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Annales Geophysicae Discussions

# *Interactive comment on* "Spatial and seasonal effects on the delayed ionospheric response to solar EUV changes" *by* Erik Schmölter et al.

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Thank you so much for the detailed comments and suggestions to our manuscript! We will revise the manuscript according to your advice.

1. Title and abstract

(Line 1) "...EUV radiation to analyse the delayed ionospheric response to test and improve previous studies on the ionospheric delay. Several..."

(Line 4) " ..the analysis at an hourly resolution..."

(Line 13) "...Results confirm that geomagnetic activity and the 11-year solar cycle also affect the ionospheric response to solar EUV changes"



Alternatively, lines 6–14 could be re-written to more accurately summarise the conclusions.

Answer: We will change the abstract as suggested.

2. Major Issues and Questions

1 The motivation provided through GNNS in the introduction (around Line 25) is not appropriate. If the authors wish to continue with this motivation, the following issues need to be addressed:

(a) Not all terms are defined (e.g., a different definition of "high temporal resolution" is used on line 27 when compared to the rest of the paper).

(b) Citations to GNSS work are absent. The motivation would be strengthened by citations of articles that have proved high accuracy GNSS products require accurate ionospheric models, as well as citations to articles that highlight missing physics in ionospheric models when handling the ionospheric delay. Given studies such as Ren et al. (2018), which show that ionosphericmodels do capture the ionospheric delay to solar EUV irradiance, I would recommend that the authors find a different motivation for their study.

(c) Finally, this motivation also requires citations that demonstrate that other higher order GNSS correction issues (such as the bending terms) are not as important as the parts of the refractive index terms that would be affected by the (to have been) demonstrated issues with ionospheric models that are affected by the ionospheric delay.

Answer: We will change the motivation for our study:

"The delayed ionospheric response to solar EUV radiation is captured in various ionospheric models (Ren et al., 2018; Vaishnav et al., 2018) and respective simulations can confirm results of previous studies estimating the ionospheric delay with observational data on daily resolution. The calculation of the delay with observational data in high temporal resolution ($\leq$1 hour) is of interest to describe features like seasonal and spa-

tial variations in more detail. The dependence on solar and geomagnetic activity (Ren et al., 2018) can be explored further. In the future, results for the ionospheric delay on high temporal resolution will strengthen the understanding of ionospheric processes and help to validate physics-based models."

2 The authors highlight the differences between the regions covered by the two ionospheric parameters used in this study. While it is true that GNSS TEC includes information about the entire ionosphere-plasmasphere system through which it travels, it is also true that the F2 region is responsible for most of variations in TEC (e.g., Petrie et al. 2011). Text and data interpretations would benefit from clarifying the relative contributions from the different ionospheric regions and plasmasphere to the TEC, as well as the expected agreement between the column integrated plasma density and the critical frequency of the F2 layer based on past studies.

Answer: We will add an explanation about the ionospheric and plasmaspheric contribution to TEC and clarify the dominant role of the F2 layer:

"The variations of TEC are mostly controlled by the F2 layer (Lunt et al., 1999; Petrie et al., 2010; Klimenko et al., 2015) and for mid-latitudes the total plasmaspheric contribution to TEC is between approximately 8 to 15 % during daytime and approximately 30 % during nighttime (Yizengaw et al., 2008)."

We will add a clarification for the high correlation between TEC and foF2, but also mention the difference of both parameters, which could result in different ionospheric delays.

"Both ionospheric parameters are highly correlated (Kouris et al., 2004), but variations like different peak time of the diurnal variation (Liu et al., 2014) could have a considerable impact on the delayed ionospheric response."

3 In the introduction, the authors do not sufficiently discuss the contributions of previous ionospheric delay studies. Specifically, there is no discussion as to the physical reason



behind the ionospheric delay, although this has previously been investigated (e.g., Ren et al. 2018).

We will add a summary of the recent investigations by Ren et al. 2018 to give an overview to the processes behind the delay:

"The recent results by Ren et al. 2018 from observational and model calculations specified different features of the ionospheric delay. A strong impact of the geomagnetic activity on the ionospheric delay to solar EUV changes was found. Simulations with the Thermosphere Ionosphere Electrodynamics General Circulation Model (TIEGCM) and calculations were used to discuss the influence of ion production and loss as well as the impact of the O/N2 ratio. The ion production responds immediately to EUV variations and depends on both, the solar EUV flux contribution and the O/N2 ratio. The loss is delayed and controlled by the O/N2 ratio, which in turn is also dominated by the solar EUV flux contribution. The ionospheric response could further be modulated by dynamic and electrodynamic processes in the ionosphere. Ren et al. 2018 also showed a latitudinal dependence of the delay."

