Vito | 65.68 | 30 | 2.1 | 0.4 |
| Ascension Isl. | 18.53 | 60 | 6.6 | 4 |
| Grahamstown | 27.65 | 75 | 6.7 | 4 |
| Madimbo | 30.66 | 90 | 6.1 | 3.5 |
| 6.06E-05, 2001-09-24, 11:30 | | | | |
| Juliusruh | 55.57 | 45 | 4.4 | 3 |
| Chilton | 52.34 | 30 | 5.9 | 3.4 |
| Rome | 42.94 | 180 | Nan | Nan |
| Grahamstown | 38.2 | 0 | 5.9 | 3.5 |
| Madimbo | 32.88 | 90 | 7.95 | 5.6 |
| 1.59E-05, 2003-10-27, 13:00 | | | | |
| Juliusruh | 72.68 | 0 | 4.3 | 1.2 |
| Chilton | 66.18 | 0 | 4.9 | 1.8 |
| Rome | 61.83 | 0 | 7.6 | 0.9 |
| San Vito | 63.38 | 0 | 5.1 | 2.1 |
| Grahamstown | 46.19 | 0 | 4.9 | 1.9 |
| Ascension Isl. | 6.64 | 15 | 6.7 | 3.1 |

Intensity of X-ray rad. [Wm$^{-2}$], time of the measurement [UTC]

| Station name | Solar zenith angle [°] | Duration of fade-out [min] | fmin [MHz] | dfmin [MHz] |
|---|---|---|---|---|
| 8.22E-06, 2006-12-06, 10:00 | | | | |
| Pruhonice | 73.39 | 0 | 2.1 | 0 |
| Rome | 65.89 | 15 | 2.4 | 0 |
| San Vito | 63.76 | 0 | 2.1 | 0.4 |
| Ascension Isl. | 42.95 | 75 | 5.6 | 3.2 |
| Grahamstown | 10.86 | 75 | 4.8 | 2.1 |
| Madimbo | 2.9 | 90 | 6.9 | 4.1 |
| 3.39E-05, 2003-10-27, 09:30 | | | | |
| Juliusruh | 69.56 | 0 | 4.3 | 2.9 |
| Chilton | 71.22 | 0 | 3.9 | 1.8 |
| Rome | 58.13 | 0 | 6.6 | 3.2 |
| San Vito | 55.41 | 0 | 5.1 | 3.3 |
| Ascension Isl. | 47.96 | 0 | 7.5 | 4.8 |
| Grahamstown | 21.77 | 150 | Nan | Nan |
| 3.26E-05, 2001-09-28, 08:30 | | | | |
| Chilton | 68.97 | 0 | 3.7 | 1.7 |
| Juliusruh | 64.28 | 0 | 3.7 | 1.8 |
| Rome | 55.63 | 0 | 7.5 | 2.7 |
| Grahamstown | 38.25 | 0 | 5.4 | 3.0 |
| Madimbo | 27.86 | 0 | 6.6 | 3.1 |
| 2.53E-05, 2001-09-28, 10:15 | | | | |
| Chilton | 57.85 | 0 | 3.2 | 0.9 |
| Juliusruh | 57.42 | 0 | 3.9 | 2.1 |
| Rome | 45.27 | 0 | 8.9 | 2.6 |
| Grahamstown | 31.25 | 0 | 4.8 | 2.4 |
| Madimbo | 21.25 | 0 | 6.5 | 2.9 |

**Table 4.** The value of the X-ray radiation in Wm$^{-2}$ and the date and exact time when the measurement occurred are shown in the header in every case. The ionosonde stations (first column) with their solar zenith angle (second column) at the time of the measurement after the peak of the flares. The duration of the total radio fade-out at the station appear in the third column. Also included are the measured fmin (4th column) and dfmin (5th column) values at the time of the measurement after the peak of the flares.
