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Interactive comment on "Investigation of the ionospheric absorption response to flare events during the solar cycle 23 as seen by European and South African ionosondes" *by* Veronika Barta et al.

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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, χ (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.

Please also note the supplement to this comment:
https://www.ann-geophys-discuss.net/angeo-2019-14/angeo-2019-14-AC1-supplement.pdf

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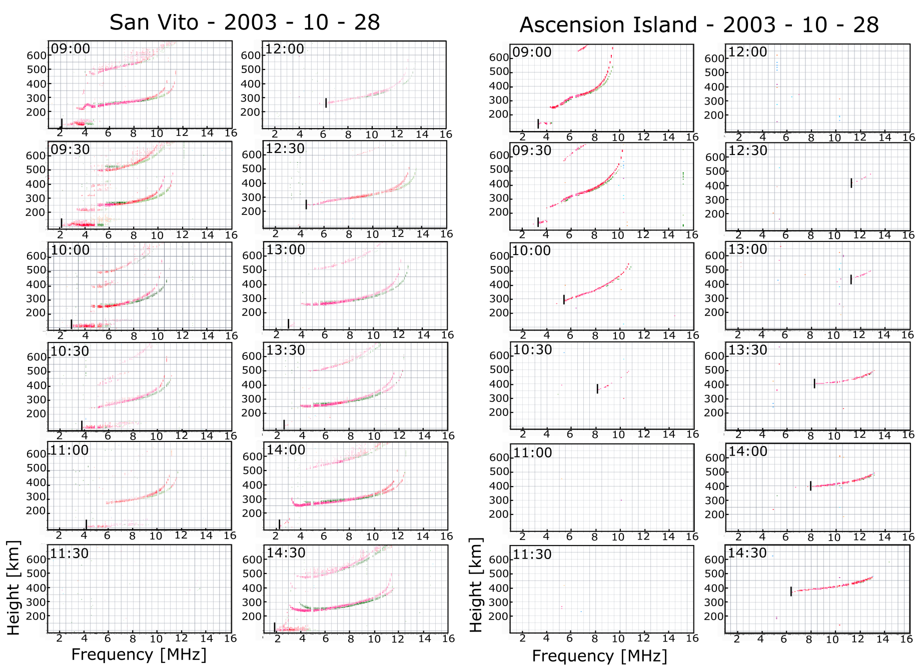

Fig. 1.