4 A motivation behind using the European and Australian regions is needed. For example, why not use North and South America (see coverage for 1 January 2011 in the attached Figure)? This figure is included not to say that there is not a good reason to use European and Australian data, but to show that "good data coverage for Europe" is not a good reason in and of itself.

Answer: We will add a reference to back our statement about data quantity/quality of TEC and ionosonde data for the European region:

"The dense coverage of GPS stations over Europe allows a good comparison with TEC data for these locations (Belehaki et al., 2015)."

We will clarify that not only the European region has good data coverage:

"The availability of TEC in maps with good data coverage for certain regions (e.g. Euro-

pean or North American region) allows a spatial analysis of the delay and a comparison with the foF2 data for specific locations."

We will add magnetic declination and inclination in Table 2 and explain further, why a comparison between both regions seems appropriate:

"The conditions of Earth's magnetic field for the European and Australian stations are comparable with small magnetic declination and similar absolute value of magnetic inclination (see Table 2). The selected stations seem appropriate for a comparison between northern and southern hemisphere due to these similar conditions."

5 The authors state that they use two important ionospheric parameters that are appropriate to investigate the processes responsible for the ionospheric delay (data section), but they state in the conclusions that the processes for the delayed ionospheric response still need to be described. If the first statement is true, then an investigation of the underlying physical processes should be included in this paper. If such a study is beyond the scope of this paper, than the statements made about the ionospheric parameters used to study the characteristics of the ionospheric delay should be altered.

Answer: We will change the statement to clarify the actual use of the parameters in the study:

"In the analysis, we correlate EUV with two important ionospheric parameters, appropriate to investigate features of the ionospheric delay."

6 The authors state that the TEC is more important than the foF2 but do not back up this valuation, especially since they say in the introduction that the ionospheric delay for the two parameters is very similar. The reason given, "TEC is...less sensitive to disturbances, such as plasma redistribution, than other parameters" is not substantiated. Additionally, since TEC is regularly used to study plasma redistribution (e.g., Foster 2008; doi:10.1029/181GM12) , the degree of sensitivity difference between TEC and foF2 needs to be shown to be significant (either by the authors or through appropriate



referencing) for this valuation to be believable.

Answer: We will change the statement to clarify, why TEC is used:

"The first parameter is TEC, which is an integral measurement of the electron density and well suited for the analysis of the ionospheric response to solar EUV variations. The parameter was used in several preceding studies to calculate the ionospheric delay (see Table 1)."

7 (Line 64) The resampling method needs to be described in more detail. Was an interpolation used? If so, between which points? Was the nearest value taken?

Answer: We will clarify the process: the data were extracted from IGS TEC maps without any interpolation (spatial or temporal).

"In preparation for the delay calculation, TEC values at seven ionosonde locations and one region (Europe) were extracted from the IGS TEC maps. For each ionosonde location the nearest grid point in the maps was used."

8 (Line 67) What is the temporal resolution of the ionosonde data and were they hand scaled or autoscaled?

Answer: We will clarify the temporal resolution and scaling of the ionosonde data:

"The other ionospheric parameter included in the analysis, foF2, is derived from ionosonde station data (NOAA, 2019) provided by the National Oceanic and Atmospheric Administration (NOAA), and are available for the same time periods with temporal resolution of 15 minutes (Wright and Paul, 1981)."

"In the northern hemisphere, the European stations Tromsø, Pruhonice, Rome, and Athens were selected (auto scaled), [. . .]"

"Instead we use data from the Australian stations Darwin, Camden, and Canberra for the analysis in the southern hemisphere (auto scaled)."

9 What is the effect of the difference in geographic longitude and magnetic location (including location relative to the auroral oval, declination, and inclination) on the locations in Europe and Australia?

Answer: We will add the declination and inclination of each location to Table 1 showing again the similar conditions for the comparison between northern and southern hemisphere. The specific conditions for Tromso (the only auroral station) are already explained in the manuscript.