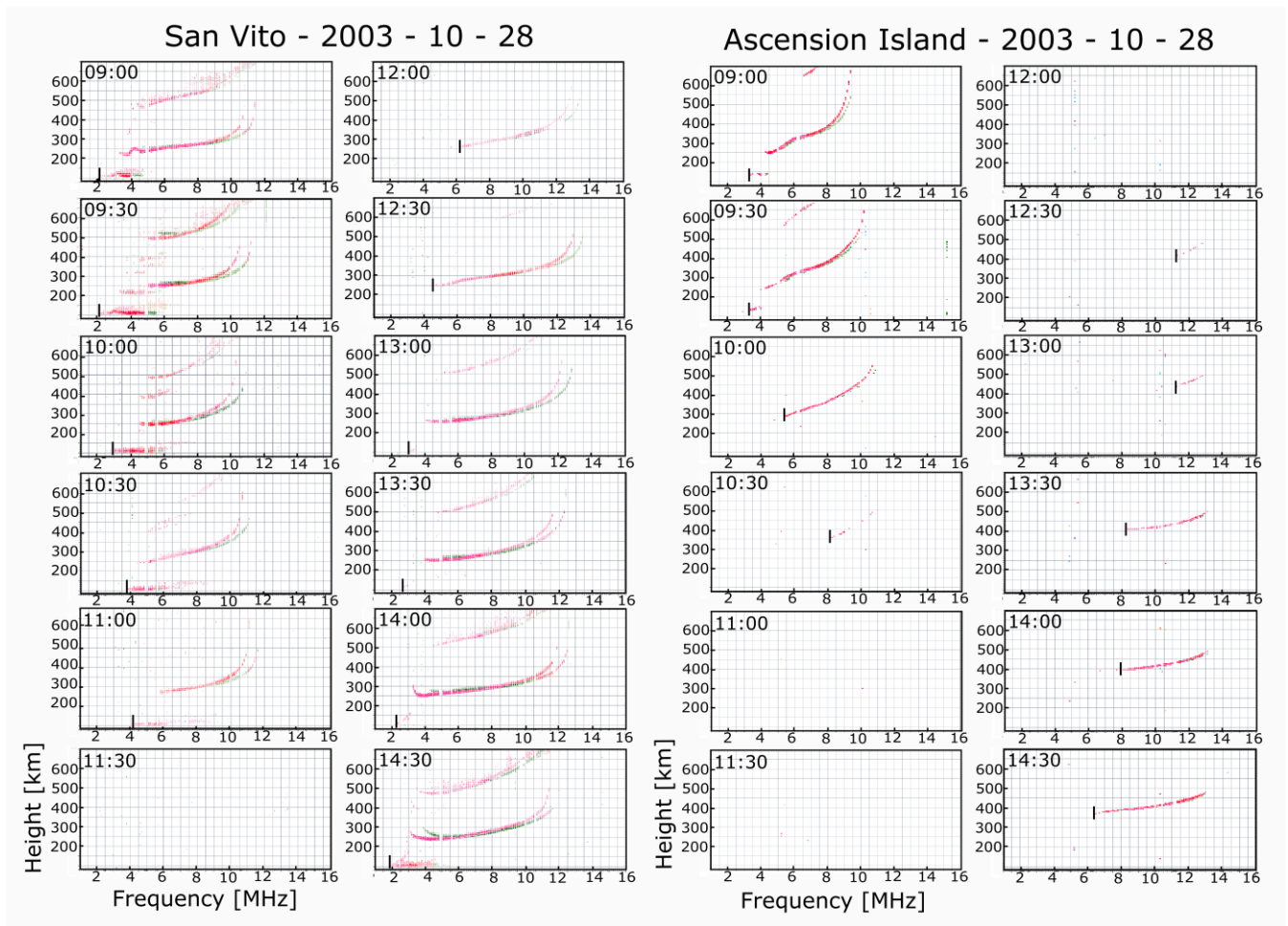
19

**Figure 1.** Sequence of ionograms at 30 min intervals recorded at San Vito (40.6, 17.8) and at Ascension Island (-7.95, 345.6) from 09:00 UTC to 14:30 UTC on 28 October 2003. This period covers the start, the peak, and decay (incomplete) of the flare X-ray flux variation. The total and partial fadeout of the sounding HF waves can be seen in the ionograms. The black vertical lines show the fmin parameter on the ionograms.
