Response to Reviewer Letter

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January 26, 2024

Manuscript Title: Subauroral Crosstalk in POES/Metop TED proton channels

We would like to thank the reviewers for their helpful comments and hope that these answers and the revised manuscript meets their approval.

1 Reviewer 1

The paper investigates the quality of the POES/Metop TED proton channels, in particular the cross-talk-produced background in proton channels at sub-auroral latitudes. The paper aims at establishing a Kp and channel dependent latitudinal cut of the cross-talk dominated area that should be excluded from analyses. The topic is important since the interest in the low-energy data is increasing due to the connection with atmospheric ionisation related to climate models.
The presentation is clear apart from some minor language issues, typos, and a small issue with Fig. 2 (see minor comments). The conclusions reached by the authors (highlighting cross-talk contaminated proton fluxes) are substantial. The title and the abstract are pertinent and understandable. Appropriate credit is given to earlier work, as far as I am aware.

Major comment:

The only substantive comment on the analysis I have is that the authors are clumping all longitudes into one although the effects of contamination seem to be very different in the various (APEX 110 km) longitude and between north and south. I wonder if the data could be used in a bit broader latitude range if the longitude would be pieced in sectors. Also the clear north-south asymmetry might be considered. The contaminating electrons drift eastward and their mirroring altitudes are different in the north and south hemispheres, which is clearly visible in Fig. 1: in the north, regions between 40° and 120° longitude, for example, are almost free of contamination. Thus, the latitude cutoffs found by the authors might be overly conservative in some spatial regions. This could be pointed out as a topic of further study.

Reply: *We want to address the main issue regarding longitudinal differences and the north-south asymmetry in the crosstalk contribution. Reviewer 1 argues that the latitudinal cutoffs might be conservative in some (longitude and hemisphere specific) regions where the crosstalk contribution is low.*

We completely agree with that. The crosstalk contribution varies with longitude and shows hemispheric differences. Fig. 1 (left panel) gives an estimation of that. A minimum crosstalk contribution can be seen at about 70° E in the northern hemisphere. If we consider this as uncontaminated flux, the latitudinal cutoff removes about 4 degrees with real data which rapidly decreases to background levels.

We updated Figure 3 and added another longitude, namely 160° E, where North and South have relatively low crosstalk contribution. The lower graph of the same color always represents the 160° E fluxes (or the according background count rates). Note that the color code also changed in order to increase the readability. The figure is a little crowded but we can see that all the TED proton channels show the same crosstalk maximum at L= 4, even at 160° E. The dashed lines that mark the contaminated area also hold for both longitudes and crosstalk seems to be the main source of the measured TED proton particle flux within this area at both longitudes as well.

Thus the presented approach of 'global' cutoff latitudes is conservative and leads to an underestimation of the

precipitating flux (area). But given that crosstalk seems to be the major subauroral contribution except for a very small longitudinal range (at about 60-80° E) in the northern hemisphere, a sectorial approach will probably not lead to significant improvement of the cutoff latitudes.
As topic for further studies the authors would suggest a recalculation of all affected channels taking into account the TED background counts which might preserve the equatorial boundary in a more natural form than this approach does.
This information has been added to the paper in form of an updated Figure 3 and an updated discussion and summary.

Minor issues:

line 26: "high relativistic" → "highly relativistic"
Reply: *Corrected.*
line 26: "Inspite of these data are" → "Despite of these data being"
Reply: *Adopted as suggested.*
line 50: "by dividing the energy range" → "by dividing by the width of the energy range"
Reply: *Adopted as suggested.*
line 51: "geometric correction factors" → "geometric factors" (?)
Reply: *Corrected.*
line 55: "high-energetic" → "high-energy"
Reply: *Corrected.*
line 56: "high-energetic" → "high-energy"
Reply: *Corrected.*
line 78: "Therefore is" → "Therefore it"
Reply: *Corrected.*
line 87: "prominantly" → "prominently"
Reply: *Corrected.*
line 92: "in mod. APEX" spell out the abbreviation!
Reply: *Thank you for addressing this. Actually it is not an abbreviation. We made some changes to the "coordinates" section in order to clarify it and we added a reference to Van Zandt et al. (1972) who invented the Magnetic Apex Coordinates. The figures have been updates accordingly.*
line 111: "dropc" → "drops"
Reply: *Corrected.*
line 122: "(Yando et al., 2011)" → "Yando et al. (2011)"
Reply: *Corrected.*
Fig. 2: the vertical lines are not very visible at first glance on top of the curves. Please consider making them longer, for example, to allow the reader to spot them immediately.
Reply: *The lines are in black now. Additionally the legend has been reduced in size so that more space is left for the figure itself.*

2 Reviewer 2

The main objective of the paper is to investigate potential cross-talk in POES/Metop TED proton channels at subauroral latitudes and provide a preliminary Kp-dependent cutoff latitude where the observations can be used safely. It also presents evidence of cross-talk in the MEPED electron and proton detectors. I do, however, have major concerns about the validity of some of the results. Moreover, the following discussion are somewhat superficial and inaccurate which makes the conclusions potentially erroneous.

Major comments:

1 Comment

Missing discussion on the physics of cross-contamination Both introduction and discussion focus on relativistic electrons in the radiation belts being the source of cross-talk in the TED and MEPED proton and electron detectors. Besides stating that TED is a cylindrical electrostatic analyzer and MEPED has a passive shielding, there is no technical specification nor discussion on how the potential cross-talk from relativistic electrons could happen. I recommend a short overview of relevant technical specifications on which type of particles and associated energies the detectors are designed to shield. This will provide a fundament for a much more relevant discussion on how contamination could still occur. Note that we combined this comment with a later one asking "Which particle energy is crosstalking?"

Reply: *For the MEPED instrument all necessary information on detector setup and shielding is written in the instrument description. Thus it has also be used for theoretical studies. The ability of relativistic electrons to create counts in the MEPED detectors e.g. is shown in Yando et al. (2011). Using the Monte-Carlo Simulation Toolkit Geant4 (Agostinelli et al., 2003), Yando et al. (2011) calculate the geometric factor for electron in the proton channels (their Fig. 4) which shows that P1, P2, P3 and especially P6 are susceptible for high-energy electron incidents.*
For information about the MEPED electron detector and possible impact from radiation belt electrons, see answer to Comment 2 of Reviewer 2.
The information on the shielding of the TED detector is not given in the instrument description in a similar

way. At least we did not find any technical memorandum that states the passive shielding thickness, its material, the exact size of the TED detector or which energies should be stopped by the shielding. The only information that is public available seems to be the mass of the TED predecessor instrument on TIROS-N being 3200g, see `https://www.ngdc.noaa.gov/stp/satellite/poes/docs/Seale1987_part1.pdf`*, page 3, the volume of the SEM-2 instrument (containing MEPED, TED and a processing unit) being* $0.0186\ m^3$*, see* `https://www.eoportal.org/ftp/satellite-missions/p/POES5-22032021/POES5.html` *and one image of these components that shows that all components are roughly about the same volume and that the TED instrument is housed in a metal box. This information is not sufficient for a precise study in the shielding, but we may use it for an (upper) etimate of the expected shielding.*
Estimation:
Tungsten is a typical material for shielding and it is used in the MEPED instrument, thus it is probably also used in the TED instrument. From the Green (2013), their Fig. 1 it seems that there is no special shielding except for the housing itself. The housing itself is a rectangular box. For simplicity and since we do not have the exact dimensions we may assume TED to be a cube with one third of the total volume V *and the total mass* m *is used for a tungsten shielding. As the cube has the smallest surface of any rectangular box this describes an upper estimate of the shielding:*

$$a_{cube} = \sqrt[3]{\frac{0.0186\ m^3}{3}} \approx 0.184\ m \quad (1)$$

$$A_{cube} = 6\, a_{cube}^2 \approx 0.2025\ m^2 \quad (2)$$

Assuming that all of the mass is used as thungsten shielding of the instrument, we can derive its thickness. This again is an upper estimate.