10 (Line 76) How are data resampled in this instance? From the context, it appears that the authors are downsampling data from a minute-scale resolution to a one hour resolution, but this is unclear (especially since the same wording was used for a different process on line 64).

Answer: The wording for the method in line 64 was adjusted (see comment 7). We will change the description to clarify the use of the mean value to calculate the resampled data sets:

"In preparation of the analysis, all data are resampled to an hourly resolution using the mean value [. . .]"

11 (Line 90) A better explanation of why the correlation coefficient is still useful even though the values specify that the data sets being compared are uncorrelated is needed.

Answer: We will add an explanation, why the analysis of times with high and low correlation coefficients between solar EUV and ionospheric parameters is useful/important:

"The varying correlation between solar EUV flux or solar proxies like F10.7 with TEC is known from preceding studies. Solar EUV radiation is not able to describe the ionospheric variability at all time periods and on all time scales sufficient resulting in low correlation coefficients (Unglaub et al., 2012) and indicating a stronger impact of other processes (Verkhoglyadova et al., 2013). Analyzing both, times of high and low corre-



lation between solar EUV flux and ionospheric parameters, is important to understand the changes of processes and interactions in the ionosphere on the whole."

12 What data quality constraints were applied to the input and processed data? Why were periods when the data quality is stated to be poor included?

Answer: We didn't accept data into our analysis with data gaps for longer time periods (e.g. gaps of several days) or with periods with lots of smaller data gaps. The correlation coefficients were then calculated for the whole available time period to get an impression, how periods of poor data quality impact the results. In Figure 7 and 8 these periods are removed due to the uncertainty for the delay calculation.

13 The authors state that the ionospheric delays show a good correlation with the geomagnetic activity, but this is not demonstrated. If the authors believe that they have demonstrated this correlation, they should improve the clarity of the figure presentation and the text surrounding it.

Answer: We will add a Figure comparing the gradient of the delay with the Kp-index and explain the modulation of the geomagnetic activity on the delay. The correlation coefficients in each year are 0.53 in 2011, 0.70 in 2012 and 0.77 in 2013 (see supplements).

14 (Line 184) The authors are quick to attribute differences between the TEC and foF2 ionospheric delays to differences between the F2 peak and the ionosphere-plasmasphere system, but there are other possibilities (including the background model used in the TEC calculation) that should be acknowledged or eliminated.

Answer: We will clarify the concerns about other impacts causing the difference in TEC and foF2 results:

"These results could indicate a strong seasonal variation of the ionospheric delay in the F2 layer compared to the whole ionosphere-plasmasphere system, but there are other possible sources for the difference (e.g. the background model of the IGS TEC

maps)."

15 There appears to be an offset between solstice and equinox occurrence and the seasonal variations shown in (Figure 10). Why is this? Has it been seen before?

Answer: We will mark solstice and equinoxes in the Figure. An offset for the difference in the delays doesn't appear consistently. In addition, such a detailed analysis of features in the seasonal variations requires model calculations to eliminate uncertainties due to the specific locations. This question could be addressed in future studies though.

16 Figures 7 and 8 show a lot of scatter at the individual stations. The analysis presented in section 5 makes claims about latitude variations based on these figures that do not appear to be significant, due to this scatter. This analysis would be improved by including another figure with delay differences between the sites or, possibly, by adding confidence bars (perhaps standard deviations) to the hourly delays in Figures 7 and 8.

Answer: We will add a figure similar to the comparison between Rome and Canberra for Rome and Tromso (see supplement) to show the difference between the two stations and discuss the trend of the difference with latitude in more detail (especially in regards of the different variation with latitude in winter mentioned in comment 17):

"Figure 12 shows the difference between the stations Rome and Tromso for both ionospheric parameters. The results for TEC show a greater or similar ionospheric delay for the station Rome compared to the station Tromso. There are only a few short time periods during winter with a greater ionospheric delay for the station Tromso. A stronger seasonal variation appears for the parameter foF2, but overall the ionospheric delay is still greater for the station Rome. The mean difference for results in Figure 12 is 1.08 hours for TEC and 0.52 hours for foF2. The changes with latitudinal dependence of the trends during winter are due to the stronger increase of the ionospheric delay for Rome during summer."