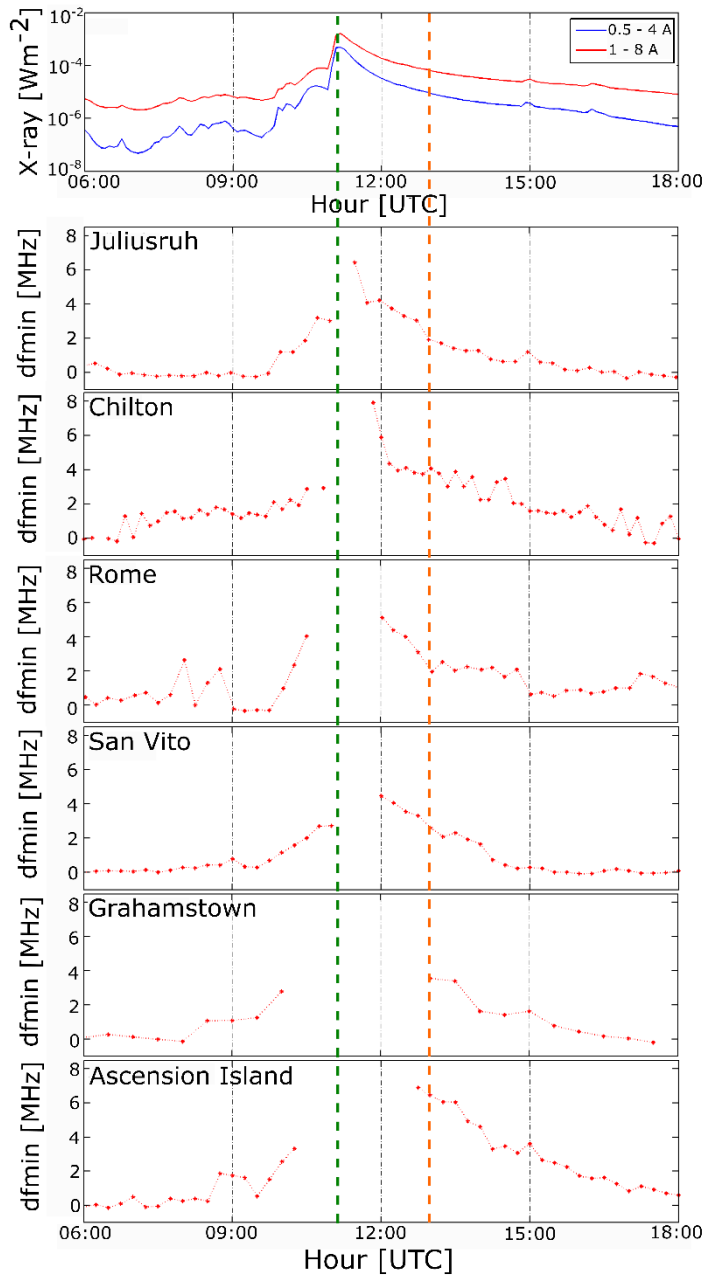
**Figure 2.** The variation of the X-ray flux (upper panel), the changes of the dfmin (red dots and red dashed line) parameter detected at different ionosonde stations with different zenith angle (from larger to smaller) on 28 October 2003 between 06:00 and 18:00 UTC. The vertical green dashed line shows the peak time of the X17 flare while the vertical orange dashed line shows the time used for the second comparison (13:30 UTC, in Sec. 3.3).

21
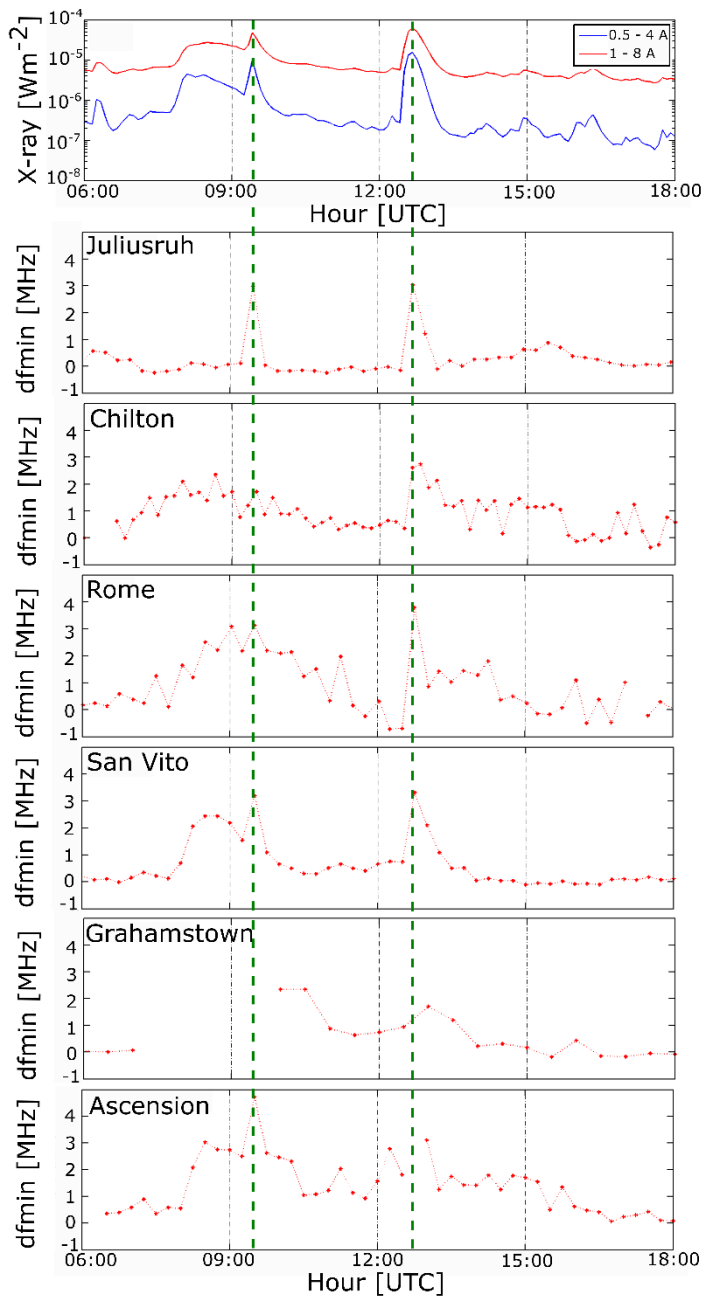
**Figure 3.** The variation of the X-ray (upper panel) and the changes of the dfmin (red dots and red dashed line) parameter detected at different ionospheric stations with different zenith angle (from larger to smaller) on 27, October 2003 between 06:00 and 18:00 UTC. The vertical green dashed lines show the time of the M5 (peak at 9:27 UTC) and M6.7 (peak at 12:43 UTC) flares.