$$d_{shielding} = \frac{m_{TED}}{A\, \rho_{tungsten}} \approx 0.821\ mm \quad (3)$$

According to the continuous slowing down approximation (CSDA) from the estar/pstar database from NIST `https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html`*, electrons with an energy of 2 MeV and above are able to reach the channeltron detector for this upper shielding estimate. (For protons this must be above 25.0 MeV.) Given that we used upper estimates for the shielding it is likely that particles with less kinetic energy are able to penetrate the housing.*
Which particle energy is crosstalking?
The TED 0 degree background counts (and unfortunately also the differential TED proton bands 4/8/11 and 14) are significantly increased at L=4. This is even more emphasized close to the SAA at about 60 geomag. Longitude. Looking at the mirrored electrons (90 degree), their maximum approaches L=4 with increasing energy (see differential energy channels mep90e1-e2 and mep90e2-e3 and the highest nominal electron channel mep90e3). But even the mep90e3 maximum does not reach L=4. So it looks like the cross-talking electrons are more energetic. Referring to Fig. 5 of Peck et al. (2015) the virtual electron channel E4 (based on the P6 proton channel) has its flux maximum at L=4. So it is likely that electrons with an energy of 300 keV-2.5 MeV with a center energy at approx. 800 keV could be responsible for the crosstalk. Actually that would be similar to the GOES instrument. Most of this information has been added to the discussion.

2 Comment

The particle data and the associated discussion:
Line 124: "The MEPED electron channels mep0e1 to mep0e3 are sensitive to high energetic electron by design (compare Yando et al., 2011, for modeled sensitivity)." This is true, but it is very unlikely to be a problem. MEPED is integral channels which is designed to also measure relativistic electrons. The same relativistic electrons are counted in >30, >100 and >300 keV. Making this into differential channels effectively removes the contribution of relativistic electrons. Do the authors believe that the relativistic electrons penetrate the detector house and become non-relativistic electrons before hitting the detector?
Reply: *The original MEPED electron channels are integral channels without a clear upper energy threshold. The construction of differential channels by substracting the higher electron channel was chosen in order to get rid of an unknown upper energy threshold. Yando et al. (2011) however shows that relativistic electrons have a higher geometric factor in the lower channels than in the highest channel. Thus the construction of differential channels may result in a remaining sensitivity for high energy electrons seen in the differential channels. The shielding of the detector house should eliminate out-of-view electron crosstalk up to about 6 MeV (Evans and Greer, 2004b). Consequently this may be a source of crosstalk inside the radiation belts.*
This has been included to the discussion.

3 Comment

How is this (the energetic electron crostalk) only relevant for low Kp?
Reply: *This is very nicely shown in Ross et al. (2021). Their Fig. 14 compares 4.2 MeV radiation belt electron*