17 (Line 191) The authors state that the latitudinal dependence in the European sector is not visible in the winter. However, Figure 7b shows a latitudinal variation that is perhaps clearer than that in the summer, just different.

Answer: We will clarify, that there is a difference in winter (see comment 16).

18 How is the resampling for Figure 12 performed? Is a running period or binned week used? Clarify this analysis process so that others may reliably replicate these results.

Answer: We will clarify that the weekly value is calculated with the mean:

"The results are summarized with epoch plots in Figure 12 having a resolution of one week (mean value) to allow a better presentation of the long-term changes of the ionospheric delay."

19 (Line 211) What about the winter variations? Does the longitudinal ionospheric delay variation have a seasonal variation at all? It seems likely that this lack of variation is related to the small range of magnetic declination over Europe, which leads to longitudinally similar ionospheric transport processes regardless of season. Whatever the authors believe the reason to be, it should be discussed.

Answer: We will discuss the possible explanation of the lack of longitudinal variations with the similar declination for the whole European region:

"The small and similar magnetic declination for the European region could be related to the small variations of the ionospheric delay with longitude. There is an influence of the magnetic declination on the mid-latitude ionosphere, which leads to similar longitudinal transport processes in all seasons (Zhan et al., 2012, 2013). This behavior has to be explored with observational data for different regions or modeling efforts in the future."

20 The last sentence of the conclusions omits the work done by Ren et al. (2018). The article would be improved by a discussion of the results in the context of the physical mechanism presented in that article and also by providing a clearer motivation behind using the ionospheric delay to validate or improve physics-based models.

Answer: We will change our motivation and add an explanation of the work by Ren et al. (2018) in our introduction (see comment 1 and 3).

3. Figures and tables

1 (Table 1 caption): "...provide an approximate ionospheric delay to solar activity at a daily resolution.

Answer: We will change the description according to the suggestion.

2 (Figure 1): This figure would benefit by over-plotting magnetic field information (such as the IGRF declination or at the hmF2) and the geomagnetic equator.

Answer: We will plot the magnetic field information in the figure with data from the World Magnetic Model provided by NASA.

3 (Table 2): Which magnetic coordinate system is used for the geomagnetic coordinates?

Answer: We will add magnetic declination and inclination to the Table. All magnetic parameters will be calculated with the IGRF.

4 (Figure 2): Rows should be labeled with "Weekly", "Daily", and "Hourly"

Answer: We will add the labels to the figure.

5 (Figure 2 caption): "...data, as well as the resulting correlation coefficients (red), for..."

Answer: We will change the caption.

6 (Figure 10): Mark the locations of the equinoxes and solstices.

Answer: We will mark equinoxes and solstices and add a discussion (see major comment 15).

7 (Figure 11): Mark the locations of the European stations, to improve comparisons between Figure 11 and Figure 7.



Answer: We will add marks for the locations of the European stations.

4. Grammar and organisation

1 Throughout the paper both 3rd person and impersonal tenses are used. This should be changed so that the tense throughout the article is consistent

Answer: We will remove the use of the 3rd person.

2 Throughout the paper approximations are used for numbers that do not need them (e.g., the locations on Line 95 specify the approximate location of Rome and this is already appropriately expressed by limiting the number of significant figures)

Answer: We will remove the use of approximations for numbers that don't need them.

3 (Lines 27, ) "which" should either be preceded by a comma or replaced with "that" 4 (Line 17) "dominating" should be "dominant 5 (Line 20) "...ionospheric variations that may depend on time or location." 6 (Line 21) "...in the solar spectrum'...'. This change is necessary because the authors, in this sentence, are referring to the entire ionosphere, which means that X-rays and higher energy irradiance that impact the D and E regions are also important. 7 (Line 22) "...and composition at specific..." 8 (Line 23) "...electron density distribution. An understanding of the ionospheric chemical and physical processes is important, since..." 9 (Line 28) remove duplicated text "is needed" 10 (Line 32) "...have revealed that ionospheric parameters have a delayed response to solar variability. A selection of these studies..." 11 (Line 33) "...was calculated using different EUV proxies or measurements of the EUV flux at daily resolutions." 12 (Line 35) "...the delay at a higher temporal resolution of one hour. Furthermore, we examine the hemispheric dependence of the ionospheric delay with a detailed study of the European region." 13 (Line 37) "is made based on" should be "uses" 14 (Line 37) "The" needed before "Time series" 15 (Line 43) "...the ionosphere without complicating contributions from the plasmasphere and lower ionospheric layers. As expected, the results... 16 (Lines 45-47) This text belongs in the data or analysis section, not the introduction.