22
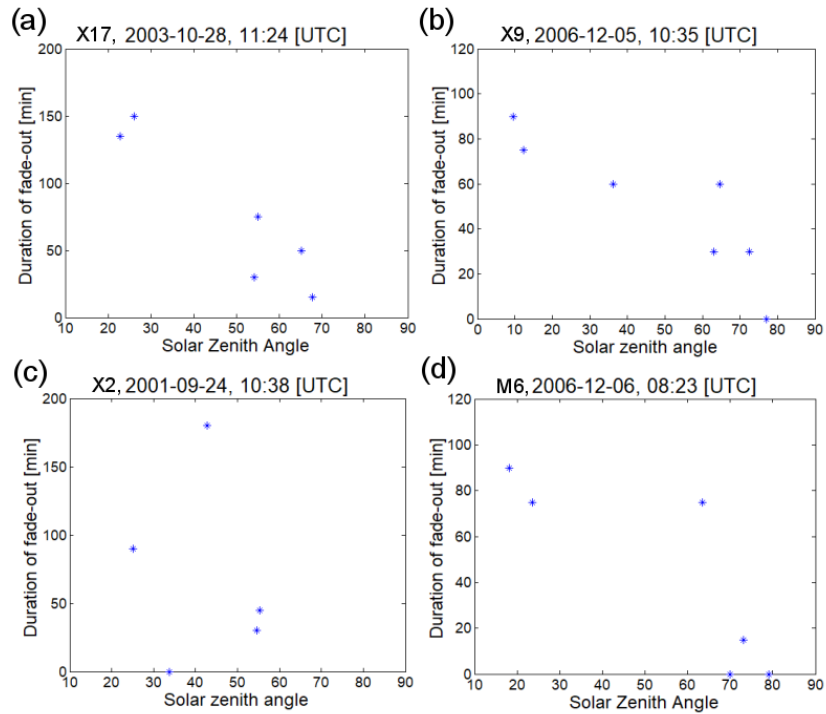
5 **Figure 4.** The solar zenith angle of the ionosonde stations at the time of the peak versus the measured duration of the total radio fade-out in the case of flare events which occurred on 28 October 2003 (a), on 5 December 2006 (b), on 24 September 2001 (c), and on 6 December 2006 (d).