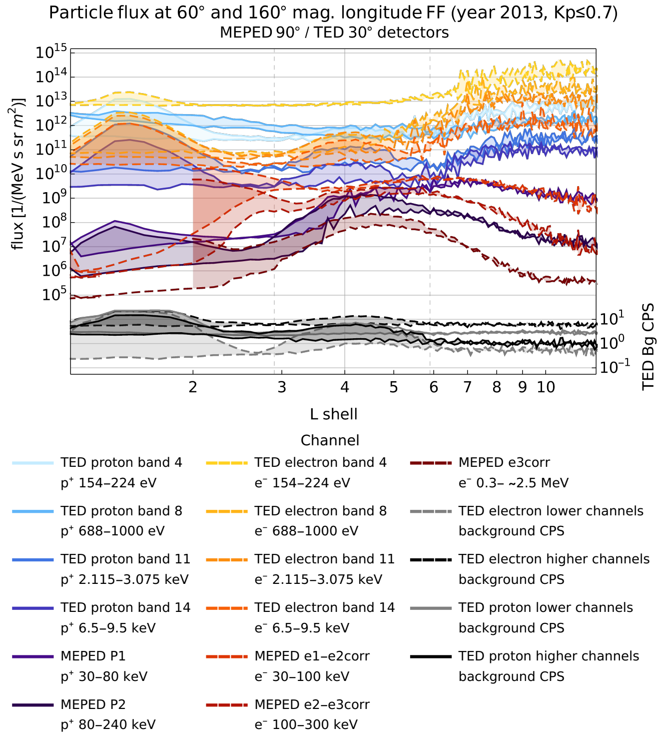
measurements of the Van Allen Probes at different L-shells with Kp. Whenever the Kp rises to higher levels (say above 5) the electron flux decreases by orders of magnitude. This is most prominantly seen at around L≈4. This is a good indication for a radiation belt crosstalk that dissappears at higher Kp. Ross et al. (2021) also states that EMIC or hiss waves are responsible for the radiation belt losses, while the contributions depend on particle energy and L-shell.
This has been added to the discussion.

4 Comment

Are the MEPED electron data used in this study corrected for the well-established low-energy proton (210–2700 keV) contamination in the MEPED electron channels? Cross-contamination by proton was documented already by (Evans and Greer, 2004b) and confirmed by Yando et al. (2011). It is strongly questionable to consider other sources of contamination before ruling out the well-known problems. I appreciate that the authors use the Omni detector to effectively exclude solar proton events, but it does not account for cross-talk of low energy protons. I highly recommend that the MEPED electron data is either corrected for low-energy proton contamination or excluded in the current study.
Reply: *The MEPED electron data is not corrected for contamination by low-energy protons. This might be a source of error and this should be noted in the paper. Also we agree that this correction should be applied before a recalculation of the uncontaminated fluxes. Proton channel mep0P3 acually shows a similar pattern. This however might be due to radiation belt crosstalk as well. For the current paper we would prefer to note that there is probably crosstalk contribution in the original MEPED electrons channels at the shown latitudes but that the origin might be radiation belt electrons or low energy protons.*
This has been added to the discussion.

5 Comment: 0° detector

The discussion section ends with suggesting that for the MEPED energy channels the 0° detector might observed the "out of nominal field-of-view" electrons as pointed out by Selesnick et al. (2020). This is a good point, and raises the question why the authors limit their study to the 0° detectors? If cross-talk contamination is real, it should be evident in both the 0°/30° TED and 0°/90° MEPED channels.
Reply: *The limitation originates from the fact that we observed the contamination in 0° detectors while using these for another study. But of cause it makes sense to include the 30°/90° detectors as well. And, as noted by the reviewer, there is no good reason why this cross-talk contamination should be limited to the 0° detectors.*
The following graph shows the 30°/90° counterparts:



The main difference in comparison to the 0° channels, see Fig. 3, is that the MEPED channels show a typical flux maximum at lower L-shells, which consists of trapped particles. The flux enhancement of the mep90e3 channel (electrons up to about 2.5 MeV) for example is already very close to the L-shell range that shows intense cross-talk in the TED proton channels, which supports the idea that the contamination originates from radiation belt electrons.
Regarding the TED protons we should note that crosstalk response of the TED 30 proton band 8 is not as expected. There is a longitudinal difference but no clear maximum at L=4 as in all other proton channels.
This has been added to the description of Fig. 3.

6 Comment: SSA

Moreover, the paper states that the potential contamination occurs predominantly at longitudes corresponding to South Atlantic Anomaly (SSA). Figure 2 also illustrates that this is mainly an SH issue. At the longitudes associated to the SSA the detectors' pitch angle coverage are altered as previously documented by Rodger et al. (2010). This will naturally elevate the particle count rate simply due to seeing a different part of the particle distributions. Potential cross-contamination should therefore be assessed in terms of longitudes.