Answer: We will change the manuscript according to the suggestions.

17 (Data) This section would benefit by subsections for either the different data sources or between the presentation of the data sources and the data analysis techniques

Answer: We will add two subsections: “Solar EUV radiation” and “Ionospheric parameters”.

18 (Line 49) “...spectrum have been continuously measured since 2000 C.E., with EUV observational data publicly available from...” 19 (Line 55) “...have a temporal resolution of 20 seconds. EVE data also cover several years (2011 to 2014)... 20 (Line 106) Description of the IGS TEC maps belongs in the Data section. 21 (Line 108) remove comma between “show” and “that” 22 (Line 109) “...be calculated at an hourly resolution for fixed...” 23 (Line 123) The sentence, “Se do not see any...different variations” is confusing and should be rewritten. 24 (Line 124) “...keeping in mind that their magnitude may differ due to...” 25 (Line 128) “...in Table 1. For example, Jakowski et al. (1991) used the...” 26 (Line 129) “...satellite-based EUV-TEC measurements (Unglaub et al., 2011) and also calculated the delay with EUV fluxes. The validation with EVE EUV flux measurements was important because the solar rotation variations...” 27 (Line 135) The first two sentences of this paragraph belong in the introduction. The remaining sentences belongs in the data section.

Answer: We will change the manuscript according to the suggestions.

28 (Line 138) Which calculation are the authors referring to?

Answer: We will clarify that the calculation of the ionospheric delay is referred to.

29 (Line 144) “...negative values. In Figure 4, this was interpreted as a possible effect of geomagnetic activity.” 30 (Line 145) “...time period, the correlation coefficient drops due to data gaps and the applied interpolation method. (start new paragraph after this sentence)” 31 (Line 146) “...are smaller than those of the TEC. However, the trends of the two correlation coefficients are similar for the...” 32 (Line 148) “...Tromsø again



show that the largest deviation from...” 33 (Line 152) “The TEC and foF2 correlation coefficients for the Australian stations are shown in Figure 6. In general, the Australian correlation...” 34 (Line 155) “...these results. Most notably, the decrease and...”

Answer: We will change the manuscript according to the suggestions.

35 (Line 156) Which seasonal variations do the authors expect to be impactful? Referencing is appropriate but the text description should be slightly more detailed.

Answer: We will clarify which thermospheric conditions and season variations are meant:

“The difference might be due to further impacts on the correlation, e.g. thermospheric wind conditions or seasonal variations due to composition changes (atomic/molecular ratio), which are not covered in this study, [. . .]”

36 (Line 174) “...the delay at a daily resolution for longer time periods than the one used in this study.”

Answer: We will change the manuscript according to the suggestions.

37 (Line 175) The sentence is unclear and needs to be reworded. 38(Line 179) What do the authors mean by “global trend”? 39 (Line 179) The sentence is unclear and needs to be reworded.

Answer: We will clarify the sentences:

“The difference between the ionospheric delay for the European and Australian stations in Figures 7 and 8 show only small differences due to the assumed trend with the geomagnetic activity. This trend has to be removed in the further analysis. [. . .]The non-seasonal trends are removed by calculating the difference between the ionospheric delays of both stations.”

40 (Line 183) “...a stronger seasonal variation...” 41 (Line188) “...with latitude in northern summer. The station at...” 42 (Line 193) remove “where data from high latitudes are

missing" because the Australian stations have a larger low-latitude extent than the European stations and this phrase does not reflect that. 43 (Line 194) recommend replacing "agree" with "are consistent" 44 (Line 197) "...good observational coverage..." 45 (Line 198) Remove repeated description of the IGS TEC map 46 (Line 202) "...Figure 11, which maps the mean delay values for the mid-latitudes in summer (May-August) and winter (November-February). Figure 11 shows delays that are consistent with the results from the European ionosonde stations (Figure 7b). 47 (Line 205) "...hours over the entire region."

Answer: We will change the manuscript according to the suggestions.

48 (Line 205) The sentence that begins at the end of this line is unclear and needs to be reworded.