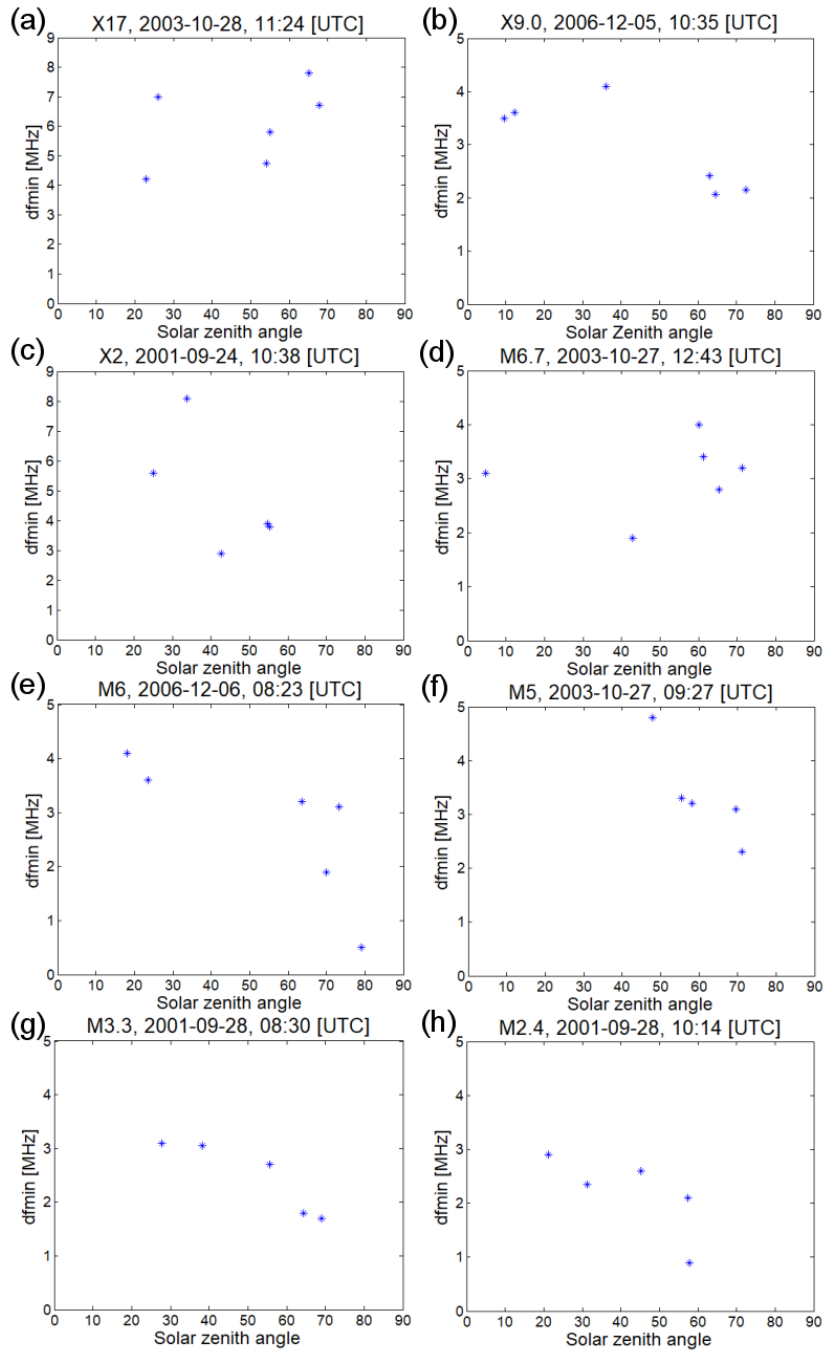
10
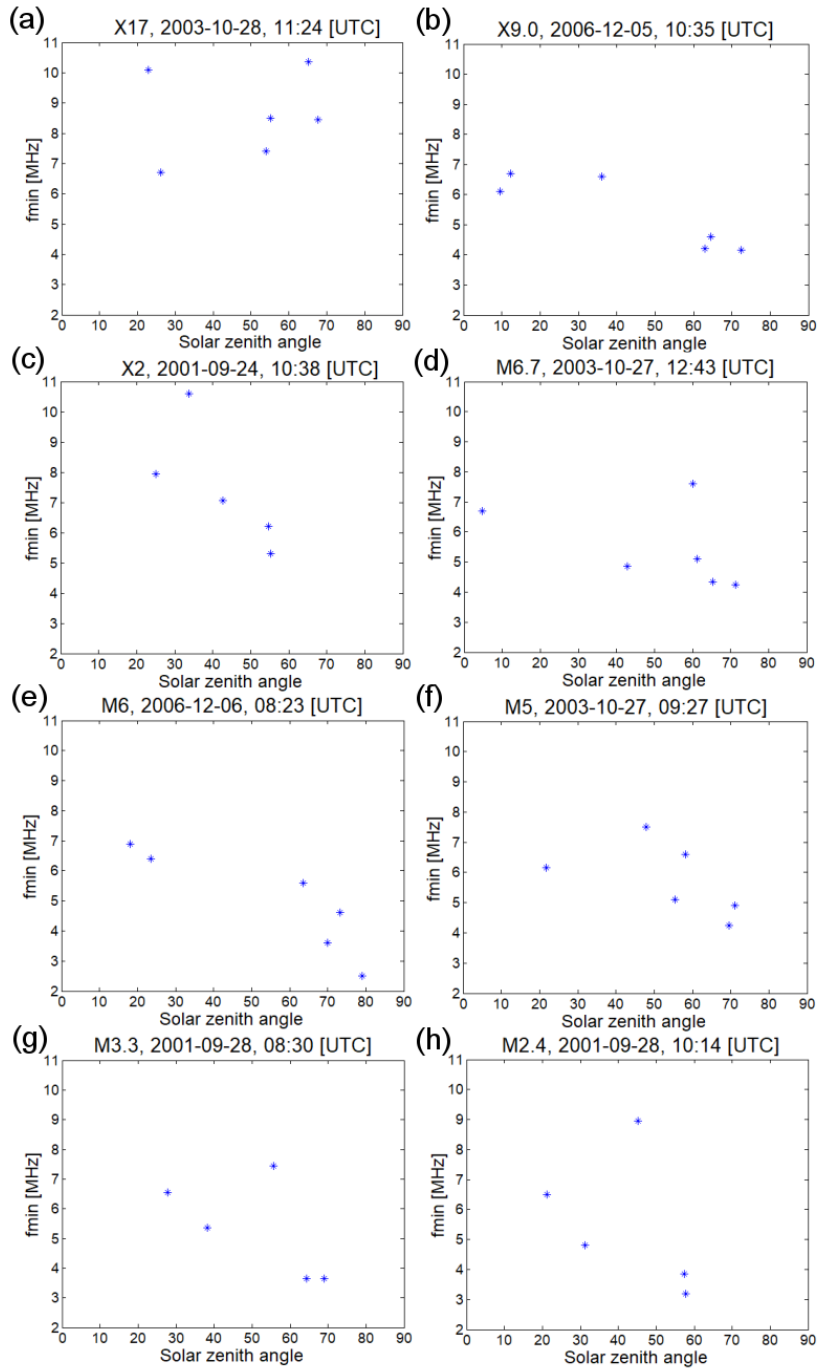
**Figure 5.** The solar zenith angle of the ionosonde stations at the time of the peak versus the fmin value at the peak of the flare events or after the fade-out. The X-ray class and peak time of the solar flares are seen in the title of the different panels. The results related to different flares from high to lower intensities are shown from a to h panels, respectively.
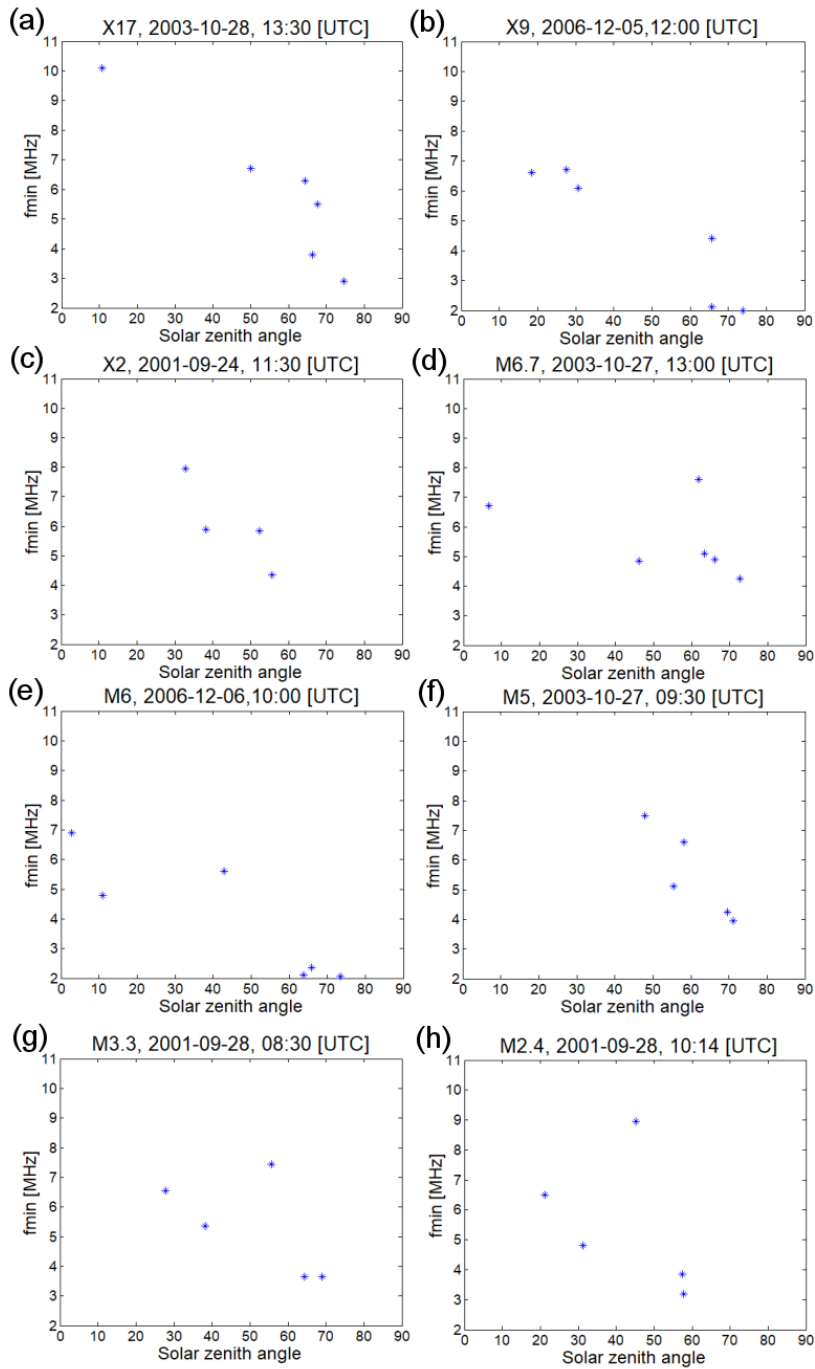
**Figure 6.** The solar zenith angle of the ionosonde stations at the time of the peak versus the dfmin value at the peak of the flare events or after the fade-out. The X-ray class and peak time of the solar flares are seen in the title of the different panels. The results related to different flares from high to lower intensities are shown from a to h panels, respectively.