Reply: *We agree that the particle counts will potentially increase if we are observing a different part of the pitch angle distribution. However, the background counts are increased, so it doesn't seem to be an issue of seeing a different part of the pitch angle distribution.*
And as noted in the answer to Comment 1 of Reviewer 1, the cross-contamination is longitude-dependent (as seen in e.g. Fig. 3), but the latitude is not (except for a very small longitude range where we do not find a significant contribution). Since we are defining a latitudinal cutoff we are probably fine the way it is.

7 Comment

Result, table 1: What are the criteria for "enhanced subauroral peak" in the different flux measurements?
Reply: *The criteria are that a local maximum was observable in plots like Fig. 1. This affords a flux difference of more than a factor 1.778 (meaning every order of magnitude divided into 4 logarithmically equidistant flux levels) compared to the minimum at the equatorial boundary of the auroral oval in a significant fraction of the longitudes so that statistical fluctuations can be ruled out.*
This has been added to the description of Table 1.

Minor comments

8 Comment: Introduction, line 21-24

The authors highlight the importance of the study based on its potential impact on lower thermospheric and mesospheric chemistry. However, this is not relevant for the proton energies that is the main target examined in this study. The typical energies 1-10 keV measured by the TED proton detector are depositing their energy at altitudes corresponding to the F-region. They are not relevant for the production of NOx in the lower thermosphere nor HOx in the mesosphere. A proton needs an initial energy of 1 MeV to reach the lower thermosphere. Please, rephrase the introduction to avoid potential misunderstandings regarding its relevance and application.
Reply: *The reviewer is right in excluding a main impact for mesospheric chemistry. This is probably not possible/at too low altitudes. However the thermosphere at an altitude of 130-150 km should be impacted. We will use the term "lower thermosphere" including the mentioned altitude range in order to exclude a misunderstanding. We added some facts to point that out:*
Altitudes taken from Encyclopedia Britannica:
Thermosphere: 80-450 km
F-region: 160-400 km
Wissing and Kallenrode (2009), their Fig. 2: main energy deposition (using isotropic pitch angle assumption):
initial energy — altitude
p^+ 1 MeV — at 90 km
p^+ 10 keV — above 130 km

Wissing and Kallenrode (2009) their Fig. 9 lower panel: proton ionization peaks at 120 km in auroral latitudes elevated by 2 orders of magnitude compared to polar cap. Electron ionization rates are about factor 6 higher, but still this means the protons are responsible for about 14% of the NO production at auroral latitudes.
This paper: Without a correction of the crosstalk contamination we end up with a subauroral ionization peak at auroral levels, meaning artificially boosted ionization rates in the lower thermosphere (mainly between 130 and 150km).
In sum: We think that the proton contribution to the auroral ionization rates should be about 14% (and similar NO production rates). And that a missing crosstalk handling leads to similar but wrong proton ionization rates in subauroral latitudes. In so far we think it is relevant for the lower thermospheric chemistry.
Changes to the paper: Added the altitude range and the restriction to NOy to the introduction, the possible impact to discussion and summary.

9 Comment: Data

In terms of the MEPED electron data it is unclear which data the authors have used. Line 51: "All particle count rates have been converted into differential flux by dividing the energy range and applying satellite/channel specific geometric correction factors (Evans and Greer, 2004b)." To my knowledge data using these geometric factors are available only up to around 2014 as Green (2013) updated the geometric factors. How did the authors merge the data before or after 2014? Please, elaborate.
Reply: *The data is produced from the raw count rates. These have been provided in the old bin-format as well as in the raw data files after 2013. Therefore the data before and after 2013 is consistent.*
This has been added to the data description.