Answer: We will clarify the sentence and add a reference to preceding studies to back up our discussion:

"The decrease of the ionospheric delay at latitudes greater than 65°N and smaller 35°N confirms a latitudinal trend, which was found in preceding studies (Lee et al., 2012)."

49 (Line 207) "...the delay decreases with increasing latitude. From..." 50 (Line 208) "...70âŮęN, or about -0.06 hours per degree in latitude." 51 (Line 211) "...is much smaller than the variation in latitude for the same season, with a change of..." 52 (Line 224) "...main analysis, we confirmed..." 53 (Line 234) Move the last two bullet points starting on this line to the previous paragraph where the authors were discussing the portions of previous studies that this study validated. 54 (Line 242) "Future analysis would benefit from high resolution ionospheric delay calculations for longer time periods that cover different..."

Answer: We will change the manuscript according to the suggestions.

55 (Line 243) Sentence starting at the end of this line is unclear and needs to be reworded



Answer: We will clarify the suggestion of including the thermospheric conditions in future analysis:

"The thermospheric conditions (e.g. neutral winds or composition changes in the atomic/molecular ratio), which are known for their impact on the ionosphere (Rishbeth, 1998; Rishbeth et al., 2000) should be included in future analysis as well."

56 (Data availability and acknowledgements) Not all acronyms are defined 57 (Line 297) "F 2" should be "F2" 58 (Line 327) page numbers missing and filled using n/a–n/a

Answer: We will change the manuscript according to the suggestions.

5. Referencing

1 Reference needed for the impact of solar irradiance on the vertical ionospheric structure

Answer: We will add the reference: M. Kelley, The Earth's Ionosphere, vol. 96. Academic Press, 2009.

2 (Line 44) Citation to a source that explains or demonstrated that TEC is dominated by the F2 peak response is needed

Answer: We will add the reference (see major comment 2): Elizabeth J. Petrie and Manuel Hernandez-Pajares and Paolo Spalla and Philip Moore and Matt A. King, "A Review of Higher Order Ionospheric Refraction Effects on Dual Frequency GPS," Surveys in Geophysics, vol. 32, no. 3, pp. 197–253, Nov. 2010

3 (Line 63) Which model is included in the TEC calculation? Include a very short description and a citation to this model.

Answer: We will add the references and move the model description to this line:

Orus, "Improvement of global ionospheric VTEC maps by using kriging interpolation technique," Journal of Atmospheric and Solar-Terrestrial Physics, vol. 67, no. 16, pp.

1598–1609, Nov. 2005.

M. Hernandez-Pajares et al., “Comparing performances of seven different global VTEC ionospheric models in the IGS context,” in IGS Workshop 8-12 February 2016, 2016.

4 (Line 106) Citation for IGS TEC maps needed.

Answer: We will add the references for the IGS TEC maps.

5 (Line 196) Citation needed.

Answer: We will add the references:

C. Watson, P. T. Jayachandran, and J. W. MacDougall, “GPS TEC variations in the polar cap ionosphere: Solar wind and IMF dependence,” Journal of Geophysical Research: Space Physics, vol. 121, no. 9, pp. 9030–9050, Sep. 2016.

N. Maruyama, “Dynamic and energetic coupling in the equatorial ionosphere and thermosphere,” Journal of Geophysical Research, vol. 108, no. A11, 2003.

Please also note the supplement to this comment:
https://www.ann-geophys-discuss.net/angeo-2019-91/angeo-2019-91-AC2-supplement.zip

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Interactive comment on Ann. Geophys. Discuss., https://doi.org/10.5194/angeo-2019-91, 2019.