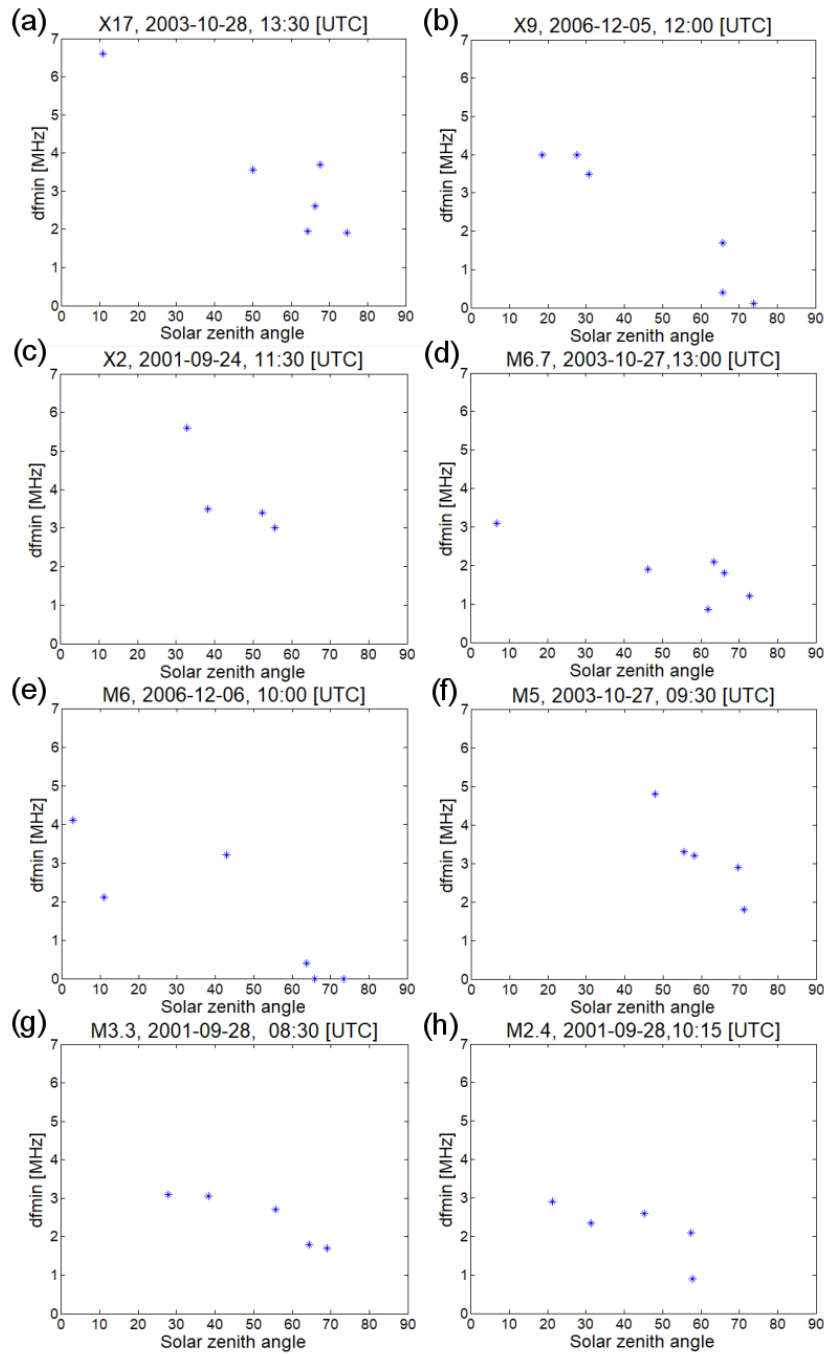
**Figure 7.** The solar zenith angle of the ionosonde stations at a certain time after the peak of the flares versus the fmin value at that time. The X-ray class of the flares and the time when the measurement occurred are shown in the title of the different panels. The results related to different flares from high to lower intensities are shown from a to h panels, respectively.