10 Comment: Discussion Line 106

It would be useful with a sentence to elaborate on the background correction by Green (2013).
Reply: *Well, that was a very good question. We were sure that this data is at least partly corrected for crosstalk. The reason for this is that the documentation is very misleading here:*
Green (2013) for example writes in Section
"2.2.5 Assessing the background

The last major task of the instrument is to ***assess the background that must later be subtracting by ground processing****. The primary sources of background are energetic protons predominantly in the South Atlantic Anomaly and energetic electrons from the radiation belts at subauroral latitudes."*

Note: Table 15 in Green (2013) clearly marks the differential TED bands as "processed".

In Section "3.0 ALGORITHM DESCRIPTION" of Green (2013) it reads:

"3.1 Algorithm Overview

The algorithm consists of a number of different steps or procedures because the instrument puts out a variety of measurements sometimes at different time cadences. These outputs include integrated energy flux in 2 bands for both protons and electrons and two look-directions, characteristic energy, energy flux at the characteristic energy, ***differential particle flux at 4 energies*** *and background measurements at a lower time cadence (for a complete list of outputs see Appendix B table 15)."*

So the differential channels are part of the algorithm output. And finally in Section "3.2 Processing Outline" it reads:

"These are the basic functions performed by the level-2 processing algorithm:

1. Read the level1-b file and calibration tables

2. Take the ones complement of the sensor data

3. Decompress data to raw counts

4. Calculate magnetic parameters needed to map to the ionosphere

5. Check for backwards times and resort

6. Linearly interpolate background measurements

7. ***Subtract backgrounds***

8. ***Change counts to physical units using calibration table values***

9. Calculate pitch angles at the satellite and at the foot of the field line

10. Calculate energy flux at the 110 km

11. Calculate errors"

All this implied that the differential flux is already corrected for crosstalk.

However we checked the TED data and compared the differential bands to the original sensor counts and there is no difference except for a constant geometric factor even in latitudes with strong background contribution. Thus we should say this very clearly: The differential TED bands are uncorrected, no matter which data format is used (before or after 2013).

All TED corrections mentioned in Green (2013) or in earlier versions (Evans and Greer, 2004a, 2006) are dealing with crosstalk impact on the total energy flux only.

Some notes shall be given for a future crosstalk correction for the differential TED bands: a) the background counts are measured for 3.2 s while the single bands are measured during 0.2 s only. b) even when considering the different measurement periods the background counts can be significantly higher than the single band counts. c) at least some of the background channels show saturation when being inside the SAA. Interestingly ony the background counts show saturation, the single band seem to be OK. In sum the background correction of the single TED bands cannot be a simple substraction of counts but requires a nonlinear function.

This has been added to discussion and summary.

11 Comment: Discussion Line 110-111

"Energetic electron crosstalk also explains the Kp dependence as Turner et al. (2012) point out that the radiation belt electron flux drops by orders of magnitude during geomagnetic storms." Although magnetopause shadowing can account for relativistic electron drop-outs, Turner et al. (2012) also shows how the radiation belt is rather quickly replenished and increased compared to pre-storm levels. Hence, I find the statement in 110-11 questionable and not supported by the reference.

Reply: *The strong correlation of the relativistic electron population with Kp is presented in Ross et al. (2021). It is true that the radiation belt recovers quickly after a storm - however these periods are not during high Kp-values any more. See also answer to Comment 3.*

This has been added to the discussion.

12 Comment: Figure 3

Acronym CPS not defined in the paper. Which energies do "lower and higher channels" refer to?

Reply: *CPS means counts per second and describes the sensor output. The lower channels are energy bands 1-8 (50 eV-1 keV), the higher ones are band 9-16 (1-20 keV). This information has been added to the description.*

13 Typos:

Conclusion, point 1: 60 N/S cannot be both southward of the SAA.

Reply: *Slightly rephrased.*

Abstract, line 7: a L< 6 → at L< 6

Reply: *Corrected.*

Result, line 95: extend → extent

Reply: *Corrected throughout the paper.*

Discussion, line 111: dropc → drop

Reply: *Corrected.*

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