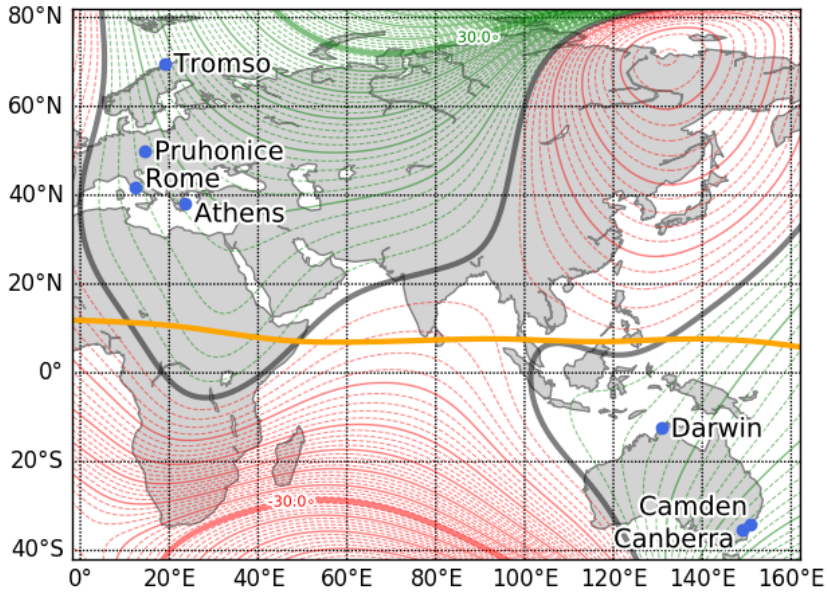


**Fig. 1.** Map of ionosonde stations with overlayed magnetic field configuration.

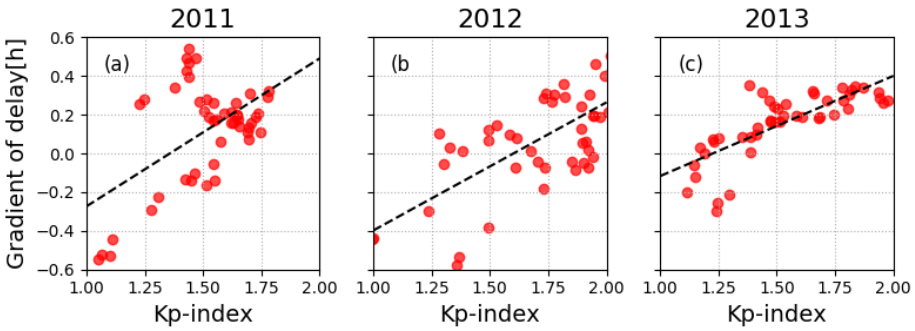


**Fig. 2.** Scatter plots for gradient of the ionospheric delay and Kp-index.



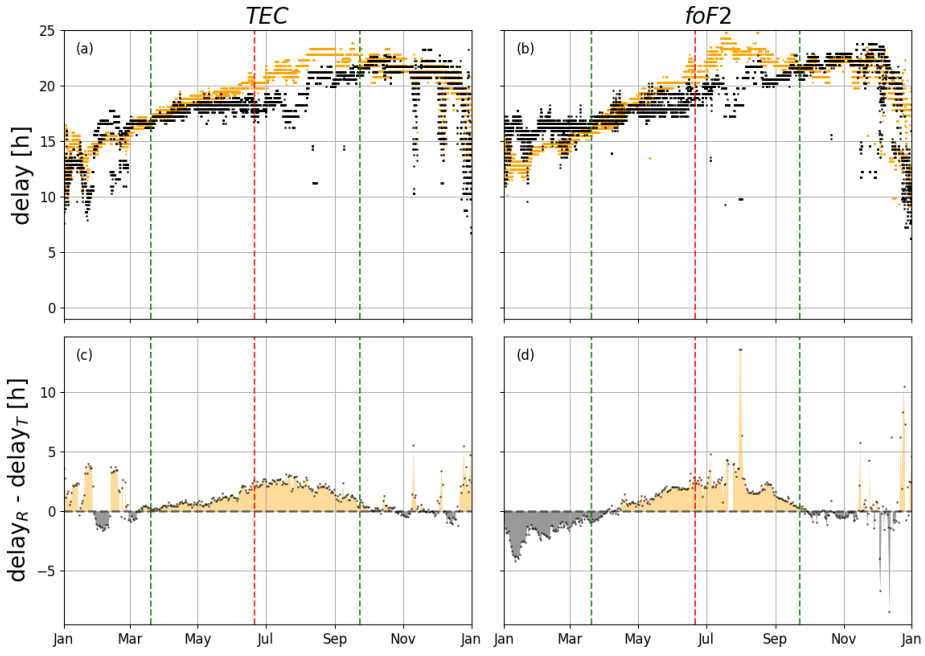


**Fig. 3.** Comparison of the ionospheric delay for Tromso and Rome.