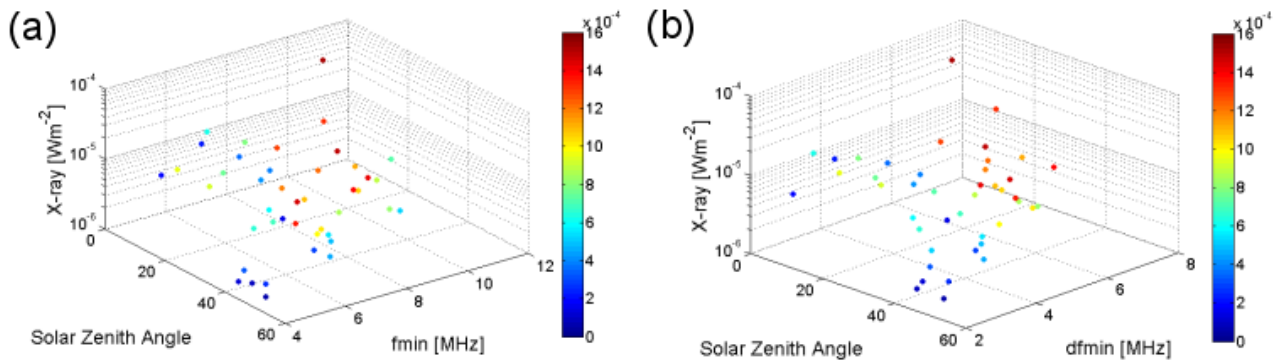
26

**Figure 8.** The solar zenith angle of the ionosonde stations at a certain time after the peak of the flares versus the dfmin value at that time. The X-ray class of the flares and the time when the measurement occurred are shown in the title of the different panels. The results related to different flares from high to lower intensities are shown from a to h panels, respectively.

5
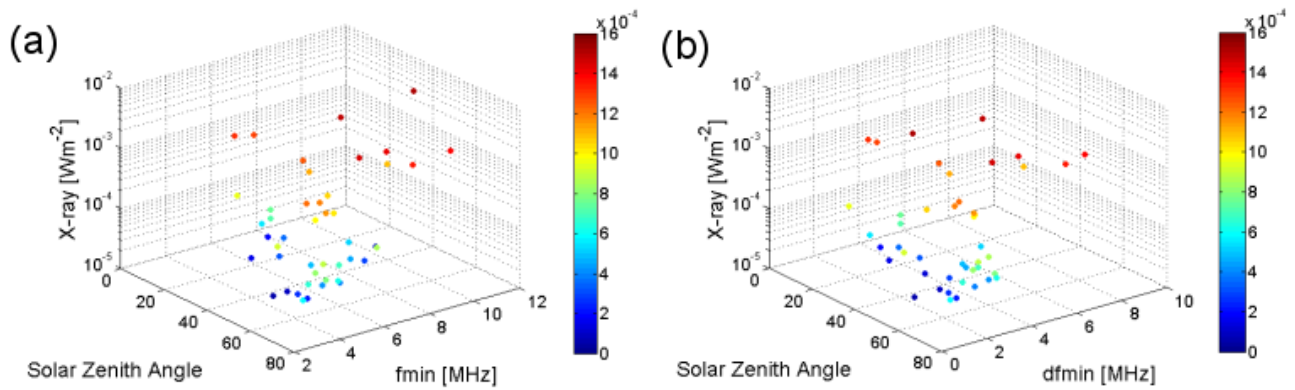


10

**Figure 9.** The solar zenith angle of the ionosonde stations at the time of the peak, the X-ray radiation at the peak and the value of the fmin (a) and dfmin (b) parameters at the peak of the flare events or after the fade-out. In order to represent the X-ray radiation dependence a colorbar has been connected to the different measurements during the flares with different intensities. The colorbar shows the X-ray radiation in Wm$^{-2}$.

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**Figure 10.** The solar zenith angle of the ionosonde stations at the measurement time, the X-ray radiation at the measurement time and the value of the fmin (a) and dfmin (b) parameters measured at a certain time after the peak of the flares (see text). In order to represent the X-ray radiation dependence a colorbar has been assigned to the different measurements as in Figure 11 in the previous case. The colorbar shows the X-ray radiation in $Wm^{-2}$.

15